Incubating Dreams

Awakening Creativity

by

Adam Jedidiah Haar Horowitz

SUBMITTED TO THE PROGRAM IN MEDIA ARTS AND SCIENCES, SCHOOL OF ARCHITECTURE AND PLANNING, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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Abstract

This research centers on the question of whether interfacing with dreams can help us explore and augment the creative potential of our minds. The dreaming experience at sleep onset, called hypnagogia, is the main focus of this thesis: these first minutes of sleep provide ideal conditions for incubating specific dream content and recalling it after awakening. This thesis presents Dormio, an interactive system which uses biometric-based audio interaction in hypnagogia to incubate and capture sleep onset dreams.

Dormio incubates specific dream themes; allows for multiple bouts of hypnagogia in one nap session; has automated capture of dream reports; and enables users to explore phenomenology at adjustable levels of consciousness. Dormio further augments human creativity, benefitting both objective and subjective ratings on a battery of creative performance metrics including Creative Self-Efficacy, Creative Storytelling Task, Alternative Uses Task and Verb Generation Task. Both the hypnagogic state and specific hypnagogic content confer creative benefits, suggesting a causal effect of dream content on creativity.

The incubation of dreams has fascinated people for millennia, yet reliable protocols have proved elusive. Dormio offers a mobile and inexpensive protocol, enabling controlled experimentation on all the ways in which nightly dreams help construct daily cognition. Understanding sleep onset allows us to understand the mechanisms that bridge daytime and nighttime thought, consciousness and unconsciousness. Understanding creative boosts in hypnagogia allows us to understand cognitive flexibility across the sleep-wake cycle, from how we see ourselves to how others see us. Understanding devices which go beyond design for daytime to interface across levels of consciousness opens a broad swath of possibilities for interacting with humans as we truly are — thinkers on a 24 hour cycle.

Thesis Supervisor:
Pattie Maes,
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None of this, from step one, was done alone. Nor could it have been. I am a bridge builder and bricoleur, and nothing without the nodes. You might think this is a lot of names, niceties, neighborhoods--but believe me, this thinking was and is inextricably situated.

I proposed this ludicrous, dreamy idea while awash with new technological prospects in class with my soon-to-be advisor Pattie Maes, energized after a lecture from Robert Stickgold on memory and dreams, which followed a talk with John Gabrieli on the need for applied neuroscience. Each of these individuals inspired me, worked patiently with me, mentored me. Ishaan Grover sent me a message, let's do it, and suddenly it was all possible. When it was time to pilot, Pedro Reynolds-Cuéllar was ready to join forces with Ishaan and I, while Marie-Therese Png was willing to be the ultimate subject. Back in Fluid Interfaces, Tomás Vega and Oscar Rosello were my co-conspirators, collaborators, brothers, more giving and gifted labmates than anyone could ask for on this project and every other, thank you. Judith for dreaming, Abhinandan for your generosity, Eyal Perry for expertise and execution, Matthew Ha for the momentum, Christina Chen for sensibility both aesthetic and pragmatic, Kathleen Esfahany for the force which made the final leg feasible. The sleep scientists who have been so welcoming to me and my work, Michelle Carr and Tore Nielsen, Ed Pace-Schott and Dierdre Barrett. And Massachusetts might have beaten me back before all of this if it weren't for Seth, Erik, John, and Jordan making it an unlikely home and Joseph Keller making space for me in BCS. In the Media Lab, I looked to the inspired Ani Liu, the grand Gerxin, the whole Hotmilks Foundation for life and love. In the extended MIT campus I found refuge amongst the will-o'-the-wisps and wanderers in the MIT Museum Studio with Seth Riskin, Sarah Schwettmann, Adam Burke and Ben Miller. At home at the Egg House I was nourished from head to heart, backseat frying and backyard fires with Agnes Cameron, Gary Zhexi Zhang, Zacharia Jama, Devora Najjar, Jake Read. For magic and memory and moments of instability I lean on Tessa, Tim, Jukie, Sam, Emily, Old Will, Thanos, Luisa, Martini, Prathima, Theoretical Ernest, Dani Linda, Marcial, Noemia.

Jessie for being who you are, Will for being who you are, Mom for being who you are, Dad for being who you are, and each of you for being who I am.

For Nan

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The Outline

1. Introduction: An extremely abbreviated history of how science has approached sleepers, how I came to care, and why you should too.

2. Background
    a. How We Sleep: Relevant mechanisms of sleep in the brain and body.
    b. How We Dream: Relevant mechanisms that drive the dreaming mind.
    c. Hypnagogia: What sets Hypnagogia apart from other types of sleep and dreams, and how these differences create opportunities for sleep and dream interfaces.
    d. What Use Is Sleep: The benefits of sleep, each opportunity areas for interfaces. This section focuses on restoration, storage and creativity.
    e. What Use Are Dreams: The benefits of dreams, each opportunity areas for interfaces. This section focuses on self-examination, memory, learning, emotion, and finally creativity.
    f. Creativity: To build a dream interface which augments creativity, we need to define creativity. This section details past attempts to understand, and assess creativity.
    g. Related Work: Related HCI and Neuroscience work focused on measuring and influencing sleep and dreams.

3. The Dormio Device
    a. Serial Incubation: How the Dormio device incubates dreams using our Serial Incubation technique for targeted dreaming.
    b. Hypnagogia Detection: The ways in which the Dormio device detects sleep onset, including passive behavioral, physiological, and subjective measures of sleep.
    c. Hardware: The form factor, circuit board and sensing setup of the Dormio system.
    d. Software: The iOSApp, Web App, and Data Analysis platform built for Dormio.

4. Experiments
    a. Pilot Experiment: The pilot (n=6) Dormio experiment, which incubated dreams of 'Fork' or 'Rabbit' and tested for within-subjects differences in creative performance.
    b. Thesis Experiment: The follow-up (n=50) Dormio experiment, with conditions of incubated dreams of 'Tree' in sleep, incubated thoughts of 'Tree' in wake, and sleep and wake without incubation. Participants were tested for across-subjects differences in a battery of creativity tasks in which the central theme on each task was 'Tree'.
        i. System: Device updates from the pilot experiment
        ii. Methods: The experimental design and assessments used.
        iii. Results: The good stuff! Results on dream control, dream capture, hypnagogic phenomenology and physiology, creative benefits of incubated dreams for the Creative Storytelling Task, Alternate Uses Task and Verb Generation Task, and correlations between degree of dream incubation and performance on each task.

5. Discussion
    a. Our Results: Expounding: The meaning of these results, which have implications for how we can understand creativity, dreams and the self in sleep.
    b. Other Techniques: Expanding: Two small pilot experiments which are relevant for future work--one in which we see whether the Dormio system maintains stage N1 sleep by PSG standards, and one in which we try iterative dream incubation where each suggestion builds on the last to send a subject deeper into a dream story,
    c. Other Communities: Extending: Dreams are a subject both personal and universal. This section covers work done to bring Dormio into the broader scientific and artistic communities.
    d. Ethics: Considering the serious ethical implications of any sleep and dream interface.
    e. Limitations: Controlled experiments are limited in scope and science is messy. Here we cover the many pieces which future research and readers can improve on.

6. Conclusion: It's Just A Dream
    a. The Why Tying Neuroscience and HCI: How this work engages in translational neuroscience, enables new experiments, and informs introspection. How the results of this thesis experiment can be understood in the context of each.
    b. The Much That Calls for More: Now and Next: A lullaby, a wakeup call.

Prelude

My mother whispered dreams to me as a child, whispered as I fell asleep, as she had whispered to my father. She whispered rabbits to me, prodding my grogginess with queries, offers of visions. And 20 years later, as I whisper rabbits to my subjects, this memory dawns on me, the cycles of then and now, day and dusk, reminiscence stuck and shaken loose, the cycles of stories. If you can put a dream in a rabbit, can you put a rabbit into a dream? I wonder.

What dances into a dream, and why?[1] And who dances out?

[1] "They have a lot of things going for them," my mother says, explaining her choice of incubation theme. "They're silent except in extremes. They thump the floor and fling themselves in the air in the most extraordinary fashion so that they're almost sideways and it is a dance of joy. They only make a sound when they are terrified unto death. They can know you and come to you but they only communicate by coming close. They're silky, they're embedded, they imply a landscape. They're intimate but distant, elusive but yours. Like a dream." Dreamy indeed.

Introduction

> *"...one cannot properly describe human life unless one bathes it in the sleep into which it plunges night after night and which sweeps round it as a promontory is encircled by the sea…"*
>
> — Marcel Proust, *The Guermantes Way,* 1920

Sleep, our strange, forgotten country of the mind. It truly astonishes me, the magic of it, this nightly experiment in total loss and reconstitution of consciousness, the otherworld to which we are inexorably pulled: Each cell in our body containing tiny molecular clocks, producing and breaking down CLOCK proteins in tick-tock-clocking 24 hour cycles to keep time, intimately tying our bodily rhythm to the rhythmic rotation of the Earth. As our planet turns toward the dark, so too our mind's eye darkens on it. We walk across the borderland into unconsciousness twice daily, tracking invisible residue back and forth from each world as we come and go. The 'I' that I call 'I' leaves me every night and somehow I trust it to return.

For quite a while, this was the end of the story. The brain was, by all scientific accounts, turned off for a wee respite, a break from all the hard daily work of processing and predicting the lit landscape, then snapping back on in the morning. Benefits from a night of sleep were considered passive, just a product of a lack of sensory interference during sleep in contrast to periods awake.[2] It is only in the last half-century, after Eugene Aserinsky placed electrodes on his sleeping 8-year-old son and saw separate, identifiable stages of REM and NREM sleep, that researchers began testing whether specific aspects of sleep physiology may enable the cognitive boosts we get from a night in bed.[3]

There has been a veritable explosion in this young sleep neuroscience field since, and much of it reveals a crucial contribution of sleep in composing our daytime cognitive performance, from emotional stability to creative output and memory encoding.[4] Socially, cognitively, and emotionally we are dependent on sleep — not to mention for our physical health, educational performance, economic outcomes[5]…we'll dive into specific experiments and mechanisms in the 'What Use Is Sleep' section, but reader, just take a moment to:

a) consider the remarkably varied kinds of problems you benefit from 'sleeping on', whether it's taking a night of rest before sending that angry email or going to bed anxiously cramming for a test and waking up ready to tackle it, and

b) another moment to consider how many simultaneous ways you feel and behave awfully after a night of sleep deprivation[6] and

c) one more moment to realize that 'you' (the awake reading conscious you I have the pleasure of speaking to from a great mental distance) do *nothing* whatsoever to actively orchestrate these benefits or protect against these detriments, you simply lie down, and some wave washes over and brings (a) and (b) to your doorstep.

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[2] (Jenkins and Dallenbach 1924)
[3] (Aserinsky and Kleitman 1953; Duff 2014)
[4] (M. Walker 2017) This book is thorough and super readable. If nothing else, it will scare you straight into an 11:00 pm bedtime for an 8 hour sleep cycle, and very likely extend your lifespan.
[5] This is a remarkably recent conclusion! In the 1990's a leader of the sleep science field, Allan Hobson, quipped "the only known function of sleep is to cure sleepiness" (Konnikova 2015).
[6] Prolonged wakefulness leads to a progressive impairment of fundamental functions such as attention, learning, sensorimotor integration, and a range of executive cognitive functions (Vladyslav V. Vyazovskiy 2015; Killgore 2010)

The brain, it turns out, is not passive at all during sleep, just differently active than wake. And this whirring of activity is not just ongoing in the sleeping brain, it is experienced in the sleeping mind, active in dreams even as we (we who?[7]) lie still and silent. As we cut ties with the world of our bedrooms, the buzz of an internal universe begins, and we find ourselves where the wild things are. A hallucinating, emotionally labile, delusional, disoriented, amnesiac on a 1000 thread count carpet ride. We are liberated by our imaginations, consumed by them, immersed as pieces of our past float by, melt and morph, rerun-recombine-rewire. And overnight while we dream we are remade, soothed by adaptation to stress[8] and molded by consolidation of memory, and there is evidence that dreams plays a role in this composition.[9] Passing through the intensely imaginative stories we tell in our nightly dreams can be a source of overnight therapy, memory strengthening, or even creative inspiration.

My interest lies in building a technology which can enable the direction of dream content and allow for reliable memory of dreams, so that you can actively drive these various dream functions rather than passively wait for spontaneous eureka moments, consolidation, or healing.

Figure 1. *You can lead the wild things, but you cannot tame them.*

This thesis focuses specifically on the dreaming we experience at the onset of sleep, in a semi-lucid twilight zone between wake and sleep called the hypnagogic state. A great neurochemical transformation is coming over us, as the whole brain and body shift towards sleep, and yet it takes 9 definable stages to truly descend into sleep — all while phenomenology[10] shifts too, with varying levels of agency, imagery, and immersion.[11] These states of descent offer literal, trackable ties to the ontological dissolution of the self [12]

[7] If I leave my body behind for a first person, multisensory dream rodeo on a caterpillar made of coconuts, who is in fact in bed? Can I be in two places at once? Doesn't this violate my daily concept of unified selfhood, body and brain?
[8] (R. Cartwright 2013)
[9] (Wamsley and Stickgold 2019)
[10] I will say this word a lot. It basically means experience. The 'what it is like' of a brain-state. What's it like to see red? Not the wavelength, not the v8 occipital activation...what's the redness of red?
[11] (Ogilvie 2001) This paper is so good! Check it out!
[12] (G. Vogel, Foulkes, and Trosman 1966)

experienced as dreams. How magical is that, that a couple sensors can track your loss of sense of 'you', and that you lost 'you' at all?

The hallucinations reported at sleep onset are sometimes fragmentary, flashing symbolic imagery and sounds,[13] and sometimes emotionally intense, narrative and difficult to distinguish from reports of REM dreams later in the night.[14] For the purpose of this thesis, hypnagogic hallucinations are dreams, though they are often more emotionally flat, less figurative and faster than classically studied REM dreams. But what is so exciting about hypnagogic dreams is not the comparative emotionality or narrativity, it is the semi-lucidity: As we are not fully asleep, we can survey the changes in our mind during sleep onset, watch where dreams go, feel our executive function fail and watch our thoughts take on a life of their own, and report them at rates above 90% when we're woken up.

What is causing all these alterations in consciousness, and how do they create or relate to the awake mind? The primary roadblock in forming a scientific understanding of the dreaming mind is that while we can get high dream content report rates, we cannot direct dream content. The logic is simple: If we cannot control dream content, then we cannot do controlled experimentation on dream content.[15] The reliable control and capture of dream content has been an object of fascination in popular culture and in the brain sciences for decades [16]. Sleep laboratory techniques provide inspiring protocols for influencing dream content across sleep onset, deep NREM sleep and REM sleep: These range from influencing dreaming cognition with smell to pressure cuffs to video game play prior to sleep, yet protocols used in laboratories have consistently required expensive equipment, supervising clinicians, hours of pre-sleep training, and have largely only been able to incubate sensations or feelings.[17] Historical efforts using brief pre-sleep stimuli to purposefully include specific content in dreams have almost universally failed. [18]

And without reliable ways to control dream content, the study of the active role of dreams in conferring sleep-related benefits has been largely stagnant. Leading theories in the sleep science field posit dreams are the result of random neural firing, unimportant for learning or task benefits.[19] Dreams are denounced as meaningless, as a screensaver, as an epiphenomenon of the sleeping brain-state.[20] These dismissals of dreams are reminiscent of the earlier notion of sleep as passive, rather than active, a byproduct or correlate of ongoing adaptive processes. Many attribute benefits of sleep only to the brain state in which dreaming happens, as opposed to the dream content, calling dreams a byproduct of ongoing adaptive sleep processes. The vast majority of sleep studies which focus on cognitive changes pre-post sleep do not even collect dream reports, choosing to overlook changes in cognition in the intervening period. It is as if the cognitive revolution has somehow skipped over much of sleep science: Dreaming is, after all, just thinking in a different brain state, and though we learned long ago that ignoring the activities of the mind produces impoverished research, the sleeping mind is treated in large part as an experiential black box.

Before the debates on dream function in the laboratory, famous scientists, artists and engineers from Proust to Andre Breton, Otto Loewi to Edison, and Salvador Dalí to Sylvia Plath actively used their dream content for creative inspiration. Edison and Dalí regularly practiced the 'steel ball technique' to make use of hypnagogic dreams specifically; napping with a heavy object in hand and, when muscle tone lessened and

[13] (Noreika et al. 2015)
[14] (G. W. Vogel 1972)
[15] (Nir and Tononi 2010) this paper too, read this one
[16] (Brill and Freud 1934)
[17] (Baekeland, Koulack, and Lasky 1968; R. Stickgold et al. 2000; Sauvageau, Nielsen, and Montplaisir 1998)
[18] (R. D. Cartwright et al. 1969; Goodenough et al. 1975; J. Allan Hobson et al., n.d.; D. Foulkes and Rechtschaffen 1964)
[19] (J. A. Hobson and McCarley 1977; Allan Hobson 2003)
[20] (David Foulkes 1982; Flanagan and Journal of Philosophy Inc. 1995)

the object dropped to the floor below, awakening during sleep onset to capture ongoing hypnagogic cognition.[21] Edison purposefully napped while musing over an unfinished problem, and when it did come up in his hypnagogic dream, called this twilight zone of semi-lucid hypnagogia his 'genius gap' and found it fertile for creative solutions.[22] These luminaries sought benefits specifically from the dream content, not just dream state. As dreaming is thinking in a different brain state, it potentiates thought we might not think with a waking brain.

Creating a reliable protocol for placing problems of our choosing into the genius gap, by bridging brain science and technology design, is the goal of this thesis. In collaboration with designers and engineers in my Master's studies I have created a new method for dream incubation, called serial incubation, inspired by the 'steel ball technique'. This method involves multiple wakeups in hypnagogia with repeated auditory dream theme suggestions and collection of dream reports upon each awakening. To enable serial incubation we built the Dormio technology, a system composed of a hand-worn wearable electronic device and an open-source software interface. Dormio automatically monitors heart-rate, skin conductance and muscle tone biosignals to track hypnagogia, delivers audio cues in the sleep onset period to incubate specific dream themes, and prompts for multiple dream report recordings in each session to capture content. Dormio includes a web interface for visualizing biosignals and programming audio interactions, a server for storage and automated analysis, and an iOS app for mobile interactions. This inexpensive, portable, serial incubation device is a closed-loop, sleep state aware system enabling presentation of dream direction stimuli specifically during hypnagogia. We have tested the device in a pilot experiment (n=6) and this thesis experiment (n=48) with promising results for dream control, dream capture, and augmented creativity. These results are the first of their kind, demonstrating direct causal links between dream content and post-sleep performance in a controlled experimental setting.

Dormio enables dream incubation without the need for extensive pre-sleep training, expensive and uncomfortable sensor equipment or supervising sleep staging technicians. The applications of dream themed human-computer-interaction (HCI) devices range from nightmare alleviation in PTSD to creativity augmentation, anywhere that dream content has a marked effect. Serial incubation protocols in hypnagogia enable simple, mobile, cheap dream science, and potentiate a new form of controlled experimentation linking daytime and nighttime cognition. With a protocol for dream control, we can empirically test whether targeting dream content creates performance benefits post-sleep. Suddenly we can probe the causal active, as opposed to correlative passive, role of dreams in sleep-dependent processes. This project thus unites psychology, technology design and neuroscience to bear on the central question of whether sleep interfaces can be utilized to explore and even unleash our dreaming minds — to explore the forgotten country.

> *"I believe in a resolution of these two states, dream and reality, which are seemingly so contradictory, into a kind of absolute reality, a surreality…"*
>
> — André Breton, *Surrealist Manifesto,* 1924

[21] The steel ball technique used by Edison and others, while inspiring, remains an extremely limited dream interface. It allows for only one entry into hypnagogia as it jolts users fully awake, it restricts users to only one option of wakeup depth immediately after muscle control loss, it requires an uncomfortable napping upright position, it sets no reliable protocol for capture of multiple dream reports, and allows for no reliable dream theme incubation.
[22] Heller, H. Craig. *Secrets of Sleep Science: From Dreams to Disorders*. Great Courses, 2013.

Your Experience as an Experiencer

> *"The camera is an instrument that teaches people how to see without a camera."*
>
> — Dorothea Lange, *Dorothea Lange: A Photographer's Life,* 1978

I am interested in dreams because I am interested in myself. Interested, especially in what I mean by 'myself', and who is meaning it. I hope you, too, are interested in you, and perhaps are interested in me, enough for you to read on with me about us.

We know ourselves by looking in. And yet paradox abounds in this introspective loop — especially when we are attempting to understand thought in periods like sleep which range into unconsciousness and inattention. How, for instance, could I know if I am aware of something I am not attending, when any answer I attempt to give brings my conscious attention to that thing?

If this feels a little abstract, consider with me all the mornings I've set my alarm for 8:00 am and woken up at 7:59 to turn it off before it rings.[23] A normal occurrence at first glance, but uncanny when reflected on. Who woke me up? Well, it was me… but me waking me up doesn't make much sense, because I would have to be conscious (aware) to know the time, know I wasn't awake, and wake me up, meaning there are two me's…[24] And this unconscious me, this one I don't have conscious executive control over, it seems to have a concept of time that's even more accurate than my waking one! If I asked you right now what time it is, after you had your eyes closed and hadn't looked at a clock for 8 hours, do you think you could guess it with a 1 minute margin? And yet, 'you' can, and not only that, that unconscious version of you is listening to conscious you all the time — if I decide one morning to set my alarm for 7:30 instead, then my endogenous wakeup moves to 7:29. Somehow they know, somehow they listen, yet they can't talk — or we can't hear them, perhaps suppressing, perhaps tuned to the wrong frequency.

How can I come to know the character of that unconscious awareness, of my inattentive self; the sense of time, the structures of association, memory, implicit bias, the personality extant in my attentional periphery, my unconscious personhood, when introspection is itself conscious and attentive? What do I know that I don't know I know? And beyond knowing it (me), how can I (it) aim it, harness it, amplify it, direct my unconscious to calculate or contemplate this or that while my attentional fovea goes about my day? It's extremely frustrating that the 'me' that looks for me (attentional, aware) in fact structures the 'me' that I find, and as such, places hard limits on introspection. If Schrödinger's cat was in a boring lecture instead of a box, in an attentional/ inattentional superposition, and I pointed the attentional spot inwards to examine it, the light would make it attentional every time!

Sleep is an access point, and an opportunity, for a sneaky superposition investigation. Suppressed unconscious thoughts and unfinished conscious ones bubble up from the day when we settle into sleep,[25] begin to speak (not in the Freudian sense, or at least not only, simmer down dear reader, see the citation). Every night we slip into states where we each become someone else, with different memory sources,

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[23] (Born et al. 1999)

[24] Maybe, dear reader, you're thinking that I'm unfairly conflating awake and aware, and that's a fair contention; there is a sleeping awareness in dreams, but that's not the one that wakes me up, at least not in any way I can consciously introspect on from a dream state.

[25] ("Dreaming of White Bears: The Return of the Suppressed at Sleep Onset" 2008; Wegner, Wenzlaff, and Kozak 2004)

associative patterns and emotions than while we walk awake.[26] Where we 'get out of our own way', which is what my subjects keep saying about their experience in hypnagogia — implying there is both a 'we' being blocked and a 'we' doing the blocking — and hear ourselves anew. Where metacognitive control (the ability to reflect on our thought) and cognitive control (the ability to direct our thought) erratically decouple, and we can pay attention to thoughts we cannot control, watch our minds wander.

> *"The word 'I,' then, is primarily a noun of position, just like 'this' and 'here."*
>
> — William James, *A Pluralistic Universe,* 1908

What's Here for You

> *"It is hard to be finite upon an infinite subject, and all subjects are infinite."*
>
> — Herman Melville, *Hawthorne and his Mosses,* 1850

Maybe this introspection all sounds a little wonky to you. There are purely practical uses for the sleep science and technology presented in this thesis as well, clinical opportunities, cognitive augmentation enabled and evidence to back it up. But this thesis is not a textbook on sleep and dreams, and there are some great ones out there. If you want to read about the health benefits of sleep in depth, you should read Matthew Walker's *Why We Sleep.*[27] If you want to understand the history of the study of dreams from the vantage point of philosophy, neural network modeling, clinical medicine, neurobiology and more read Allab Hobson.[28] If you want to dive into the neural mechanisms of sleep, you should read Ed Pace-Schott's *The Neurobiology of Sleep.*[29] If you want to understand the intricate links between sleep and memory, watch Robert Stickgold's *TED Talk.*[30] If you want to understand mechanisms of memory across the lifespan, watch John Gabrieli's 9.00 lectures on MIT OpenCourseWare.[31] If you want to understand broad possibilities for cognitive boosts using technology that builds on brain science, watch Pattie Maes speak on her work in Cognitive Augmentation.[32]

This thesis is instead an offer of a specific, novel technological vantage point into experience of the inner workings of sleep and dreams. Unlatching the windows for a view, not showing you the blueprint for the house. My suggestion, and the focus of this thesis, is using this lever for augmenting creativity, for a dreamt rediscovery of your imaginative impulse, but it is not prescriptive. Subjects in our experiments have suggested we apply this tech to therapy, memorization, lucid dreaming, empathy building, roller coaster rides and evenings spent as Aquaman, and more power to them. I want you to rediscover a part of yourself that has been lost, an extremely slippery character hiding in the interstitial space between sleep and wake, and do with yourself what you will.

- If you are a brain scientist, read on for characterizations of a brain state which mixes wake and sleep in terms of EEG profiles, local brain activation and neural network interactions. This thesis

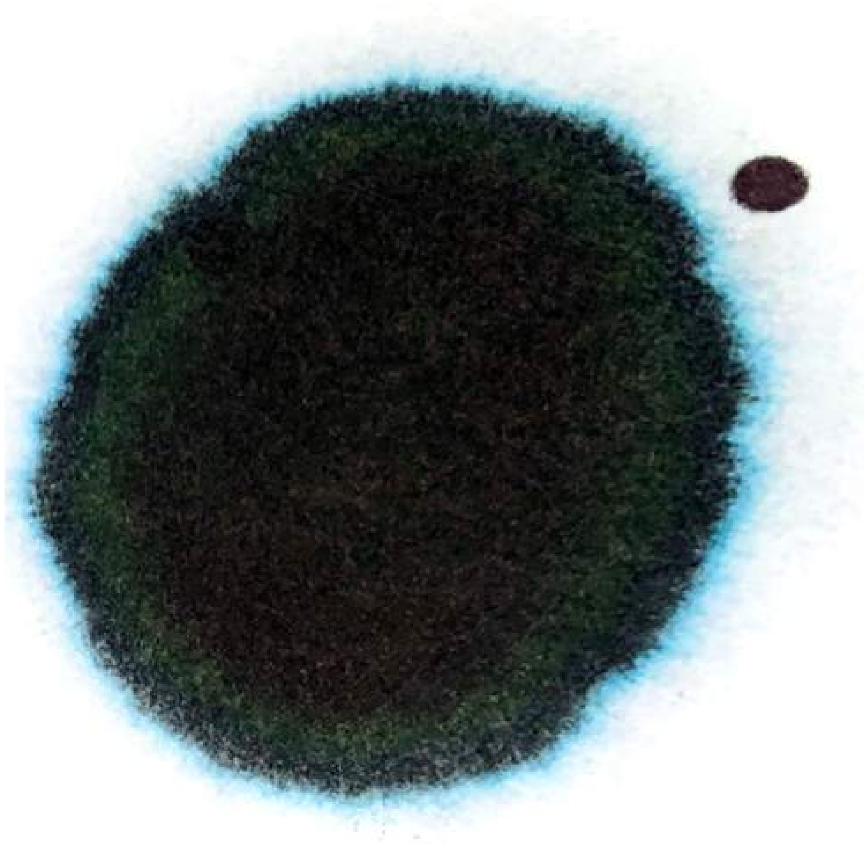
[26] Another introspective split is the commonly reported 3rd person dream: I see myself, from behind, on a date with a dragon shaped car. Who here is the 'real me'? The one with my body, or with my perspective? And what if this 1st person has a different feel, more accepting perhaps, than my waking personality? What if 3rd person me is more extroverted? The dream offers strange splits where body, perspective, even personality seem dissociable.
[27] (M. Walker 2017)
[28] (M. Walker 2017; Allan Hobson 2003)
[29] (Pace-Schott and Hobson 2002)
[30] (*TEDxRiverCity - Robert Stickgold - Sleep, Memory and Dreams: Fitting the Pieces Together* 2010)
[31] (*Lec 1 | MIT 9.00SC Introduction to Psychology, Spring 2011* 2012)
[32] (*MIT's Pattie Maes LiveWorx Keynote- From Distraction to Augmentation* 2019, "MAS.S63: Cognitive Augmentation" n.d.)

has direct relevance for those outside of the sleep science field interested in mind-wandering, meditation, metacognition, creativity, and the default mode network and executive mode network interactions underlying them.

- If you work in human-computer-interaction, read on to understand possibilities for interventions across all stages of sleep in a wide range of sensory stimuli, ripe for translation from the laboratory setting and limited specifically by immobile, expensive technologies. This is an engineering opportunity with wide applicability in cognitive augmentation, and an opportunity to design interaction across states of consciousness.

- If you are an artist or scientist, read on to understand the dynamics of, and find new routes to, a state of mind which has been an access point to creative inspiration for Salvador Dalí, Sylvia Plath, Thomas Edison, Edgar Allen Poe and many more. Your muses may be hiding in hypnagogia.

- If you are a curious self-explorer, read on to see yourself in a new light, with opportunities to experience changes in sense of self, time, body, space, and semantics. Learn more about why we sleep, how science has experimented with optimizing the sleeping brain, and what opportunities there are for citizen scientists and hackers to engage with that science in new settings.



Background

How We Sleep

Sleep is a global alteration in brain and body state, manifest at every level of biological organization from genes to intracellular mechanisms to networks of cells. In a beautiful set of cycles, sleep is entrained to the 24hour rhythm of the day and night: The suprachiasmatic nucleus (SCN), sits above (supra) the optic chiasm (chiasmatic), where the optic nerves cross (chiasm) in the brain, and samples light which the eyes receive. This small bundle of neurons sets its clock accordingly, and once it's entrained to the rhythm of environmental light and dark it guides the brain and body autonomously through time-dependent functions, the rhythms of eating and sleeping and more.[33] This is why, if you're jet lagged, it's recommended you get morning sun to help sync your internal clock up with a different daytime.[34]

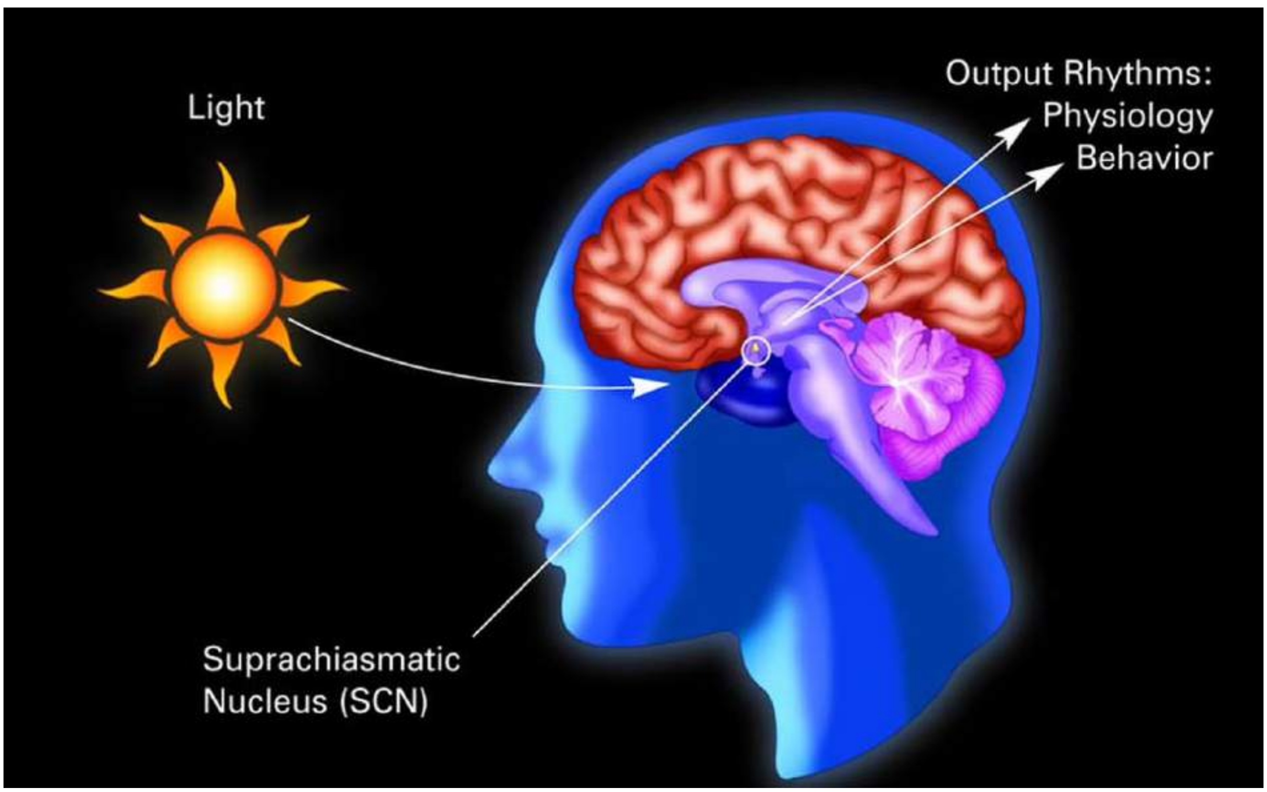


Figure 2. *Image from National Institute of General Medical Sciences, NIH*

The process of falling asleep begins based on combined input from the SCN on time of day (circadian input, *circa* meaning 'around', *dian* meaning 'day',) and from chemical signals, such as adenosine, which index your time spent awake.[35] Once sleep begins, there are two overarching types of sleep, rapid eye movement (REM) and non-REM (NREM) — which is subdivided into other NREM subtypes NREM 1, 2 and 3.

[33] (Pace-Schott and Hobson 2002)
[34] (Roenneberg, Kumar, and Merrow 2007)
[35] A very cool side note: Caffeine works by fitting into adenosine receptors on the neuron, competing with real adenosine for spots, so we do not get the same sleep pressure from docking adenosine.

Typically, these sleep stages have been defined, and tracked, with a combination of signal inputs from heart rate, breath rate, electroencephalography (electrical changes on the scalp related to neuronal firing, EEG), electrooculography (electrical changes on the face related to eye movement, EOG) and electromyography (electrical changes related to muscle tone, EMG), collectively termed polysomnography (PSG). EEG, EOG and EMG are the signals classically used in scoring sleep.

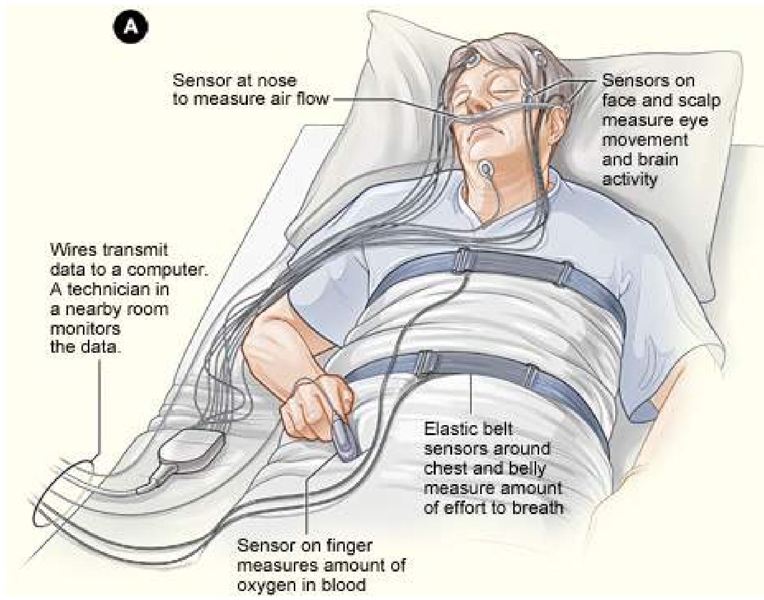


Figure 3. *A typical PSG setup. Not so comfy, not so cheap. Image from the NIH, What To Expect from a Sleep Study*

If you come sit in a sleep lab and look at a sleeping subject with PSG, you'll see coordinated changes in these signals that suggest a 90-110 minute cycle between REM and NREM sleep. These cycles, called ultradian, happen approximately 4-5 times every night, with NREM slow wave sleep prominent earlier in the night and REM more prominent later in the night. Over a whole healthy night of sleep, about 5% of sleep is N1, 50% N2, 20-25% N3 and 20-25% REM. The cycles are characterized as follows:

- When you lie down and close your eyes but are fully awake, EEG has low amplitude and high frequency, with prominent alpha frequency brain activity (8-12 Hz).[36] EOG shows frequent eye movements, and EMG shows high muscle tone. Subjects asked to report on thought will do so at rates near 100%, and reports will not be hallucinatory. In fact, I bet you are awake right now.[37] Go ahead and introspect, and learn a bit about waking thoughts.

- Sleep begins with Stage 1 NREM, where we are falling asleep. The onset of sleep is called the sleep onset period, unsurprisingly, and this is where Hypnagogia occurs.[38] This transitional phase is characterized by a loss of EEG alpha frequency activity, prominent theta activity (3-7 Hz), the

[36] Neurons are electrically charged by pumping ions across their membranes, which is how they generate action potentials, or fire, to communicate. When many ions are pushed out of many neurons at the same time, they can push their neighbours, and start a propagating wave. When the wave of ions reaches the electrodes on the scalp, they can push or pull electrons on the metal in the electrodes. The difference in voltages between any two electrodes can be measured and recording these over time gives us the EEG frequencies described here. Waves from the brain!
[37] One of the classic ways to tell whether you're in a dream or not is to attempt reading. If you read that sentence, and have accordingly arrived at this footnote with me, it's a good bet that this is all waking life.
[38] Some say hypnagogia is the experience of hallucinations, not the stage of sleep, such that it can occur even during early Stage 2 NREM sleep or during waking relaxation. For the purpose of this thesis, we restrict hypnagogia to the sleep onset period.

beginning of slow rolling eye movements back and forth, a decrease in muscle tone, shallow breathing, a lowered but regular heart rate and falling blood pressure. This period of sleep is where you experience the hypnic jerk, the muscle twitch which is familiar to many of us and often accompanied with a feeling of floating or falling and concurrent dream imagery.[39] Subjects awakened may deny they've been asleep at all — though they're likely to have trouble recalling the last few minutes of experience. Stage 1 brings about decreased environmental awareness, and typically lasts about 1-7 minutes. Subjects will report hallucinatory visions, most often fleeting feelings or imagery, e.g. "I could feel myself moving just the way the sea moved our boat when I was out fishing today" (examples taken from [40]).

- NREM 2 comes next, after a few minutes of N1, and can be seen by EEG signatures called K-complexes (high amplitude negative sharp waves followed by positive slow waves) and sleep spindles (bursts within the 12-15Hz range that last about a second). Eye movements and muscle tone are both greatly reduced. People are largely disconnected from sensory input from their sleeping environment, and when woken up will often confirm they were subjectively asleep. Dream reports collected from N2 are longer than those from sleep onset. Early in the night these are more conceptual, more plausible, more concerned with current issues, and typically involve greater volitional control. Reports from N2 are often thought-like, i.e. "I kept thinking about my upcoming exam and the subject matter it will contain". Later in they tend to be much more hallucinatory, dreamlike and difficult to distinguish from REM.

- After N2 comes N3, where EEG shows prominent delta waves (<2Hz), eye movements cease, and EMG activity decreases even further. N3 is often referred to as slow wave sleep (SWS) or deep sleep, as it's harder to wake subjects up from this sleep stage. If you do wake them up, they'll often be quite disoriented. N3 dream reports tend to be shorter than reports from REM, and they do not reliably incorporate details from waking life events. Little is known about N3 dreams as they have been rarely studied. [41]

- After passing through N2 and N3, NREM sleep lightens and then REM sleep begins. EEG activity in REM sleep is quite similar to EEG in a waking state, and quite similar to N1, with increased power in the theta frequency band and low voltage fast activity like wake. EMG in REM is completely atonal, making people unable to move so they cannot harm themselves in acting out dreams.[42] REM awakenings yield reports 80-90% of the time, like sleep onset. Reports tend to include elevated levels of joy, surprise, anger, fear, and anxiety, but sadness, guilt, and depressed affect are much less common, perhaps because of deficits in self-reflection.[43] REM dreams do often incorporate details from waking life events. [44]REM reports often have fully immersive hallucinatory narrative, i.e. "As the climbing party rounds the trail to the right, I am suddenly on a bicycle, which I steer through the group of climbers. It becomes clear that I make a complete circuit of the peak (at this level) by staying on the grass…"[45]

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[39] This feeling of falling at sleep onset is so common that it slips into nursery rhymes (rock a bye baby…it's easy to fly…the cradle will fall). After all, falling asleep is falling…
[40] (J. Allan Hobson et al., n.d.)
[41] (Cavallero et al. 1992; van Rijn et al. 2015)
[42] With the notable exception, in male sexed subjects, of an extremely predictable erection in REM sleep. Staging accordibly is referred to as the 'Flick Test'. (Fisher, Gorss, and Zuch 1965)
[43] (R. Fosse, Stickgold, and Allan Hobson 2001)
[44] (van Rijn et al. 2015)
[45] (Julian Mutz 2017)

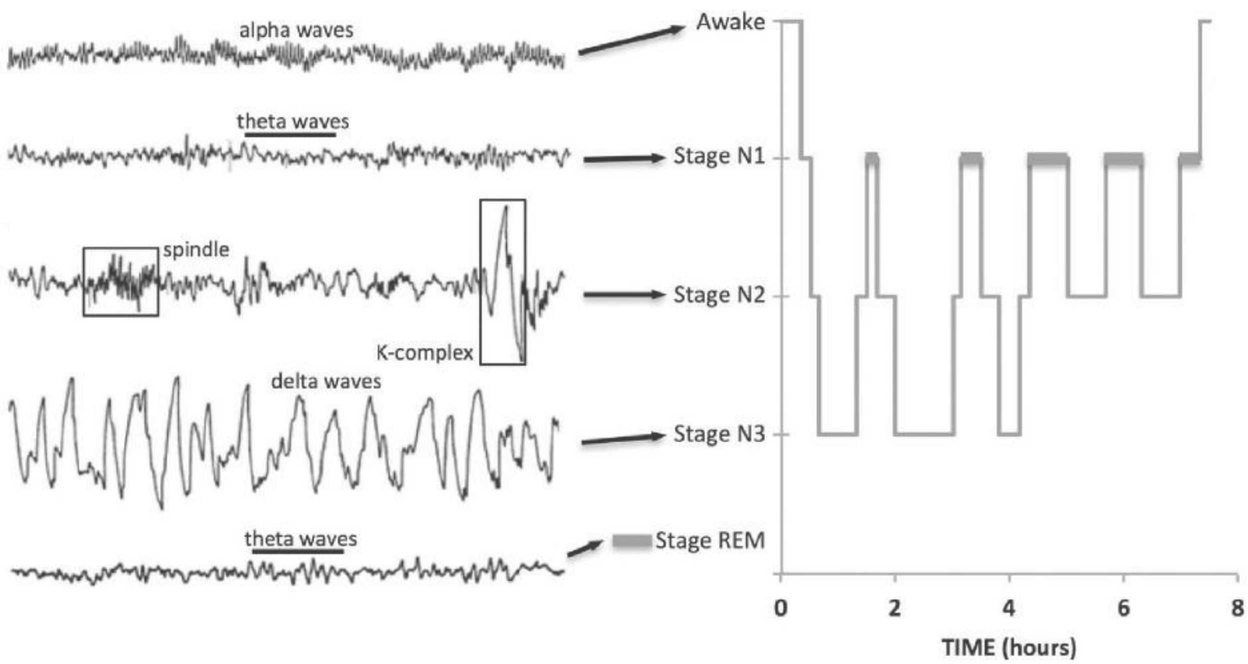

Figure 4. *Examples of EEG signatures of each sleep stage. Image Physiology of Sleep*[46]

How We Dream

> *"Once upon a time, I, Zhuangzi, dreamt I was a butterfly, fluttering hither and thither, to all intents and purposes a butterfly. I was conscious only of my happiness as a butterfly, unaware that I was Zhuangzi. Soon I awakened, and there I was, veritably myself again. Now I do not know whether I was then a man dreaming I was a butterfly, or whether I am now a butterfly, dreaming I am a man."*
>
> — ZhuangZhi, *the ZhuangZhi,* c. 300 BC.

As these cycles pass and we lie motionless, we build worlds. We dream up fictive events, heroic epics, we eat and dance and fully experience in an organized, story-like manner with integrated, primarily visual, hallucinations. This other existence is uncritically accepted in the same manner as are waking percepts. Dreamers are absorbed in the dream world and plot without awareness of an alternate reality in waking, except in rare lucid dreams (awareness that one is dreaming). The dream world is remarkably intact and intricate, and can even contain entirely novel imagery, plots and people never experienced in waking life. But upon awakening, we abruptly regain insight to decide which world is real, suddenly sure that all that dreamt experience was fictitious.[47] Coming to an awareness of this differentiation implies brain mechanisms that generate dreaming consciousness are not the same as those that generate waking consciousness.[48]

The REM state, most commonly associated with dreaming, involves profound changes in brain activation. When REM dreaming occurs the left and right prefrontal cortices, key areas in rational thought and logical decision making, are profoundly deactivated. Some posit this prefrontal deactivation drives the low recall

[46] (Carley and Farabi 2016)
[47] Most of us do, don't you? ZhuangZhi got mixed up.
[48] ("Dreaming: A Neuropsychological View" 2005; Pace-Schott 2011)

rate for REM dreams.[49] Four main clusters of the brain increase in activity: 1) the visuospatial regions at the back of the brain, which enable complex visual perception 2) the motor cortex, which instigates movement 3) the hippocampus and surrounding regions, which support autobiographical memory and 4) the amygdala, ventromedial prefrontal cortex and cingulate cortex, which help generate and process emotions and social interactions.[50]

These circuits subserving emotion processing are up to 30% more active in REM compared to waking thought, and combined with increased activation of motor cortices, may account for REM dreaming's prevalent emotions and movement. During dreaming, frontal contributions to memory retrieval may also be altered, because deactivated prefrontal regions typically subserve specification and search strategies, perhaps explaining the mixing of memories in REM dreams. The vmPFC, active in REM sleep, subserves "feeling-of-rightness" and "feeling of knowing", perhaps explaining the indiscriminate, emotional confirmation of accuracy for any item in dreaming consciousness.[51] Lastly, there is an overlap between the network of brain regions associated with self-referential processing during mind-wandering (the default mode network), and areas that are increasingly active during REM.[52]

This brain physiology illustrates the activation underlying a state of consciousness characterized by dream experiences that **can incorporate autobiographical memory; are highly visual, emotional, social, motoric, and accepting of the implausible; and are not highly logical or rational.** In fact, this functional brain activation is so tightly linked to phenomenology, that sleep scientists are able to predict the form of a dream (highly visual, highly motoric) from the fMRI or EEG signature of the ongoing dream. [53]

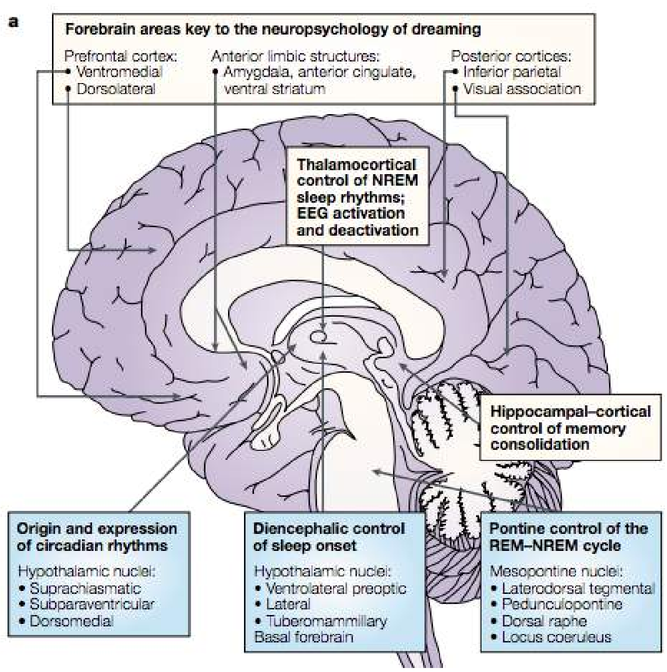

Figure 5. Ed Pace-Schott, *the Neurobiology of Sleep*

[49] (Vallat et al. 2018)
[50] (Pace-Schott 2011; M. Walker 2017)
[51] (Pace-Schott 2011)
[52] (Fox et al. 2013)
[53] (M. Walker 2017) (Siclari et al. 2017)

Since its discovery in the 1950s, REM was thought to be virtually synonymous with dreams — so much so that research often uses 'REM' and 'dreaming sleep' interchangeably — and the mechanisms and phenomenology of NREM dreams have been understudied.[54] But **REM is not equivalent to dreaming**. In fact, dreaming and REM sleep appear to be controlled by different mechanisms: Dreaming can be manipulated by dopamine agonists and antagonists (which mimic or block the effect of dopamine) while causing no change in REM sleep frequency, duration, and density.[55] Brain stem lesions can prevent REM sleep from occurring while individuals continue to report dreams after awakening.[56] And dreaming is obliterated by brain injuries which cause no clear effects on REM sleep.[57]

Recent research reveals a more complicated story, wherein **subjects dream throughout the sleep cycle.**[58] NREM wakeups reveal dreams up to 70% of the time![59] Much of the brain activation described above is likely common to NREM dreaming as well, and it's important to note that sleep has local phenomena (with partial sleep state features occurring in different locations simultaneously), so these sleep states are not homogenous or mutually exclusive. [60] It has been suggested that dreaming during NREM sleep relates to 'covert REM' brain activation processes, which have brief REM-like mechanisms.[61] **NREM and REM dreams may have similar mechanisms regardless**: in both states, reports of dream experience (any experience at all versus no experience) are associated with local decreases in low-frequency activity in the same posterior cortical regions.[62] The kind of experience reported, though, regularly differs: Later stage NREM dreams are comparatively emotionally flat, perceptually dry, less bizarre, and draw their content mainly from episodic memories, as opposed to the melding of recent and remote memories into an ongoing narrative in REM.[63]

Manipulation and interruption of sleep stages, the focus of this thesis, can increase the overlap between REM and NREM. Multiple awakenings from sleep elevate the frequency of REM physiology emerging at sleep onset in normal subjects: Dreams elicited under these conditions from NREM awakenings are 'enhanced', more bizarre and typically REM-like with different EEG correlates than NREM dreams preceded by no interruptions. Partial REM deprivation, which increases pressure to have REM sleep, also increases the dreamlike quality of sleep-onset NREM dreams.[64] Characteristics of REM, and concordant dream phenomenology, can pop up across the sleep cycle. **Dreaming might be best described along a phenomenology continuum**, ranging from thought-like to vivid narrative, as opposed to being described by sleep state.[65]

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[54] (Maquet 2000)
[55] (Solms 2000)
[56] (Solms 2000)
[57] (Solms 2000)
[58] (Siclari et al. 2017; T. A. Nielsen 2000)
[59] (R. Stickgold et al. 2001)
[60] (Mahowald and Schenck 2005)
[61] (T. A. Nielsen 2000)
[62] (Siclari et al. 2017)
[63] (Antrobus 1983)
[64] (T. Takeuchi et al. 2003; T. Nielsen et al. 2005)
[65] (Desseilles et al. 2011) A part of this continuum which I'm skirting a bit is **the relationship between dreaming and tripping on LSD**. Dreaming and hallucinating do involve some overlapping brain areas, and 50 years ago, researchers were rowdy enough to administer LSD to subjects during sleep onset and later sleep--both promoted REM sleep, interestingly enough, and haven't been replicated since the 60's, unsurprisingly. (Carhart-Harris and Nutt 2014)

Hypnagogia

> *"You know that place between sleep and awake? That place where you still remember dreaming?…That's where I'll be waiting."*
>
> — James V. Hart, *Hook,* 1991

While the interlocking of REM and NREM sleep cycles is complex, one simple fact is that we must fall asleep for them to begin. The tidal wave of chemical, electrical and experiential changes from wake, from level of brain activation to dream generation, have to happen sometime. Yet they do not happen all at once — there is no moment when 'awake' turns off and 'asleep' turns on. Instead, sleep onset lasts several minutes, and occurs in stages of descent into unconsciousness, collectively called hypnagogia, Hori stages, the sleep onset period (SOP), or NREM 1.[66]

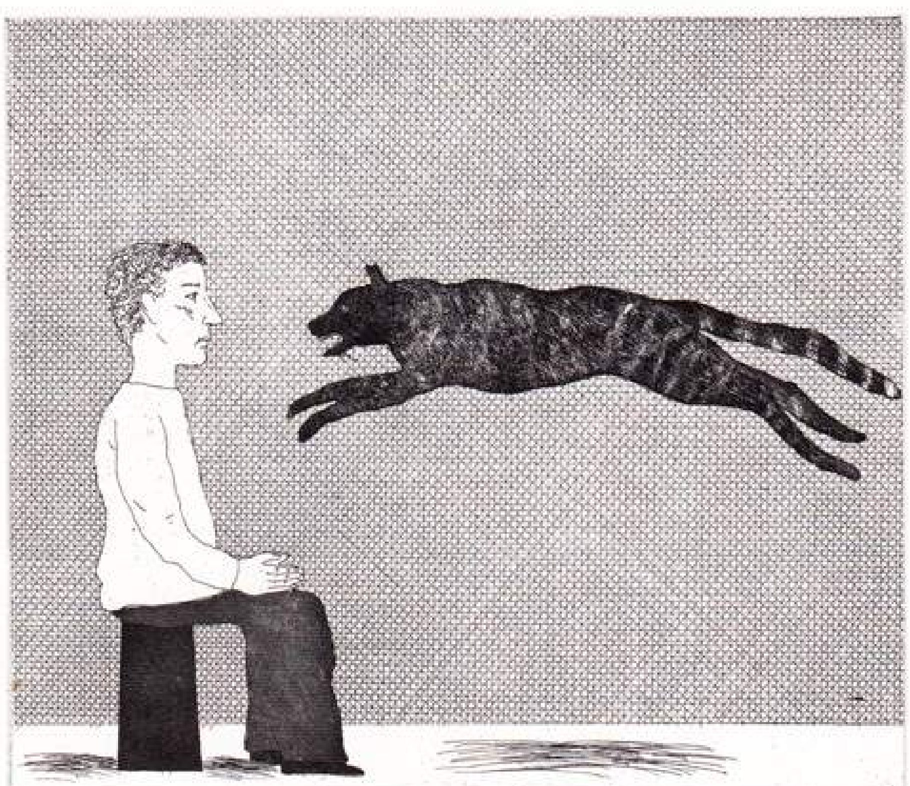

Figure 6. *Hypnagogia is familiar to many of us from passenger seat car naps. We drift off, the speed of the car slips into the content of the dream, a jetstream or a ski slope until our head falls forward and wakes us, for a moment unsure of what is wake and what is sleep. Artwork by David Hockney*

[66] The term "hypnagogic" comes from the Greek hypnos = sleep, and agagos = conductor. Other terms proposed for this strange semi-lucid state include Arnold-Forster's (1921) 'borderland state' experiences, Leroy's (1933) 'visions of half-sleep', or Chritchley's (1955) 'sleepening' state experiences. Similar phenomena occurring at the other end of sleep have been called 'hypnopompic' (Mers, 1903), leading out of sleep. In Italian, 'dormiveglia' (sleep-waking), describes both the hypnagogic and hypnopompic states. Though there have been debates and distinctions between these terms in the literature, NREM 1 or SOP or Hypnagogia, for the purpose of this thesis, they all refer to the descent into sleep preceding N2.

Hypnagogia is a middle ground, an experiential in-between. It is a space where we step outside ourselves and **begin to dream yet maintain capacity for mental surveillance**, a doorway through which we bring the world into the dream and the dream into the world. Dropping off to sleep is often accompanied by imagery, sounds and narrative so surprising, confusing, and bizarre that many subjects describe them as coming from outside of them.[67] Much of this can be accounted for because we are literally **losing functional pieces of ourselves** piecemeal. The deactivation of frontal areas occurs before the rest of the brain, concrete waking thoughts give way to unusual hallucinatory thoughts, cognitive agency declines before motor agency in these hallucinations, and the left hemisphere falls asleep before the right.[68]

The hypnopompic threshold between sleep and wake is also where sleep paralysis occurs, where sleepers wake up only partially and have a semi-lucid mind with a sleeping, paralyzed body. They commonly see demons and ghosts sitting on their chest, feel a shadowy presence, or have an out-of-body experience at sleep offset — each an intrusion of the dream into waking life.[69] Hypnagogia combines characteristics of wake, NREM and REM sleep, and seems to be the turning point where Freud's "transformation of ideas into hallucinations" begins.[70] **Here is the hinterland of the self**, here is where we dream while we suppose ourselves awake, here is where we can peer into sleep from semi wake and see the waking world anew from semi-sleep.[71] Yet hypnagogia has been **largely ignored** by science for the past 70 years.[72]

> *"...I felt like my mind was becoming more accustomed to the experience and that it was easier to relieve my inhibitions and think what my mind decided it should think, even if it was odd - or at times, a little dark. ...after being woken up once or twice, I gave up control of my thoughts and they began to flow much more freely. I particularly remember feeling that my consciousness was almost entirely untethered when I thought about the subject of my post-sleep story about a tree - when a person began exploring the freedom of space through tree imitation, before collapsing in a twisted heap and fully becoming a tree. Then, they proceeded to explore four dimensions - which was thoroughly confusing but a lot of uninhibited fun... I remember feeling like a lot of time passed in a very short period of actual time while exploring four dimensions through the lens of a tree's perspective. Another dimension was added! I didn't understand it, but it was there. I remember feeling disturbed and delighted by my thoughts throughout the process. I was thinking of how space and time work for trees. I thought about twisting...the experience wasn't pleasant for the person in my dream, and I recall being honestly disturbed by the process--by how dark exploring space got. I remember the person buckling at their middle under the strain, and falling forward until their forehead touched the ground. I recall wanting to pull the limitations away that made this happen--that made exploring space difficult and restrictive. I decided part of the issue is the human frame of mind, so the person in my vision became a tree, unshackled by the rigidity of human thought. They held the twisted pose far better, and stood straight. They decided three dimensions weren't enough, and explored a fourth. I remember a sensation of falling towards the*

[67] (Ogilvie 2001; T. Nielsen 2017)
[68] (Casagrande and Bertini 2008; Speth and Speth 2016)
[69] ("Erratum: Sleep Paralysis, a Medical Condition with a Diverse Cultural Interpretation" 2018)
[70] (Brill and Freud 1934)
[71] (Fox et al. 2013; A. Mavromatis and University of Brunel 1983)
[72] (Brill and Freud 1934)

tree's "head" as they did this, and falling endlessly and incomprehensively--until I woke up. I feel like many of the thoughts I had, particularly in the second half of the experiment, would not have been had (at least to the same capacity) without the aid of this sleep."

Subject 12, Sleep Tree-Incubation, Thesis Experiment

As A Research Opportunity

Tremendous changes in cognition are occurring during sleep onset, yet input and information continue to be processed during entry into sleep – albeit very differently. Data indicates that prefrontal areas may be the first part of the cortex to fall asleep as well as the last part to wake up.[73] Subjective reports of lessening of anxiety, increasing disinhibition and suggestibility, lessening of ego, and enhanced fluid association of ideas have all been reported from hypnagogia.[74] And yet, these changes happen while participants are still processing their auditory environment, and amazingly participants will often begin to dream before they are subjectively asleep.[75] They report hallucinating a range from static images to vivid, coherent, motoric, and spatially embedded scenes with self-participation: scene construction is thought to reflect the process of binding together disparate memory traces into a coherent whole.[76] And dream reports from hypnagogia include content of learning tasks presented pre-sleep, even in amnesic patients![77] This suggests that studying hypnagogia in depth could help us understand mechanisms underlying changes in anxiety, memory, fluid idea association and imagination, all while subjects can report ongoing experience from hypnagogic dreams.

Hypnagogic dream reports are phenomenologically more similar to those from REM than from N2 or N3, and EEG profiles show a greater similarity between the sleep onset period EEG and REM sleep EEG than between the former and stage 2 sleep.[78] The 'covert REM' hypothesis mentioned above proposes that hidden elements of REM sleep emerge during the wakefulness-sleep transition stage, and the relationship between REM pressure and vividness of sleep onset imagery suggests tight links between N1 and REM.[79] Both REM and N1 dreams seem to form links between loosely associated items, where dream sources are selected from memory on the basis of both distant temporal relationships and proximate semantic relationships. A recent study found that a third of N1 dreams in a trained participant featured semantically related items stemming from episodic memories that were separated by several years, ranging from 10 minutes to 15 years preceding sleep, yet bound together in space and time within the imagery. [80] This suggests the possibility that N1 dreams reflect offline memory consolidation and integration on the scale of decades. And recent research suggests that daytime events incorporated into N1 dream content are incorporated into later NREM and REM dream content within the same night of sleep.[81] This suggests that the focused study of hypnagogia could better help us understand changes in experience, information

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[73] It's been suggested that the deactivation here is one mechanism underlying similarities between experiences of daydreaming, sleep onset and REM sleep, on a continuum with gradually increasing quiescence of these areas. (Wamsley and Stickgold 2019; Fox et al. 2013)
[74] (T. Nielsen 2017; A. Mavromatis and University of Brunel 1983; Gruberger et al. 2015)
[75] (J. Allan Hobson and Pace-Schott 2002)
[76] (Hassabis and Maguire 2007)
[77] ((R. Stickgold et al. 2000) This is the famous 'Tetris' experiment. We'll cover it in detail later!
[78] (Bódizs, Sverteczki, and Mészáros 2008)
[79] (T. A. Nielsen 2000)
[80] (Broughton 1994); Stenstrom, P., Fox, K., Solomonova, E., & Nielsen, T. (2012). Mentation during sleep onset theta bursts in a trained participant: A role for NREM stage 1 sleep in memory processing? International Journal of Dream Research, 5(1), 37-46.
[81] (Wamsley and Stickgold 2019)

association and memory processing that we undergo in the gradual loss of consciousness and in later REM and NREM sleep.

Tracking the Fall

As sleep onset combines characteristics of states of wake and sleep, tracking this grey area in consciousness is a tough task. A useful comparison is determining the 'moment' of death — there really isn't one moment, as heart or brain or breath or blood-flow don't stop suddenly or simultaneously, we simply pick a threshold of change for a signal and agree on calling it death.[82] But historically there's been little agreement in what point to pick for determining sleep onset. Methodologies using the gold-standard in sleep science, PSG, essentially identify sleep onset based only on EEG signal and still disagree: Dement and Kleitman and Rechtschaffen and Kales scales equate falling alpha (<50%) with the beginning of sleep, while earlier scales by Loomis and contemporary scales by Roth prefer a later starting point (spindles) for locating the beginning of sleep. Common differing definitions for the moment of sleep onset are: the first 30s epoch of Stage N1, the first 30s epoch of Stage N2, the first of any 3 consecutive NREM (N1 or deeper) epochs, and the first of 10 consecutive epochs of NREM. Unsurprisingly, each leads to different PSG definitions of sleep onset. These scales are built for characterising the macrostructure of 7–8 h of nocturnal EEG activity, not the microstructure of the sleep onset period: They are scored in 30s epochs, which are unsatisfactory when a half-dozen coordinated changes can transpire within 30s as sleep is approached.[83] The classic PSG overnight sleep scoring systems are too coarse to properly track the SOP dynamics.[84] And regardless, identification of a specific point of sleep onset is fundamentally arbitrary within a set of continuous physiological changes![85]

The most granular and best researched divisions in the sleep onset period are the 9 Hori stages of sleep descent: these stages divide the standard stages Wake, N1 and N2 into nine EEG-based sequential stages passed through from waking to unmistakable sleep. There are two subdivisions of stage W, six sequences within stage 1 (with hypnagogic imagery most commonly reported at Hori stage 5), and Hori stage 9 corresponds with the beginning of standard PSG defined stage 2 sleep. Because these stages are fleeting, the epoch length chosen for scoring them is only 5 s long — yet some can even last less than 5 seconds! Awareness of being in the laboratory and of having control of the thought process declines continuously as people move through Hori stages 1-9.[86] And it's important to note that the Hori stages after Wake are all part of the sleep onset period, without a definitive point of sleep onset occurring in the descent.

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[82] The comparison between onset of death and the onset of sleep goes way, way back. Hypnos and Thanatos, respectively the Greek gods of sleep and death, are close brothers. In ancient Egypt, sleep was considered a rehearsal for death. In the Talmud, sleep is described as 1/60 death, at the threshold of human perception, where we get a view of death from life. In the morning, Jews will give thanks for the faithful return of their soul to their body after a night of sleep. (Duff 2014)
[83] (Ogilvie 2001)
[84] (Santamaria and Chiappa 1987)
[85] (Rechtschaffen 1994)
[86] Generally this is the movement from alpha activity concurrent with waking eye movements through a phase where declined alpha is accompanied by slow eye movements (Hori 1982; D. Foulkes and Vogel 1965)

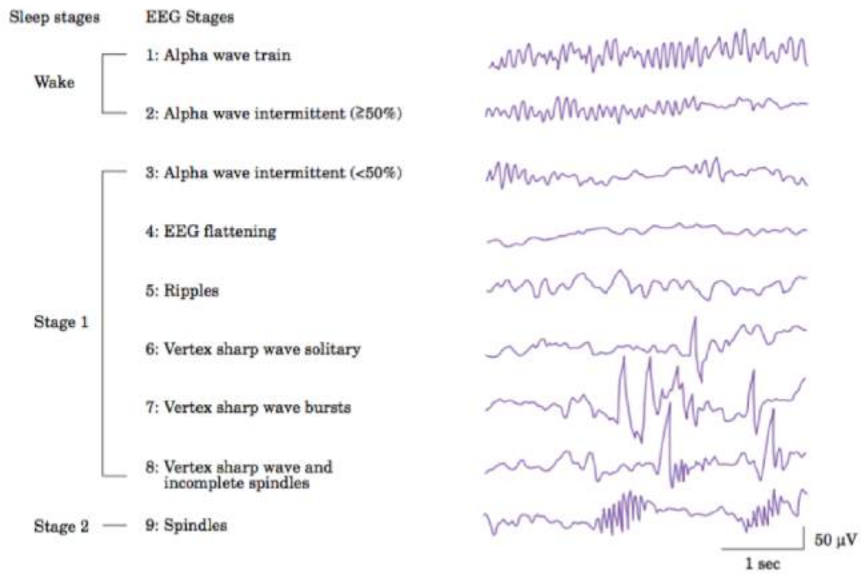

Figure 7. *The Process of Falling Asleep (Ogilvie, 2001)*

The Hori system is an exciting advance in characterizing sleep onset, yet it is hugely time consuming to score. The EEG systems required are expensive, laborious and normally immobile, restricting the study of sleep onset to well funded laboratories over short periods of time. The discomfort of the sensors and the unfamiliarity of the laboratory environment further change the quality of sleep in participants.[87] And participants often show natural individual variability in EEG alpha dynamics approaching sleep, which is a key factor in scoring the Hori stages. Even amongst experts in sleep onset, Cohen's Kappa measurements of inter-rater agreement based on EEG are often below 0.4, an agreement level generally considered unacceptable in clinical settings.[88] And though sleep is a behavior, defined in large part by declining responsiveness to the environment, clinical sleep medicine does not record behavior at all. A system which employed simpler sensors, and which allowed for study of the sleep onset period in a more naturalistic setting, would be a leap forward for sleep research.

Aiding the development of such a system, the wake/sleep transition has been shown to be continuous and dynamic in every physiological and behavioral system studied thus far. Continuous changes in respiratory rate,[89] transitory drop in oxygenated hemoglobin, heart rate decrease,[90] lowered EMG[91] and changes in skin potential activity[92] line up with the disappearance of alpha in EEG, occurring within a narrow range of Hori stages H2 to H4. Behavior changes also occur along with physiological ones, and response via cued respiration,[93] spoken responses to subjective queries about sleep state[94] or changes in continuous pressure (dead man's switch) systems[95] can be used to characterize and track sleep onset.

[87] (Tamaki et al. 2005)
[88] (Jagannathan et al. 2018; McHugh 2012)
[89] (Colrain, Trinder, and Fraser 1990)
[90] (Pivik and Busby 1996)
[91] Sleep is not a binary state, and scoring standards often oversimplify sleep dynamics by discretizing data in both time (using fixed, non-overlapping epochs) and state (by using discrete sleep stages). These signal changes are continuous. (Mezzanotte, Tangel, and White 1996)
[92] (Hori 1982)
[93] (Badia et al. 1988)
[94] (Pardey et al. 1996)
[95] (Blake, Gerard, and Kleitman 1939)

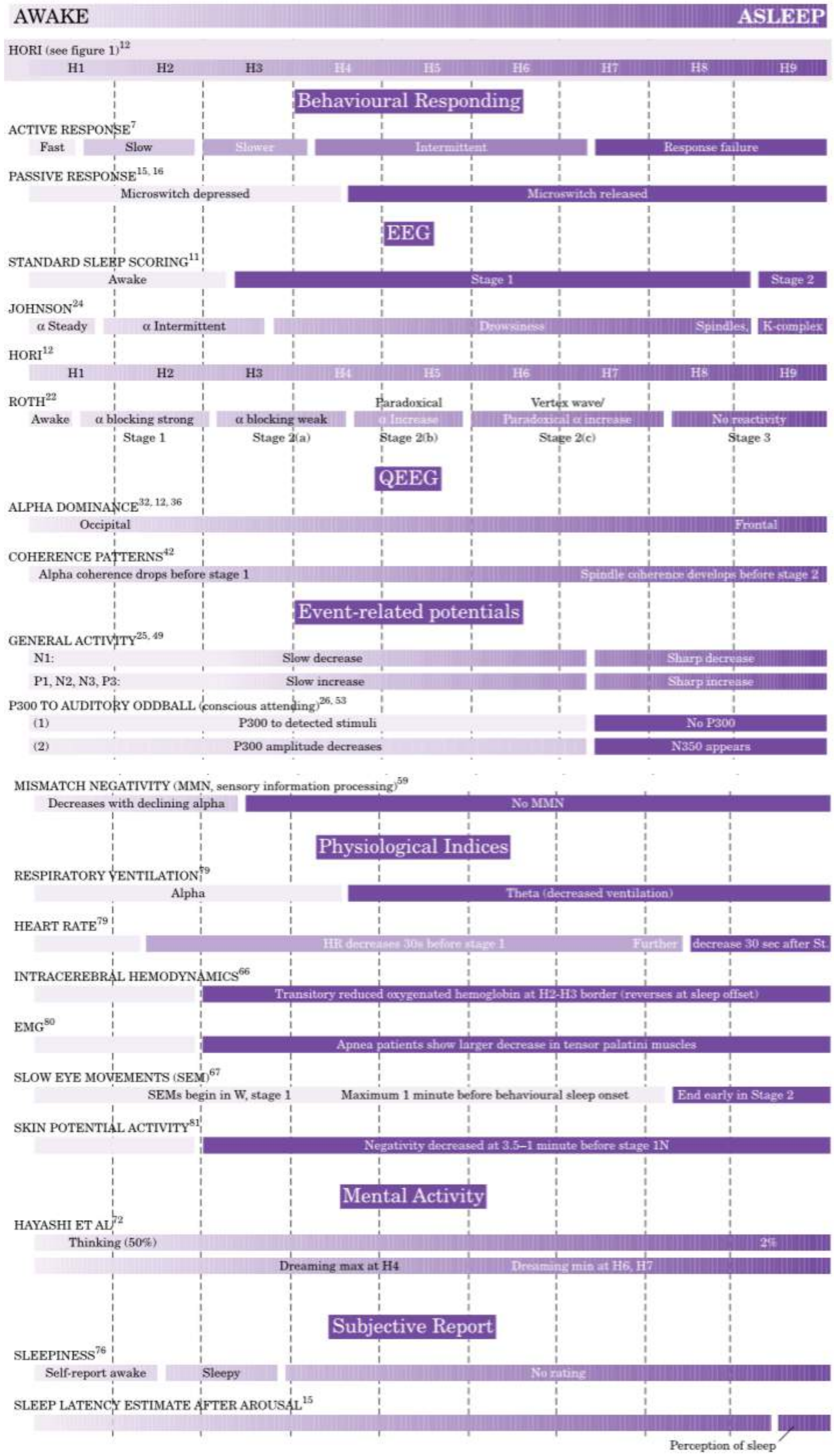

Figure 8. Image from Ogilvie, 2001, *The Process of Falling Asleep*

As A Technological Interface Opportunity:

Hypnagogia provides ideal conditions to interface with the sleeping mind, and to create Human-Computer-Interaction (HCI) technologies which communicate, alter and extract information across levels of consciousness. Each of these changing physiological signals, from heart rate to EMG, represent an opportunity to build a simpler sleep tracker than a standard PSG. Hypnagogia lasts only minutes at sleep onset, allowing for efficient interfaces with many dreams in quick succession; onset of hypnagogia begins immediately as sleep begins, enabling a dream interface that can function fully in a daytime nap, not risking interrupting nightly circadian rhythm. Historical anecdotes indicate it's a fertile territory for creativity augmentation, having been used widely for both divergent and convergent thought. And awareness of sleep onset in hypnagogia allows dreamers to actively survey semi-lucid dreams and report accordingly, at rates > 90%.[96] This is, importantly, only if we're woken up to report — sleep onset without intervention seems to cause retrograde and anterograde amnesia where we forget the few minutes before sleep begins, and sleep onset dreams are rarely remembered after a full night of sleep.[97]

The fact that we enter stage 1 while remaining aware of our auditory environment suggests the possibility of directing dream content with an audio interface. Redirection of cognitive content at sleep onset could be hugely important for those with anxiety, depression, or chronic pain, each associated with difficulties falling asleep and ruminating, negative thoughts at sleep onset.[98] Evidence that pre sleep stimuli, especially learning related, can influence sleep onset dream content, suggests a protocol to direct dream content could perhaps direct learning related functions of sleep. Evidence that sleep onset reports have the most frequent and direct daytime-related dream incorporations, make it ideal for understanding daytime-nighttime information interactions.[99] The reported increased suggestibility and decreased anxiety of participants in hypnagogia suggests possibilities for easy two-way communication between a waking experimenter and sleeping participant. The fact that audio can enter into and alter the dream state opens up possibilities for seamless interfaces which enable cognitive augmentation without requiring conscious effort.

Together, this evidence paints a pretty exciting picture. We have this weird, half-way conscious period that science has ignored for decades, and even though we all pass through it every night, we forget it almost every morning — we're totally missing out! It's easy to track, feasible to interface with, ripe with useful thinking, and a huge problem area for those with issues falling asleep. We can talk to sleepers while they slip into sleep! We can talk to dreamers while they slip in and out of dreams! We can communicate across levels of consciousness, shifting contents of cognition! But why should we care, practically and personally?

What Use Is Sleep

Sleep seems like a pretty bad idea, in terms of likelihood of getting eaten by crocodiles, or handing in your thesis on time. It seems silly to take ⅓ of your life and dedicate it to being immobile and largely deaf. Yet

[96] (T. Nielsen 2017)
[97] The ancient Greeks described this forgetting that precedes sleep onset as the river of oblivion (Lethe) that circles the cave of sleep (Hypnos) in the underworld. (Wyatt et al. 1994; Duff 2014)
[98] (Zoccola, Dickerson, and Lam 2009; Institute of Medicine, Board on Health Sciences Policy, and Committee on Sleep Medicine and Research 2006)
[99] (T. Nielsen 2017)

the conservation of sleep across all animal species[100] suggests sleep serves a vital function, and on top of that, the effects of prolonged sleep deprivation are awful, if not fatal.[101] Consistent poor sleep quality more than doubles your risk of cancer, is a key determining factor in the likelihood of developing Alzheimer's disease, and further contributes to all major psychiatric conditions including depression, anxiety and suicidality.[102] Sleep packs powerful benefits which help balance out the cost of inactivity, and skipping it has costs. I'll articulate some of the research-supported benefits of sleep below, but this research is far from finished. Are these functions truly specific to sleep? And are the cognitive deficits resulting from sleep deprivation a manifestation of the drive to initiate sleep rather than consequences of the lack of sleep itself? Do the negative effects of poor sleep mean sleep is necessarily their opposite? Is there one core function that drives sleep, and these others hop along for the inactivity ride as it presents unique opportunities? So far, the debate rages on in the scientific community, but there is strong evidence for the benefits below.[103]

> *"…[it] is a curious fact, of which the reason is not obvious, that the interval of a single night will greatly increase the strength of the memory… Whatever the cause, things which could not be recalled on the spot are easily coordinated the next day, and time itself, which is generally accounted one of the causes of forgetfulness, actually serves to strengthen the memory."* [104]
>
> — Quintilian, *Institutio Oratoria*, 95 AD

Restoration and Storage

Sleep is restorative from the cellular to the cognitive level. Sleep plays an active role in energy balance and metabolic processes throughout the brain and body,[105] engaging in prophylactic care down to the single neuron level.[106] During sleep, your brain clears the neurotoxic waste products that accumulate in the nervous system[107] during the day. Sleep is tied to an amazing 60% increase in the interstitial space between your cells, which creates an increase in exchange of cerebrospinal fluid with interstitial fluid: The brain goes through a kind of chemical car wash, making room between cell bodies to let waste be flushed from the brain. This lets us clear β-amyloid and tau, a peptide and protein called the 'trigger and bullet' in the genesis of Alzheimer's disease (AD), at increased rates during the night.[108] We use sleep to recover from the hard work of processing daytime input, and the leftovers from these processes, to stay healthy.

Of course, we not only need to recover from daytime input, we need to process and store it. Sleep exerts powerful effects on mechanisms of brain plasticity that govern initial learning of input and subsequent memory consolidation. At the molecular level, sleep elevates cortical messenger RNA levels of genes associated with protein synthesis, critical for building new synapses and strengthening existing ones.[109] At the synaptic level, information from the day is being rehearsed for storage in sleep, and patterns of brain activity expressed during training can be seen reappearing in subsequent REM and NREM sleep. Even

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[100] The birds and the bees do it. Worms do it. Zebras do it standing up. Dolphins do it with one eye open, one hemisphere sleeping at a time. Sperm whales do it while holding their breath. Otters do it while holding hands. Egyptian desert snails do it for years. We are all sleepy creatures.
[101] (Everson, Bergmann, and Rechtschaffen 1989)
[102] (Lewis 1996; M. Walker 2017)
[103] (Cirelli and Tononi 2008) (Vladyslav V. Vyazovskiy 2015)
[104] (Hammond 2004)
[105] (Schmidt 2014)
[106] (V. V. Vyazovskiy and Harris n.d.)
[107] Central nervous system just means brain and spinal cord. This has always confused me.
[108] (Ahmadian et al. 2018; Xie et al. 2013)
[109] (Cirelli, Gutierrez, and Tononi 2004)

cooler, the extent of learning during practice is correlated with the amount of reactivation during sleep.[110] At the brain network level, as we sleep encoded information from the day undergoes a shift from storage based in short term representation (dependent on the hippocampus) to long term representation (spread throughout the neocortex). The hippocampus, which helps apprehend, bind and temporarily store information from the day, has a limited storage capacity. To clear storage in the night, pulses of neural activity, known as sharp-wave ripples and sleep spindles, travel between the hippocampus to the neocortex and carry information to long term storage.

Clearing up short term storage creates both the consolidation of the original memory, and the post-sleep restoration and renewal of hippocampal encoding ability for new learning after awakening.[111] This is why participants subjected to one night of sleep loss, compared to those allowed to sleep, have twice as many episodic memory learning failures the next day.[112] And this is why sleeping after learning, compared to staying awake, offers a memory benefit of 20-40% ![113] Even a daytime nap can be restorative — learning capacity decreases across the day when we stay awake, but an afternoon nap creates a significant same-day enhancement in encoding ability.[114] And if you were wondering, napping has been experimentally proven to be superior to cramming for an exam.[115]

Yet it's not optimal to store everything we encounter during the day in long term memory — some information should be forgotten, and some should be distilled and integrated. Sleep has been shown to help us look for common patterns across memories and distill overarching rules, as well as simply stabilize the memory exactly as it was learned.[116] For example, subjects taught a rote method for solving math problems for which there was also a shortcut (subjects were not told about it) were 2.6 times more likely to discover this shortcut after a period of sleep than an equal period of wake.[117] The role of sleep in memory formation is extensive and complex, beyond simple storage, and there's much left to learn. Accordingly, the publication rate in the field of sleep and memory has doubled every 4-5 years since 1990. [118]

Amazingly, sleep even targets benefits where they are needed most: Intensive learning involving a specific brain region induces a local increase of slow wave activity (an EEG frequency band implicated in recovery sleep) in the very same region during sleep. This local increase after learning correlates with improved performance of a motor learning task after awakening.[119] The brain thus marks areas of heavy local use, likely using molecules like adenosine which indicate which cells have recently used energy, to later return during sleep for local recovery! And you can even have local naps: In humans, sleep restriction leads to intrusion of sleep into waking in the form of local sleep-like activity (local OFF periods in neuronal firing, like in slow wave activity) in an otherwise awake brain, causing specific, intermittent performance impairments [120].

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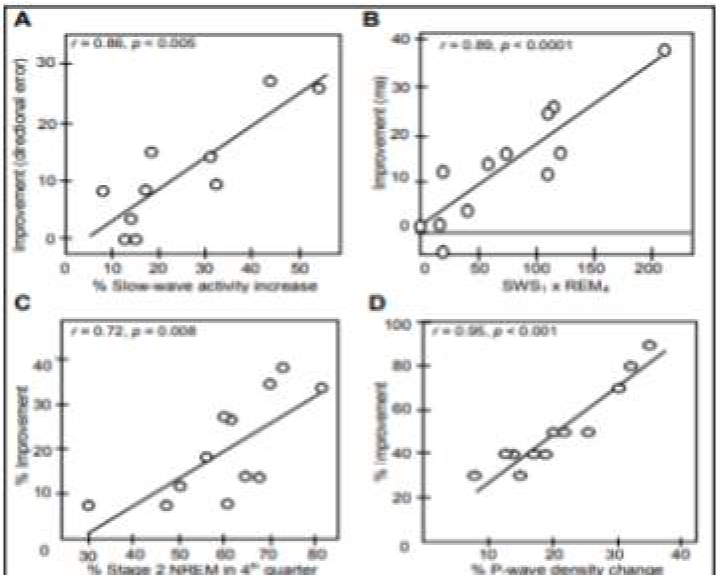
110 (Peigneux et al. 2003; Paller 2017)
111 (Abel et al. 2013)
112 (Yoo et al. 2007)
113 (Saletin and Walker 2012)
114 (Mander et al. 2011)
115 (Cousins et al. 2019)
116 (Saletin and Walker 2012; Robert Stickgold and Walker 2013)
117 (Wagner et al. 2004)
118 (M. Walker 2006; Pubmeddev n.d.)
119 And the brain targets tasks and concepts which are learned weakly, preferentially improving memory and performance of tasks which were most difficult for the awake individual (Derbyshire 2012) (Huber et al. 2004)
120 (Hung et al. 2013)

Correlation of sleep-dependent learning and brain measures taken during sleep. The combined probability of 10^{-15} reflects the likelihood of all six studies providing such low probabilities for the null hypothesis.

Brain Measure	Learning/ Memory Task	r-value	r^2	p-value	Citation
qEEG	motor adaptation	0.86	0.74	<.005	11
PET	virtual navigation	0.94	0.88	0.005	33
Time in SWS and REM	visual discrimination learning	0.89	0.79	<.0001	5
Time in Stage 2	motor sequence learning	0.72	0.52	<.01	34
PGO wave density	shuttle box avoidance (rats)	0.95	0.90	<.001	24
spindle density	paired associates learning	0.56	0.31	<.05	21
	Means and combined probability	0.82	0.69	10^{-15}	

Figure 9. Correlation of sleep-dependent learning and brain measures taken during sleep. Figure from Stickgold et. al (2005)



Correlations of post-sleep improvement with brain measures during sleep. (A) slow-wave activity vs. improvement on motor adaptation task[11]; (B) time in SWS and REM vs. improvement on visual texture discrimination task[5]; (C) time in Stage 2 vs. improvement on motor sequence task[34]; (D) PGO density vs. improvement on shuttle box avoidance task[24]. (A-C) human studies; (D) rat study.

Figure 10. Several studies show significant correlations between post-sleep improvement in memory tasks and various measures of intervening sleep physiology. Figure from Stickgold et. al (2005)

Creativity

As sleep works to connect short term information from the day with the vast, disparate stores of information in our long term memories, it associates information in ways that differ deeply from waking thought. These altered associative tendencies can create revealing, novel and creative thoughts.[121] For instance, the same ability sleep has to extract mathematical problem shortcuts, revealing overarching architecture of interlocking information, is deeply useful for creative thinking and insight.[122] REM sleep specifically is useful for work requiring insight — participants awakened from REM vs. NREM sleep to solve anagram problems gain 15%-35% improvements when awakening from REM sleep. And further, these solutions are described as more effortless, and are done faster after REM awakenings than NREM or wake. It seems the neurochemical inertia in waking up from REM, while subjects chemically are still partly in this sleep state, yields a more fluid, cognitively flexible, divergent state of information processing.[123] Even compared to a period of wake when participants are given an opportunity to review and incubate information, REM enhances the formation of associative links and the integration of unassociated information, outperforming wake for tests of creativity involving identifying links between apparently unrelated words (the Remote Associations Task).[124]

In REM specifically, our brains are specifically biased towards seeking out the non-obvious, distant associations between pieces of information. An important study on semantic priming across the sleep-wake cycle illustrated these changing associative tendencies in sleep. To study semantic priming, subjects are given a task showing a prime word (like Dream) followed by a target word (Sleep) or nonword (Sloope), and must indicate whether or not the target is a word. Word pairs of primes and targets have varying semantic relationships of differing strengths: from no semantic relationship (e.g., Dream-Canoe), to weak relationship (Dream-Laziness), to strong relationship (Dream-Sleep). The speed with which subjects determine whether target words are word/non-word has been shown to depend on the strength of the prime-target relationship: A target word preceded by a strongly semantically related prime word is semantically primed even before it comes, and is thus recognized more rapidly than one preceded by an unrelated word.[125]

[121] Not all alterations in association are created equal. Alcohol, for instance, specifically impairs encoding of items with high semantic associations. It also impairs encoding for those with low semantic associations, just less. For some types of creativity, this might be useful, but daily drinking is less sustainable than daily napping. (Norlander 1999; Weissenborn and Duka 2000)
[122] (Wagner et al. 2004; D. Nielsen 2017)
[123] (M. P. Walker et al. 2002)
[124] (Nolan 2010)
[125] (Neely 1976, 1977)

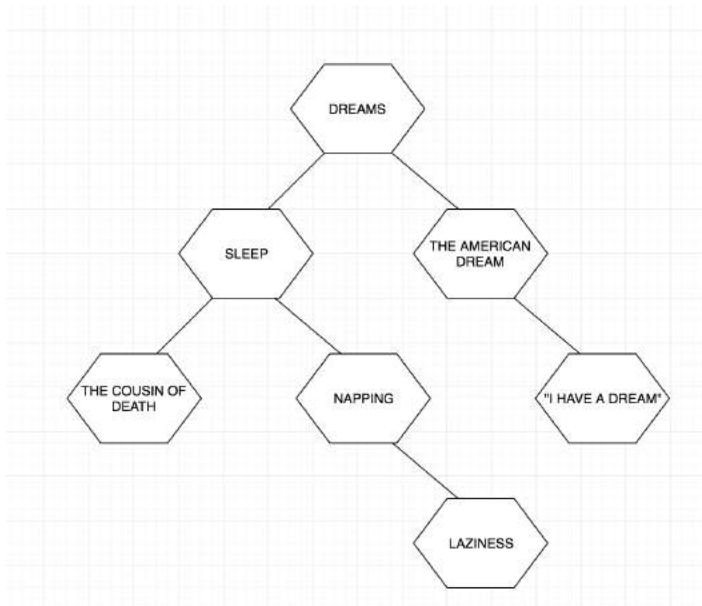


Figure 11. *My own web of semantic associations relating to prime 'Dreams'. Seeing sleep would prepare me to determine if napping was a word/non-word.*

This is super cool, because semantic priming and response times can then be used to index a participant's invisible web of meaning relationships. It can thus be used to probe for global alterations in the strengths of their semantic, associative links. And when Stickgold et al. used this task and awakened participants from REM sleep they found the amount of **priming produced by weakly and strongly related words was reversed!** In REM awakenings, "weak" primes produced more priming than "strong" primes, and in NREM, strong priming exceeded weak priming.[126]

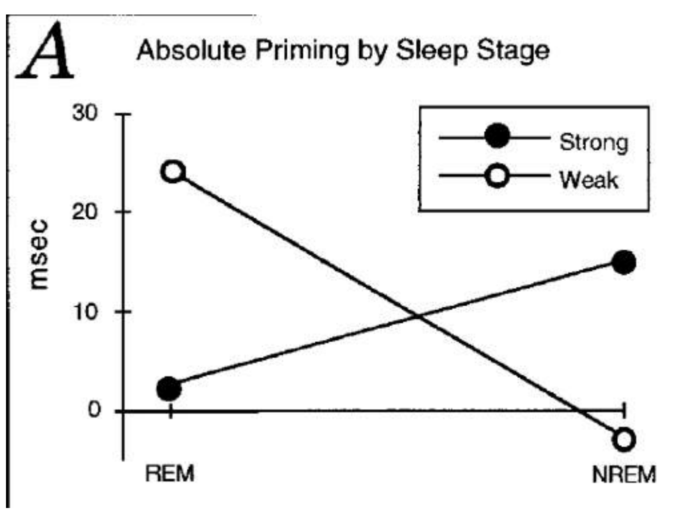


Figure 12

[126] (R. Stickgold et al. 1999)

This reversal is a truly remarkable shift in the relationships between nodes of information in the brain. The daily job of the brain is to map out the most likely associations to prepare relevant responses to input and reduce surprise.[127] Yet at night instead of generating the most likely, obvious world we are **primed to link the most distant concepts possible** and produce outlandish, hyper-associative dreamscapes. Flexible, associative cognitive processes are fundamental to problem solving and creative ability, and evidence suggests sleep provides a specific neurochemical and neurophysiological milieu which facilitates them.[128] Under conditions in which spreading activation is enhanced, associative mental processes might well be expected to be accelerated.

Crucially, the motivation for this semantic priming study and the original evidence for this massive shift in information processing came from the **experience of dreams**: "Nowhere is such enhanced association more evident than during dreaming, an automatic process in which images showing only the weakest relationships with one another are strung together to produce bizarre and incongruous dream narratives," write Stickgold et al.[129] Even 200 years before this study, the experience of dreaming caused David Hartley to hypothesize that dreaming enhanced associative networks! [130]

What Use Are Dreams What Use Are Flowers?

It is evident that the processing our thoughts undergo in sleep is far different from, and differentially beneficial than, waking cognition. Yet the question of the use of dreams isn't just a question of the utility of overnight reactivation and reprocessing of waking thoughts — it is a question of the **utility of the experience** of that reactivation. This is hairy, subtle territory which requires teasing apart the neurochemical conditions that create a dream from the dream itself. Because while our experiences are being processed, we are simultaneously having experiences of these processes — or perhaps the experiencing is in fact the process itself! So, do dreams have a purpose? And does that purpose rely on dreams being experienced? And to turn the question on its head, is there any evidence that we can gain the cognitive benefits of sleep without parallel dream content?

I am excited about the difficulty of this fundamental question about experience in sleep (**what use are dreams anyways!?**) but I do think sleep gets picked on unfairly when this pointed question gets asked at cocktail parties. Because this question should be asked in tandem with a few other parallel unanswered questions which have spawned decades of debates. If we question the use of experience in sleep we should also ask: **What use is waking experience**? What use is waking metaphor? What use is waking visualizing? What use is waking imagining? And how about free will and executive control, which we lose in sleep while continuing to make metaphors, visualize, imagine and experience?[131]

In waking life learning has a **phenomenology**, **a coherence, a consciousness**: We take in new information, reference it to the past, project it to the future, feel the emotions engendered by each of these narratives and plan accordingly. In Antonio Damasio's *The Feeling of What Happens,* he argues that none of this could happen without consciousness, and without **narrative conscious experience** specifically.[132] Without the ability to tell stories we could not synthesize or simulate effectively, and information could not be

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[127] (Bar 2007; Friston 2013)
[128] (Wagner et al. 2004)
[129] (R. Stickgold et al. 1999)
[130] (Hartley 1801)
[131] (Lakoff 2014; Libet 2005; Block and Journal of Philosophy Inc. 1993)
[132] (A. R. Damasio 2000) Many thanks to Bob Stickgold for reference to this book, and explaining the relevance to sleep and dreamt experience.

integrated and assessed across scales of space and time. Even for problems where emotions appear irrelevant, like fitting puzzle pieces together, we hover above the board and imagine the future feeling of fitting a held piece into a vacant space and act accordingly. Conscious dream experience, like waking consciousness, could offer parallel advantages beyond non-conscious brain processing. Dreaming allows us to imagine experiences beyond waking possibility or plausibility, to feel how they feel, to prospect and play, to project and plan.

Dreaming is not just one kind of conscious experience, with one use, just like waking narrative experience. We know that waking thought involves logical problem solving, but we don't then assume this is the sole function of thinking, or that finding concurrent brain activation to logical thought explains away the function of waking thought. We must avoid these pitfalls in trying to explain the dream. Just like waking thought, dream cognition encompasses a collection of many modes from metaphor to vision, which likely have many uses, which are likely useful in addition to mechanisms of the brain-states that enable them. And different facets of these many modes make dreams useful for scientists and dreamers alike.

What Use For Science

Dreaming as A Probe Into Consciousness

The alterations in thought and behavior emergent in dreams can inform science in much the same way as alterations from brain damage have in the past. Patients with lesioned (damaged) brains, from HM to Phineas Gage, enabled many of the most important historical studies of the brain. Lesion studies tie brain function and physical substrate concretely, and are often thought to have been a prerequisite for the emergence of cognitive neuroscience.[133] They point to ways that dynamic, interconnected brain networks depend causally on the function of particular components. They reveal how cognition can be at least partially decomposed into modules. They show how degeneracy, in which many brain areas could subserve one function, comes into play in brain function.[134] Lesion studies make it possible to tease apart a criss-crossed connective system by eliminating pieces selectively and producing measurable behavioral effects.

Yet lesions are not enough. Lesions cannot be reproduced for controlled study. Lesions cannot target specific neuronal groups in heterogeneous regions. Lesions give insight into the contribution of focal areas of brain tissue but rarely into the chemical contribution of brainwide neurotransmitters. Lesion studies cannot discriminate between the effects of destruction and disconnection, as the two come simultaneously with brain injury.

Dreaming provides a remarkable experimental setting for a kind of repeatable lesion study on consciousness, happening every night in every bed in the world, as the chemical and physiological components of an otherwise integrated brain go offline in predictable fashion. We each exist during the day and reflect upon ourselves as an emergent, integrated whole "i" perceiving a continuous, integrated and bound world. Yet sleep offers fractures in this continuous consciousness: the "i" undergoes major quantitative and qualitative changes as consciousness breaks down, and each crack reveals the lines where the functional puzzle pieces otherwise fit seamlessly together. Consciousness alters suddenly at sleep onset, at times an "i" with synesthesia, no concept of time, no sense of space, or even no sense of self (i.e. the dream without a dreamer[135]).[136] The conscious "i" often disappears during slow wave sleep, and

[133] (H. Damasio and Damasio 1989)
[134] (Adolphs 2016)
[135] (G. Vogel, Foulkes, and Trosman 1966)

suddenly re-emerges whole yet wholly different, hallucinatory and hyper-associative in typical REM dreams. We travel from pure perceptual experience to pure thought, from simple images to immersive stories, from being in cognitive command to loss of executive control and back again. And the bizarre but common features in normal dreams present striking similarities with neuropsychological symptoms observed in brain-damaged awake patients, suggesting specific commonalities in brain organisation and offering a more replicable avenue for study than lesions.[137] Each of these experiences, from alterations in "i" in N3 to dissociative experiences in REM, is an opportunity to link substrate to sensation with careful experimentation.[138]

Accordingly, probing the experience of dreams has been used today to test leading theories of consciousness and perception, from Tononi's Integrated Information Theory to Friston's Free Energy Principle and Predictive Processing, investigating models of consciousness posed long ago by Helmholtz and Kant and Bayes.[139] Tononi showed the precuneus, posterior cingulate, and retrosplenial cortices may be a core correlate of consciousness by studying dream phenomenology: in both NREM and REM sleep, reports of dream experience were associated with local decreases in low-frequency activity in these areas, and monitoring this zone in real time predicted whether an individual reported dreaming or the absence of dream experiences during NREM sleep.[140] Electrical stimulation of this area, in turn, produces a feeling of being in a 'parallel world' or a 'dream-like state'.[141] 100 years before this work, Leaning examined the hypnagogic state and noted the seeing of faces is so widespread among the hypnagogic imagers that it "almost suggests that there is a special 'face-seeing' propensity in the mind".[142] This hypothesis, based solely on the study of the experience of sleep onset dreams, has now been supported by fMRI work and constitutes some of the first convincing evidence for anatomical specificity of brain function, as well as a key area in the study of predictive perceptual processing.[143] The experience of dreaming in particular, and the subjective reports of dreams, have offered key experimental insight into consciousness.

[136] (Mavromatis, 1983)
[137] ("Dreaming: A Neuropsychological View" 2005)
[138] (Siclari et al. 2013)
[139] And dreaming was used to probe the nature of consciousness long before what we call modern science. Descartes' Dream Argument is the central point of his skeptical epistemology, Hobbes responds with a take on dreams and certainty, Locke chimes in with pain in dreams, and so on. (Tononi 2012; Hong et al. 2018; "Dreaming, Philosophy of | Internet Encyclopedia of Philosophy" n.d.)
[140] (Siclari et al. 2013)
[141] (Herbet et al. 2014; Balestrini et al. 2016)
[142] (Slight 1924; A. Mavromatis and University of Brunel 1983)
[143] (Kanwisher and Moscovitch 2000; Schwiedrzik and Freiwald 2017)

The historical study of dreams has separated broadly into three theories of dream function, each offering an account of what generates dreams and thus what parts of the mind they might allow us to probe:

	Psychodynamic (Freud, Solms)	Activation-Input-Modulation (Hobson)	Neurocognitive (Foulkes, Domhoff)
General	Dreams represent fulfillment of unconscious wishes. *Latent* unconscious content is disguised via censorship creating the bizarre *manifest* dream content	REM sleep and dreaming are characterized by high levels of regional brain activation, internally generated input, and cholinergic neuromodulators.	Dreaming is what occurs when the mature brain is activated and disconnected from external stimuli. Once instigated, dreaming draws on memory schemas, general knowledge, and episodic information to produce simulations of the world
The function of dreaming	According to Freud, dreams preserve sleep in the face of unconscious needs for excitement	Dreams may serve a creative function by providing a virtual reality model. The brain is preparing itself for functions including learning and secondary consciousness	Dreams are a byproduct of sleep and probably have no function, but they do have coherence and meaning, which is often conflated with function
What is the psychological meaning of dreams?	This theory emphasizes *dream content*: individual dreams carry meaningful information about the dreamer.	Dreaming is an attempt to best interpret activating signals in a coherent manner, and contents of individual dreams are nearly random. Nevertheless, the process of interpretation may carry some psychological meaning	This theory emphasizes *dream form*: dreams are based on stored memory representations and therefore reflect individual ways of abstracting knowledge, but specific dreams are not traceable back to particular episodes in our life
The origin of dreams	*"Top-down":* dreams originate from psychic motives which are later instantiated as sensory percepts	*"Bottom-up":* dreams originate from activation of sensory cortex by the brainstem later to be interpreted and synthesized high-order modules	*"Top-down":* Dreams originate in abstract knowledge and figurative thought which are processed back into imaginal copies of perceptual phenomena

Table 1. A broad overview of differing dream theories, adapted directly from Nir and Tononi (2010) [144]

[144] (Nir and Tononi 2010)

What Use For You

> *"...these strange hours of the night underpin nearly every moment of our lives."*
>
> — David K. Randall, *Dreamland: Adventures in the Strange Science of Sleep*, 2012

Memory and Learning

Sleep composes our daytime cognitive performance, from emotional stability to mathematical insight to memory encoding, and there is evidence that dreams play a role in this composition. We know that during REM sleep in mice there is a physiological replaying of the neural representation formed during waking learning,[145] and evidence suggests that humans exhibit behavioral and neuronal replay of waking experience during both REM and NREM sleep after new learning.[146] Unfortunately, the vast majority of studies on REM/NREM learning do not include awakenings for dream reports, and as such miss out on opportunities to tie experiential replay with evident neural replay.

The studies which do collect dream reports, though, suggest **dream experiences can directly reflect** ongoing sleep-dependent memory processes in the brain. The different mnemonic functions of REM and NREM seem intimately tied to their typically differing dream phenomenologies. Hippocampus-dependent memory seems to benefit particularly from NREM sleep, and subjective reports from NREM sleep stages are more likely to contain episodic memory sources (hippocampus-dependent).[147] Memory for emotional material is preferentially enhanced by REM sleep, and dream experiences from REM have uniquely intense emotions.[148] These studies suggest dream reports can provide a valuable window on cognitive processing ongoing in the sleeping brain.

Dream phenomenology further **correlates with task performance** in the laboratory. Novel waking-life experiences are incorporated into the content of NREM dreams, particularly with the formation of new memories, suggesting dream content can reflect the reprocessing of newly learned material.[149] There is evidence that dream content drives memory consolidation for recently learned facts and for language learning, wherein low latency of incorporation of a newly learned language into dream content positively predicts language learning.[150] Morning recall of short stories encoded the night before shows a correlation between story-related words in dream reports and memory for stories the following morning.[151] The extent to which participants improve on a tennis video game task testing coordination is correlated with how richly novel gameplay experiences are incorporated into the content of hypnagogic dreams. Notably, this relationship is significant for early hypnagogic dreams (the first four dream reports) but not for daydream incorporation or for late hypnagogic dreams (the last four dream reports).[152]

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145 (Louie and Wilson 2001)
146 (Buzsáki 1989; Uguccioni et al. 2013; Mainieri et al. 2019; Oudiette et al. 2011)
147 ("Memory Sources Associated with REM and NREM Dream Reports Throughout the Night: A New Look at the Data" 2001)
148 (Smith et al. 2004; Wamsley and Stickgold 2011)
149 (Fogel et al. 2018; Wamsley 2014)
150 (De Koninck et al. 1990)
151 (Wamsley and Stickgold 2011)
152 (Fogel et al. 2018)

Perhaps most convincing is the work done by Erin Wamsley and Robert Stickgold in 2010. Participants were trained on a 3D virtual maze task prior to a 1.5 hour nap opportunity or equivalent awake period. All subjects were prompted three times during this 1.5 hrs to verbally reports "*everything that was going through your mind*".

In the Sleep group, participants who referred to the maze task in their subjective reports **improved ten-fold** at retest compared to Sleep participants who gave no task-related reports! Yet thinking of the maze while awake did not provide any performance benefit. Dream experiences here are clear reflections of learning-induced reactivation of memory networks during sleep, and the experience of this reactivation correlates with hugely enhanced memory performance.[153] Importantly, the dreams in this experiment did not veridically "replay" waking experience of the maze task, but were fragmented and mixed with older memories. Again, **experience apparently matches mnemonic function** of the sleep state: The fragmented, mixed form reflects the memory consolidation process being more complex than simply strengthening memories in their original forms, instead integrating new information into established cortical memory networks, extracting meaning and more. Stickgold et. al. recently replicated this study, reproducing results of a significant relationship between task inclusion in dream reports and enhanced performance post-sleep (and a non-significant trending relationship between performance improvements and inclusion of task in waking reports).[154] In this maze, all exploration began from a tree, and the task post-exploration involved returning to that tree: This exploration and return point serves as the inspiration for the dream incubation theme of this thesis experiment, a 'Tree'.

> "*My dream experience was kaleidoscopic…I seemed to be thinking with the intention of trying not to. It felt similar to most nights I start off trying to fall asleep. Then things became more intertwined: thoughts of the people in my life would bubble to the surface of remaining consciousness, mixed with more intentional thoughts of a "tree." These latter thoughts manifested as an overhead view of a conifer forest, along with reverence for the beauty of tree root systems, specifically. I thought of large, robust and thirsty tree roots extended into the ground like capillaries. Also, regarding the contents of my thoughts/dreams, time seemed to flatten a bit: people from my past bubbled into consciousness thoughts that contained items and people from my present. Halfway in, I did not feel like I was in or identify with ML, Kendall Square, Cambridge etc. That was surprising.*"
>
> Subject 9, Sleep Tree-Incubation, Thesis Experiment
> Note cohesive scene construction across temporal distance.

Emotionally

Following from this evidence that dream content reflects ongoing memory processes, the strong emotional tone of dreams suggests that there is some form of ongoing **sleep-dependent affective processing** as well.[155] Between 75% and 95% of dreams contain emotional contexts, largely emerging from REM sleep,[156] and the most apparent link between daytime events and subsequent dream content are current emotional concerns and themes, not actual daytime events.[157] There are direct effects of waking life on dream emotions and, in turn, of dream emotions on waking-life: The two feed off of one another,

[153] (Wamsley and Stickgold 2010)
[154] (Wamsley and Stickgold 2019)
[155] (Levin and Nielsen 2009)
[156] (J. A. Hobson, Stickgold, and Pace-Schott 1998)
[157] (M. J. Fosse et al. 2003)

wherein the intensity of the negative effects of daytime events on dream content predicts—in addition to emotional intensity of the dream—the effect of that negative dream on daytime mood.

One of the functions of REM sleep, researchers such as Matthew Walker and Tore Nielsen have suggested, is to reprocess upsetting memories from the day in a neurochemically calm thinking environment: REM sleep is the only time throughout the 24 hour circadian cycle when your brain is completely devoid of noradrenaline, a key stress-related neurotransmitter. High activation of fear-related regions in frightening dreams lowers the response of these same regions to threatening stimuli in wakefulness, indicative of better emotion regulation.[158] After processing in REM, we are then able to wake with a memory largely disentangled from the emotional sting felt in the original experience. REM sleep and dreaming then serve a mood regulatory function, desensitizing affect-laden daytime events.

Findings relating daytime mood with dream mood, and relating REM with affect regulation, have clear clinical importance in the context of reactive depression. Recently divorced women who initially suffered depression dream of their ex-spouses more frequently and with stronger emotion than those not depressed. Of those who suffered depression, ones who were in remission one year later were the same patients that had significantly more such dreams. These patients may have required dreams which expressly involved dreaming about the emotional themes of the waking emotional trauma to recover, indicating a potential functional connection between dream content and recovery from emotional conflict or trauma.[159]

Patients who develop PTSD after a traumatic experience have abnormally high levels of noradrenaline during their REM sleep, and are left with repetitive nightmares replaying veridical narratives of their trauma memory. These nightmares are such a reliable PTSD symptom that they form part of the list of diagnostic features for the disorder. In turn prazosin, a blood pressure drug which happens to suppress noradrenaline in the brain, eliminates repetitive trauma nightmares in PTSD.[160] These nightmares which replay traumas exactly as they happened in the day can profoundly exacerbate PTSD, while changes in dream content alleviate symptom severity and are correlated with reductions in suicidality.[161]

Working with dream content specifically can be helpful for those suffering from trauma, nightmares or grief. In bereavement dreams following the death of a loved one, dream phenomenology reportedly mirrors phases of mourning and thus offers mental health workers diagnostic clues to the stage of mourning the survivor is experiencing.[162] Dreams of the deceased appear highly prevalent among, and often deeply meaningful for people who are grieving. Effects of the dreams on bereavement processes include increased acceptance of the loved one's death, comfort, spirituality, sadness, and improved quality of life.[163] As dreams rarely contain guilt, sadness or depression, the dreaming environment can be a useful one to reflect on difficult emotional issues in a new light.[164] Considering all this research, the content of dreams appears to be a key factor in emotional healing throughout the 24-hour cycle.

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158 (Sterpenich et al., n.d.)
159 (R. D. Cartwright et al. 1991)
160 (M. P. Walker and van der Helm 2009; M. Walker 2017)
161 (Agargun and Cartwright n.d.; Lancee et al. 2008; Spoormaker and Montgomery 2008)
162 ("Dreams in Dying, Death and Grief," n.d.; Germain et al. 2013)
163 (Wright et al. 2014)
164 (R. Fosse, Stickgold, and Allan Hobson 2001)

" Wow that was so nice! i thought of oak tree and acorns and tree made of stained glass (both natural and man made) and wood as a structure and leaves as a structure. and connections to the tree and my body and the people i care about. Time felt like it was moving slowly and hmm perhaps quickly as well. When i was underwater in a kemp tree I assumed i had been there for many years, that maybe this was my body. Whereas i imagined laying on my back under a tree after a run that could have been more real time.

i felt heavy and hurting which i think makes sense for this timing in my life, but not in how I normally think about trees (as peace and loving) but I felt weight and hardness. [My boss] seemed light and fickle leaves blowing in the wind. I imagined myself as a tree/ tree like/ tree material often...very emotional. Helpful in a way too because i felt in control of the dream. When the acorns were in my cutting through into my veins i was hurting and trapped, but then i was able to shift what that meant for me - wood organs with some mobility, to float with more comfort and ease with me body - but that came about because the breaks in the thinking made me more flexible

Feeling in control of something which I feel out of control of in this dream state I felt like I could put myself down into it in my dream state and then come out of it to a place where I want to think about this differently, about my strength. I was surprised there were moments of pain in it, physical pain, which was connected to other things in my life. If it was a real dream it would have turned into a nightmare, but I was able to think what are the good parts of having a tree in me. There was a self consciousness to the whole experience for me...where I think oh no I'm thinking of this terrible thing and I'm going to have to talk about this can I think of something, you know, a new way to think of them. "

Subject 9, Sleep Tree-Incubation, Thesis Experiment. Note the intrusion of emotion into the dreamstate, but novel perspective taking and reprocessing of emotion.

Personally

"If I don't know I know, I think I don't know..."

— R. D. Laing, *Knots*, 1970

"We listen for guidance everywhere except from within." [165]

— Parker Palmer, *Let Your Life Speak: Listening For the Voice of Vocation*, 2000

[165] "Before I can tell my life what I want to do with it, I must listen to my life telling the who I am... In our culture, we tend to gather information in ways that do not work very well when the source is the human soul: the soul is not responsive to subpoenas or cross-examinations. The soul is like a wild animal — tough, resilient, savvy, self-sufficient, and yet exceedingly shy...How much dissolving and shaking of ego we must endure before we discover our deep identity." — Parker Palmer

I would be remiss if I didn't venture into the dangerous territory of dream interpretation. Dreams, often full of emotional tone, mixed memories, uncontrollable perspective switches and variably dissociated states of self, offer opportunities to step outside one's awake self and, as it were, take a look in the mirror.[166] The interpretation of a dream as hidden content uncovered by a psychoanalyst, popularized by Freud, has no experimental backing — but this does not discount the benefits of dream journaling and personal reflection on dreams, which do indeed have experimental evidence.[167] Dream content has played a key role in almost all of the world's religions, practiced at least since ancient Mesopotamia — it seems like a silly thing to dismiss wholesale because of one slippery Freudian.[168]

Reflecting on dream content during the day offers benefits in clinical therapeutic[169] as well as personal settings. Evidence from therapeutic work suggests that focusing on dreams increases ratings of deepened self-perception and personal insight.[170] Part of the introspective opportunity provided by dreams is due to the rebound of suppressed thoughts, starting even at sleep onset.[171] In REM dreams, thoughts which subjects are specifically instructed to suppress occur more often than thoughts which they are instructed to express.[172] Experimental results like these, while limited, offer possible links between the early insights of psychoanalysis — i.e. continuities between the day and the dream, rebound of suppressed thought, utility of active reflection on dreams in waking life — and the modern day understanding of dreams.

This makes quite a bit of sense from what we know about dreaming: A time of decreased executive control where our mind wanders off, turns reflection inward instead of outward, explores novel interpretations of memories and emotional content of the day, allows us to switch our place and person, our age and face and space. It seems quite unsurprising that this would be a fruitful period for self-exploration. It is, after all, so hard to see the thoughts we suppress or the weak associations we ignore during the day — from shame to memory to a divergent solution to a problem which we push away as too aberrant, too other.

> *"I wandered in thought about all the activities that took place around those trees…I saw the darkness of my eyelid, but it was in the shape of a tree and kept fluctuating…I was playing dodgeball during recess in elementary school. One of the older kids threw a ball at the ground where I was and hit my head, which pushed my chin into the ground. I recall crying at that time. This time, I was curious to know what was going through in the older kid's head, so I tried to envision what he saw and how he felt. That's the first time I was 'woken up.' From then on I tried to recall past memories, and explore what other people saw and might have been thinking…Where it got most interesting was where I ended up envisioning a house that felt like I lived in, and I had a spouse (which is the girl I'm currently interested in) and I imagined sending off 'our kid.' It was something like, "OK have fun, and be back before midnight! Oh they grow up so fast" kind of dialogue. And it never happened, but it felt very real and I fell asleep. In the last dream, I was trying the same technique of visiting an old memory and trying to see someone else's perspective. This time however, there were no one else around that time when I*

[166] (Perlis and Nielsen 1993; Gabel 1989; G. Vogel, Foulkes, and Trosman 1966; Windt, Nielsen, and Thompson 2016)
[167] (Schredl et al. 2003; Schredl, AG Traum der Deutschen Gesellschaft für Schlafforschung und Schlafmedizin (DGSM), and Schmitt 2019; M. Walker 2017)
[168] (Dahl 2012)
[169] (Barrett 2002)
[170] (Edwards et al. 2013)
[171] ("Dreaming of White Bears: The Return of the Suppressed at Sleep Onset" 2008)
[172] (Wegner, Wenzlaff, and Kozak 2004)

was looking at the tree. So I couldn't try to imagine what other people might have seen or thought. However, I realized new things about the tree...So when I saw this tree (that I've seen in the past many times) in my dream, I realized for the first time just how old and magnificent this tree was. I also had to wake up at this time, and there was great internal struggle to do so because I wanted to keep on exploring. Since I was trying to imagine what others saw or thought, there were many times I would place my perspective in their perspective and have their vision. There was no hesitation in trying to experience what I decided to do. Anything that I did not like, I decided not to explore it. As a consequence, anything that I decided to explore, I had no hesitation about. Use this for therapy. For perspective taking, and taking a new perspective on memories. Ego death. I think I experience a lot of insecurity, insecurity at work. And in this state I experienced no insecurity. I had heard about this state of mind but never experienced it. Now I know how real it is."

Subject 11, Sleep Tree-Incubation, Thesis Experiment

Mary Oliver, America's eminent walker-in-the-woods and Pulitzer prize winning poet, writes that the creative inspiration which "supplies a necessary part of the poem — the heat of the star as opposed to the shape of the star, let us say — exists in a mysterious, unmapped zone: not unconscious, not subconscious, but cautious".[173] The Johari window, from psychologists Joseph Luft and Harrington Ingham, echoes the same concept: That we hide much of our best thinking from ourselves, especially the thoughts that are perhaps too strange or too dark, metaphors too tenuous or associations too loose to be considered useful by our attentional, executively controlled waking minds. How can we best find this hidden self, these hidden thoughts, explore our subterranean selves?

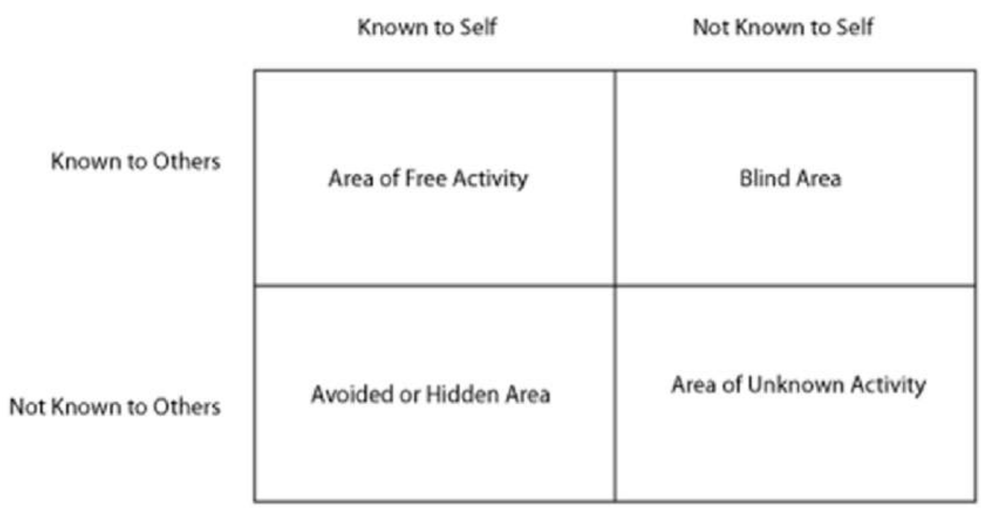

Figure 13. The Johari Window illustrates the parts of the self we know and cannot know

One of the first pilot subjects with the Dormio dream direction system offered a clue as to access points to cautious cognition. This subject was prompted to dream of a 'fork', and issued the mumbled dream report "forks are colonialism". When he woke up, and heard his report audio, his face lit up. He explained that in India, where he is from:

[173] (Oliver 1994)

"Forks have always symbolized to me a western world. In india we never use forks traditionally. We eat generally with hands. As a kid I remember feeling fork to be a cutlery used by the elite…it was more sophisticated to eat food with forks as opposed to eating with hands. After a while forks became more common and I distinctly remember that when I saw forks at tea stalls, I thought hmm, they aren't that sophisticated after all. Forks hence have been a symbol for my soul searching, defying my identity. Forks to me symbolize that you need not confine yourself to stereotypical roots, that identity is fluid, just like the work which went on from being a symbol of colonial elitism to the mere Indian household. You know I've always thought that about forks, but I've never thought that I thought that. Until I saw this dream".

Subject 4, 'Fork' Prompt Condition, Pilot Experiment

This report, especially its ending sentences, hinted at possibilities to use science, and specifically the changes in associative tendencies and executive control at sleep onset, to help find these invisible, cautious, poetic parts of our minds. It is not so surprising, given what we've learned — that dreaming is a time for exploring loose associations between memories across decades, a time where sense of self dissolves, where occupying other bodies and times is possible, where the implausible and even contradictory is accepted uncritically. What other brain-state could offer better conditions to explore the aberrant and the hidden in us all?

Creativity

"Dreaming is an act of pure imagination, attesting in all people a creative power, which if it were available in waking, would make every one a Dante or Shakespeare."

— F. H. Hedge, *Characteristics of Genius*, 1868

"Madness need not be all breakdown. It may also be breakthrough."

— R. D. Laing, *The Politics of Experience and the Bird of Paradise*, 1967

This same opportunity for seeing the aberrant, hidden thinking suggests a creative benefit of dreams. The link between creativity and dreaming has been a topic of intense speculation, mainly based on anecdotal reports of artistic and scientific discoveries made while dreaming: these include the periodic table of Mendeleyev, the *Beatles'* 'Yesterday', Salvador Dalí paintings, Otto Loewi's discovery of the neurotransmitter, and more.[174] Paul McCartney wrote The Yellow Submarine in sleep onset dreams, in "a nice twilight zone just as you're drifting into sleep and as you wake from it". [175] The dream revelations of Egyptian Pharaohs, the philosophical insights of Socrates, the literature of Fyodor Dostoevsky, and the cinema of Akira Kurusawa and Federico Fellini and David Lynch all have been credited to creative inspiration found in the experience of dreams.[176] Deirdre Barrett, a psychologist at Harvard Medical School,

[174] (M. Walker 2017)
[175] ("Beatles Songwriting & Recording Database: Yellow Submarine" n.d.)
[176] (Bulkeley 2010)

has found participants who are asked to 'incubate' a problem in their dreams (by writing it out and reflecting on it before sleep for a week) frequently dream a solution useful to solving their problem: Well over half of the visual artists and fiction writers she has interviewed say they have used dreams in their work, and within STEM fields those who benefit from visualizing problems in three dimensions are most likely to report helpful dreams . To validate these anecdotes empirically, Barrett asked college students to incubate a specific, personally relevant problem of their choosing. Using the simple incubation method of thinking about the problem for 15 minutes before sleep, participants rated 49% of their dreams as relevant and 34% of them as containing a solution, while judges ratings were 51% and 25%. [177]

Figure 14. Federico Fellini, *The Book of Dreams*

The decline of executive control in dreams is a form of disinhibition, and as such, dreaming can be understood as a form of **fully immersive, disinhibited imagination**. Both dream recall frequency and complexity have been correlated with higher creativity.[178] The acceptance of implausibility present in dreams affords an opportunity to explore non-obvious associations in sleep, and being able to access and remember one's dreams could provide a larger pool of ideas from which to draw inspiration.[179] Ability to transcend the here and now, involving imagination of vivid simulations across temporal, spatial, social, and hypothetical domains is correlated with improvements on creativity assessments in the laboratory and creative achievements in life and is exemplified by dreaming.[180]

REM sleep, associated with the most vivid dreaming mentation, has been shown to facilitate cognitive flexibility and creative solutions.[181] This cognitive flexibility could lead to an expansion of a problem space experienced as objects and characters embedded in dreams, helping dreamers reach new solutions.

[177] (Barrett 1993)
[178] (Schredl and Erlacher 2007); (Sladeczek and Domino 1985)
[179] (Kahn and Gover 2010)
[180] (Meyer et al. 2019)
[181] (Wagner et al. 2004)

Dissociated states which mix REM sleep and wakefulness in narcolepsy have a positive impact on scores for the Test of Creative Profile and the Creativity Achievement Questionnaire. This higher performance may be due to more frequent opportunities to incubate and associate ideas during sleep and to remember them upon awakening, specific to dissociated REM states. Within narcoleptics there is a further significant correlation between prevalence of hypnagogic hallucinations, experienced as semi-lucid and easy to remember, and creativity scores.[182] A tighter link between the dreaming world and waking world, it seems, facilitates creative ideation across the sleep-wake cycle.

> *"The most fertile region seems to be the marshy shore, the borderland between sleep and full awakening, where the matrices of disciplined thought are already operating, but have not yet sufficiently hardened to obstruct the dreamlike fluidity of the imagination…"*
>
> — Arthur Koestler, *The Act of Creation*, 1964

The Match *And* The Fire

> *"'How delightfully the fishes are enjoying themselves', exclaimed Soshi.*
>
> *'You are not a fish,' commented his friend, 'how do you know that the fishes are enjoying themselves?'*
>
> *'You are not myself,' answered Soshi, 'how do you know, that I do not know, that the fishes are enjoying themselves?"*
>
> — Kakuzo Okakura, *The Book of Tea*, 1906

Researching the practical impact of subjective experience on creative task performance involves building fragile links between a reported personal phenomenology, the material mechanisms that underlie it, and the personal projection of a researcher into this inscribed experiential space for examination. The fact that the experience reported in dreaming is apparently impactful, and not just the underlying brain activation observed, is a bit of a methodological pickle for sleep scientists. When we are looking at the creative inspiration found after a night of sleep and dreams, for example, we must ask which of these nearly inseparable elements is driving changes.

Which produces the heat of creative insight which so often follows a night of sleep? Is the fire the altered brain state which allows sleep and dreams to occur, and drives their many features and functions? Are the experiences of dreams simply correlational, epiphenomenal, the smoke produced by the ongoing, underlying changes? Or can dreams be the fire as well, an actual experience of a creative solution, as opposed to a dim representation of something which unconscious mechanisms have already figured out and will deliver in a moment of insight in the morning? Are the dreams the thing, or a murky reflection of the thing?

To tease apart such intertwining threads we look with many lenses, at the level of subjective report and objective task performance and physiological underpinnings, and aim to link the three. Blind with an elephant, we scope and squint and compose an animal. And we remember that measurement is not domain general understanding but domain specific framing, that we have invented our scales and that our words limit our telling of the ineffable. That dreams and creativity are not monolithic, that experience cannot be broken down into truly disparate elements, that stages of sleep are dependent on the

[182] (Lacaux et al. 2019)

instrument used to stage them, and so on. But we must do the reductionist work of separating sleep into parts and cutting creativity into chunks to build a generalizable picture of a personalized space: This is the work of science and engineering, building the tools and techniques that transcend the tales we tell ourselves, and dreams and creativity are slippery but certainly subject to investigation and definition.

> *"Experiences are both the quicksand on which we cannot build and the material with which we do build. . . . A method has to be found that makes it possible to work on experiences, and to learn from them."*
>
> — Frigga Haug, "Memory Work: the key to women's anxiety", 2000

Creativity: What It Is

> *"If I could tell you what it meant, there would be no point in dancing it."*
>
> — Isadora Duncan

Sleep and dreams have been historically associated and experimentally tied to this 'creativity' thing but what, exactly, is it? Defining the term has proved elusive, often done by a Potter Stewart-esque 'I know it when I see it' panel of experts, or done by association to other cognitive abilities which are more amenable to measurement and correlate with creative achievement.

> *"The only certainty is that inspiration cannot be summoned up by an act of will. To labour towards it, is, in effect, to move in the opposite direction."*
>
> — Alan Fletcher

Part of the challenge in defining creativity is that **we can rarely force it to emerge**, whether in the lab or at home. Everyone has their recipe — meditation, marathon running, marijuana — but creative insight often comes when it wants to. Artists and designers use brainstorming methods from exquisite corpse to storyboarding which can help, but there are no guarantees. The apple, as it were, falls on your head, and it's tough to drop it on yourself. Mnemosyne, the Greek goddess of memory, mothered the nine muses, who breath *inspire*-ation into poets and painters who are willing to hear them. The Judeo-Christian notion of inspiration is similarly reserved for those who are willing to hear the voice of the divine without filtering it: To be vessels and channels as opposed to egos in control of their cognition, and then to come back into their own minds and mouths to articulate what has come to them in dreams, visions, fires. In both empirical and mystical models of artistic inspiration, a **transient failure of cognitive control** is key to creation.

> *"Creativity…involves the power to originate, to break away from existing ways of looking at things, to move freely in the realm of the imagination, to create and re-create worlds fully in one's mind — while supervising all this with a critical inner eye."*[183]
>
> — Oliver Sacks, *An Anthropologist on Mars: Seven Paradoxical Tales*, 1995

Creativity involves skipping the dominant, common, and obvious response to a challenge or query, called prepotent response inhibition in the cognitive sciences. Effectively skipping past salient concepts which are

[183] If you're thinking this sounds a lot like Hypnagogia, then we're on the same page!

strongly related to the task at hand is thought to facilitate creative thought by allowing us to explore further into our associative web for non-obvious answers.[184] It makes sense, then, that fluid intelligence (the ability to improvise with new information), divergent thinking (the ability to generate many possible solutions to a problem), and access to a broad spread of memories have been shown to benefit creative performance.[185] It also makes sense that restrictive attentional focus, increased self-assessment and reduced mind-wandering are shown to be detrimental to creativity.[186]

> *"The difficulty lies, not in the new ideas, but in escaping from the old ones, which ramify…into every corner of our mind."*
>
> — John Maynard Keynes, *The General Theory of Employment, Interest and Money*, 1936

Creative thinking involves a marriage of controlled and spontaneous cognitive processes — wherein we must loosely direct the theme of our thoughts and generate myriad possible solutions (a little control), not be so controlled as to only see obvious responses (a little spontaneity), and must keep a watchful internal eye out for spontaneous weak associations that bubble to the surface (a little surveillance). The blind variation and selective retention (BVSR) model of creativity, posited in the 1960's and supported by recent neuroimaging work, proposes blind variation — an uncontrolled process of random conceptual combination — may occur in the brain's default mode network when cognitive control in the prefrontal cortex goes offline. This blind variation works hand in hand with selective retention — a controlled process that involves evaluating blind variation activity — and may occur in overlapping executive control regions of the brain when they are online.[187] These two kinds of thinking can happen, to a degree, in one brainstate: Highly creative participants fail to suppress activity in the precuneus (a key region of the default mode network, involved in uncontrolled mind-wandering) while engaging in a working memory task (requiring focused external attention), suggesting that creativity may benefit from simultaneous activation of executive control and default mode networks.[188] And fMRI work on the brain activation underlying highly creative thought suggests higher functional connectivity between executive and default mode networks in the brain underlies the mix of generative and evaluative thought needed for creativity.[189] Much like narcolepsy and hypnagogia, a brain-state that flows in and out of control seems ideal for creative ideation: A mind that freely wanders through novel, weak strange semantic associations but maintains a capacity for introspection, idea selection and retention.

> *It's like producing a movie, just more flexible with my angle of view and props. I cannot control what I will see next, new scenes just switch in with no relation to previous ones…It helped me understand more about what I can do with hallucinations, I've never spent this much time unconstrained and free, it helps me see more in the world. I started with a tree but actually I can walk everywhere with this task, I can walk into the lego office and see it covered in trees, I can walk into my own building and see my professor turn into a tree, it became supremely absurd but that made me see all ways I can use a tree in ways I never imagined before, so now I can see the trees with a new sort of eyes because I will maybe continue challenging myself on the task. And it inspired me to learn new way of thinking…Just now it was as if my scenes I was seeing change every once a second*

[184] (Benedek et al. 2014)
[185] (Beaty and Silvia 2013; Beaty et al. 2014)
[186] (Gable, Hopper, and Schooler 2019; Baird et al. 2012; Beghetto 2008; Baas, Nevicka, and Ten Velden 2014)
[187] (Campbell 1960; Simonton 2013; Beaty et al. 2014; Jung and Haier 2013)
[188] (H. Takeuchi et al. 2011)
[189] (Ellamil et al. 2012)

so that new ways to use a tree come up every second and I couldn't even keep up… at the beginning of my dreaming experience I was seeing scenes that were the same size and functionality of real trees, but then the second time I was much bigger than the trees and I could eat them like finger food. You wouldn't come up with that idea at the beginning, but this time I had hundreds of them. The hope is to break out of the banal stories. Which is why I liked this experiment. I'm afraid when I walk out that I will see everything changing like fantasies. But yeah why not. Who says that I must live in the world that everyone is living in? I could write it as if I'm living in a novel. "

Subject 6, Sleep Tree-Incubation, Thesis Experiment
Note the intersection of spontaneity and surveillance, with control of theme.

Daydreaming and Creativity

" The Artist is no other than he who unlearns what he has learned, in order to know himself."

— E. E. Cummings, A Miscellany Revised, 1965

Our understanding of hypnagogic and REM dreams, with their **hyper-associative** nature, experiential **exploration** of weak semantic links, and **passing hypofrontality** (deactivation of cognitive control regions), ties in tightly with the BVSR model of creativity. Serial awakenings at sleep onset, where we create multiple rounds of deactivation and reactivation of cognitive control regions in a short period, seem **especially exciting** in the BVSR framework. Yet what of daydreams, of the waking, wandering mind, naturally snapping in and out of attention?

" Writing is nothing more than a guided dream."

— Jorge Luis Borges, *Dr. Brodie's Report*, 1970

Freud and Jung asserted that daydreaming is essential to creative writing, crediting the access to unconscious inspiration.[190] T. S. Eliot's called it idea incubation, Alexander Graham Bell called it unconscious cerebration, Lewis Carroll called it mental mastication. Much like nighttime dreaming, daydreaming was largely ignored by a brain research field which instead sought to understand the productive, attentional, focused mind. In the 1970's psychologist Jerome L. Singer brought mind-wandering into the research spotlight, putting historical anecdotes linking daydreaming and creativity to the empirical test. He found evidence that daydreaming released tension, increased creativity and illuminated hidden solutions to problems. And he turned these findings into techniques, offering ways for readers to increase their capacity for fantasy and imagery for richer lives.[191] The current research field has enumerated myriad creative benefits of mind-wandering, characterizing it **not as useless chaotic chatter, but as a source for introspection and insight** where the richness of inner experience in daydreaming is directly tied to creative performance.[192] The daydreaming mind has intermittent meta-awareness, where the ability to survey ones thought fades in and out, much like hypnagogia.[193] An increased individual tendency to mind wander is positively related to solving creative problems with sudden insight rather than a gradual analytic strategy.[194]

[190] (Madden 2016)
[191] (Singer 1976)
[192] (Zedelius and Schooler 2016; Gable, Hopper, and Schooler 2019; Leszczynski et al. 2017)
[193] (Schooler 2009; Noreika et al. 2015)
[194] (Zedelius and Schooler 2016)

While daydreaming can be a source of distraction and a professional detriment, just like a nap at one's desk, it is also a time for mental exploration and incubation.[195]

> *"You have to dream intentionally…to be a writer, you have to dream while you are awake, intentionally…"*
>
> — Haruki Murakami, 2008

Similarities in subjective content between daydreaming and nighttime dreaming have been noted since the beginning of mind-wandering research. Early studies found that 24% of thoughts in awake mind-wandering could be categorized as visual, dramatic, and dreamlike.[196] The similarities between neurophysiological aspects of MW and dreaming have recently been explored in some detail, showing that dreaming may share the same associative mechanisms and recruit the same neural networks as daydreaming, particularly the default mode network (DMN) implicated in internally focused cognition. A range of researchers have **proposed waking thought, waking MW, and dream mentation lie along a continuum of intensity** with respect to executive function as well: executive regions are most active during waking goal-directed thought, undergo deactivation during mind-wandering, and become quiescent, perhaps even actively suppressed, through sleep onset and into REM sleep. Dreaming mentation, then, can be understood as a longer, immersive, more intensive version of waking spontaneous thoughts and daydreams.[197]

> *"The implication is that fantasy and dreams are part of a single continuing fantasy process which is subject to certain transformations imposed by physiological and stimulus events. It is unnecessary to sleep in order to generate dream-like ideation, and, apparently, it is unnecessary to be awake in order to produce relatively coherent, undream-like ideation."*
>
> — Eric Klinger, *Structure and Functions of Fantasy,*[198] 1971

Assessing Creativity

Subjective Measurements

As creativity is hard to define, so too is it hard to assess. Existing approaches can be arranged on a continuum ranging from a focus on subjective judgments to a greater focus on objective evaluation criteria. Tasks which test **divergent thinking,** measuring ability to generate many mixed possible solutions to a problem, have a long tradition in the creativity literature and remain widely used in modern research. The most common divergent thinking assessment is the **Alternate Uses Task**, which involves producing novel uses for common objects (e.g., alternative uses for a brick, beyond house building).[199] These novel uses are then evaluated by a group of trained raters for relative originality (novelty), flexibility (category switches), fluency (number of uses) and elaboration (descriptiveness). Divergent thinking tasks are **especially well validated, and have powerful predictive power**: a longitudinal study of divergent thinking ability in school-aged children found that the top performers eventually lead highly successful careers in the arts and sciences.[200] Performance on divergent thinking tasks in the lab predicts both the quantity of

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[195] (Baird et al. 2012)
[196] (D. Foulkes and Fleisher 1975)
[197] (Fox et al. 2013)
[198] (Watson 1972; Klinger 1971)
[199] (J. P. Guilford 1950; Benedek et al. 2019)
[200] (Plucker 1999)

self-reported creative achievements and the quality of expert-rated creative performances.[201] As such, we used the Alternative Uses Task as a measurement of divergent thinking assessed by consensual subjective judgments.

For assessing creativity in a less constrained task, like creative storytelling, The Consensual Assessment Technique (CAT) is used. Instead of trying to measure things that might be associated with creativity or that might be predictive of creativity, the CAT looks at the creative products and has a group of experts assess the creativity of those creations on a Likert scale from 1-5. This technique mimics the way creativity is assessed in the 'real world', is done using panels ranging from 2-10 judges, and typically yields inter-rater-reliabilities among judges in the 0.7-to-0.9 range.[202] The Consensual Assessment Technique yields comparisons of levels of creativity within a particular group, not comparable to any norms across creative domains or settings. While most intelligence, aptitude, and achievement tests report different mean scores for different races, ethnicities, and sometimes genders, CAT scores show very little evidence of differences based on race/ethnicity.[203] In this thesis, we used the CAT to assess a Creative Storytelling Task to understand impacts on creativity in a less constrained task space using consensual subjective judgments, borrowing methods from the closest comparable paper.[204]

Objective Measurements

We adapted a classic task from the cognitive science literature, known as the Verb Generation Task (VGT), to get at objective computational measures of creativity. In this task, subjects are instructed to simply respond to a presented noun with a verb that comes to mind, for a set of 30 nouns. This task engages semantic processing, at the behavioral and brain level, as participants have to generate semantic associations on demand.[205] Prabhakaran adapted this task by instructing participants to generate creative semantic noun-verb pair associations specifically, and showed that semantic distance (degree of similarity of meaning) between cued creative word pairs strongly correlated with verbal, non-verbal and achievement-based creativity measures (including divergent thinking and creative storytelling tasks).[206] As dynamics of semantic association have been shown to change across the sleep-wake cycle, and unconstrained associative thinking has been proposed as a feature of sleep-related changes in cognitive flexibility,[207] we used the VGT as an objective proxy for changes in thinking across conditions of wake and hypnagogia.

For computational linguistic analyses of longer texts than word pairs, a collection of tools called Coh-Metrix has been used to produce automated measures of cohesion and readability. Just as analyses of VGT word pairs gives a sense of the semantic relationships between two words, Coh-Metrix gives a sense of the semantic relationships on multiple hierarchical levels of a text, from words to phrases to sentences. This is accomplished through a combination of semantic analysis, syntactic parsers, and indices like word and sentence length. These metrics have been validated across several studies with Coh-Metrix and shown to successfully predict human ratings of essay quality and human ratings of creativity.[208] As these results

[201] (Jauk, Benedek, and Neubauer 2014; Beaty et al. 2013)
[202] (Baer and McKool, n.d.; Baer 2008)
[203] (Kaufman, Baer, and Gentile 2004)
[204] (Zedelius, Mills, and Schooler 2019)
[205] (Petersen et al. 1989)
[206] (Prabhakaran, Green, and Gray 2014)
[207] (M. P. Walker et al. 2002; R. Stickgold et al. 1999)
[208] (Crossley, Roscoe, and McNamara 2011; Jeon et al. 2006; Zedelius, Mills, and Schooler 2019)

provide initial evidence that creative writing can be evaluated reliably based objective features, we used Coh-Metrix to analyse the stories produced by each subject and complement consensual subjective ratings.

Related Work

In HCI

Sleep Tracking

Bridging the study of human behavior and the design of electrical wearable devices, Human-Computer-Interaction is in an ideal space to make an impact on the tools and techniques built to track and change how we sleep. Research shows 9/10 Americans report using a technological device in the hour before sleep, facilitating the introduction of technological interventions for the bedroom.[209]

Although polysomnography (PSG) in the neuroscience laboratory is the gold standard for sleep staging, it is prohibitively expensive and is impractical for users to use at home.[210] In recent years, there has been an increase in engineers developing low-cost sensors aimed at tracking sleep outside of the laboratory without the need of a PSG setup.[211] These technologies have the potential to overcome the limitations of PSG studies while providing long-term, low-cost, and accurate representations of people's daily sleep patterns in their natural and comfortable home environment. Many sleep trackers are based on mobile apps, although other form factors such as wearables, smart pillows and smart sheets present opportunities for designing a myriad of future sensor-based interactions.[212] For example, Tal et. al. presented a novel contact-free, under-the-mattress piezoelectric sensor which senses heart, breath and body movement patterns and shows 90.5% sleep stage detection accuracy.[213] Sensors like the Oura ring offer non-intrusive, wireless sleep tracking with clinically satisfactory differences in staging sensitivity from PSG.[214] These trackers show promise for users getting more information about their sleep but don't do real time sleep staging, and don't enable or focus on interventions or interaction in sleep.

Figure 15. *The Oura Ring, which stages sleep using pulse and temperature. Image from Ouraring.com.*

[209] (Gradisar et al. 2013)
[210] (Ravichandran et al. 2017)
[211] (Ravichandran et al. 2017; de Zambotti et al. 2016)
[212] (Lawson et al. 2013; Heise et al. 2013; Schreiner and Staresina 2019)
[213] (Tal et al. 2017)
[214] (de Zambotti et al. 2017)

Technologies to Intervene in Sleep

Human-Computer-Interaction research also presents new opportunities for interactions across the sleep wake cycle. HCI interventions have explored support of behavior change during the awake state to benefit efficient sleep, highlighting the need for scheduling sleep.[215] Other research, such as Shuteye,[216] provides a peripheral display on the wallpaper of the user's mobile phone to promote awareness about activities that promote good sleep quality. The work of Gieselmann et. al. presents an Internet-based accompanied self-help intervention to reduce nightmare severity through online interaction.[217] A series of simpler apps provide interfaces for dream logging in the morning after a night of sleep via text or audio recording. These mirror past, less technologically advanced methods of dream capture: Lewis Carroll made a *nyctograph*, a cardboard stencil with he kept under his pillow to record his dreams in the dark without having to awaken and light a candle; Charlie Chaplin, who composed film music while asleep, used a tape recording device so he could wake up, hum a few bars, and fall back asleep.[218]

HCI research has been applied to the design of interfaces that interact with the user during sleep, to change sleep in real time. Essence, a wearable olfactory system, is built to introduce odors in REM and deep NREM sleep for nightmare alleviation and memory augmentation.[219] All of the work HCI has done to create wearable electronics for experience sampling could be adapted for sleep mentation.[220] The Breathing Bear uses rhythmic stimulation from an actuated toy to entrain infant breath, easing sleep onset and improving.[221] Haptic interfaces such as NightShift have been used to alleviate sleep apnea by delivering vibration to make users change from unhealthy body positions during sleep.[222] Introduction of pink noise has been shown to increase the depth of sleep.[223] Visual cues delivered during REM sleep have been used to trigger lucid dreams, wherein participants train to associate a light cue with lucidity in wakefulness, and then it is represented in REM.[224]

The most comparable project to Dormio is the Nightcap, which bridges HCI and sleep science. This home sleep monitoring system uses eyelid, eyeball and body movement to track sleep onset, REM and deep NREM and acquire mentation reports. The Nightcap is able to do sleep staging in real time, is much more cost effective than PSG, and has only a 5-10% decrease in accuracy in sleep state identification.[225] Unfortunately it is no longer manufactured, and relies on custom and uncomfortable sensors stuck to the eye. It enabled a host of important new studies in the wild in the 1990's, including the Alpine Racer study[226] mentioned above.

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[215] (Aliakseyeu et al. 2011)
[216] (Perry, Patil, and Presley-Cantrell 2013)
[217] (Gieselmann et al. 2017)
[218] (Fletcher 2001)
[219] (Amores and Maes 2017)
[220] (Hernandez et al. 2016)
[221] (Ingersoll and Thoman 1994)
[222] (Scarlata et al. 2016)
[223] (Suzuki et al. 1991)
[224] (LaBerge and Levitan 1995)
[225] (Ajilore et al. 1995; Robert Stickgold and Allan Hobson 1994)
[226] (Wamsley et al. 2010)

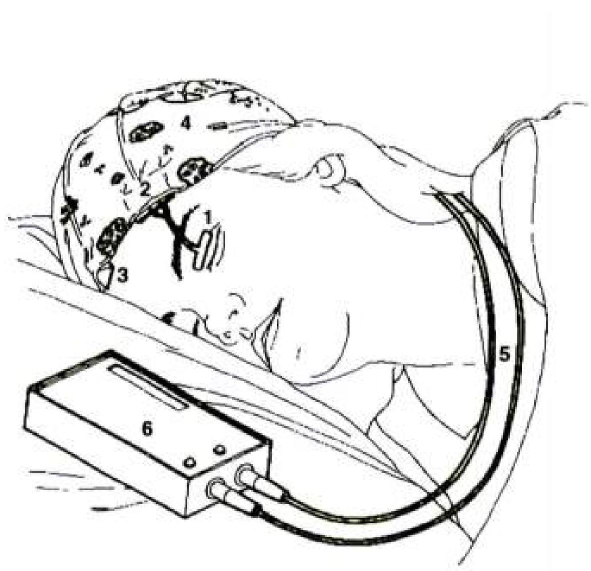

Figure 16. *The Nightcap System, from Stickgold and Allan Hobson (1994)*

Hypnagogic Interfaces

Specific interfaces have been built to leverage the cognition present in hypnagogia. The steel ball technique used by Edison and others is an example of a rudimentary interface built for hypnagogia.[227] The psychoanalyst Kubie fed back sounds of breathing to subjects to induce hypnagogia, and reported ''hypnogogic reverie, a dream without distortion; represents unfinished business of a lifetime: significant information about the past can be made accessible without the interpretation of dreams". Others used sensory deprivation with a depthless visual field (called a ganzfeld) and white noise, coupled with the instruction of continuous free associations, for inducing hypnagogia. [228]

Neurofeedback, wherein brainwaves are shown to subjects in real time as audio or visual signals to allow greater control of specific brain mechanisms, can be used to induce hypnagogia as well. Remember, this transitional phase of sleep is characterized by a loss of EEG alpha frequency activity and prominent theta activity compared to the awake-with-eyes-closed state. Green and Green used a 10-week programme of five daily sessions consisting of breathing relaxation exercises followed by 15 min of auditory alpha and theta feedback, and then 30 min of theta feedback. They found that all participants could increase alpha and most theta, and that hypnagogic phenomena could be reported without interruption of the hypnagogic state. In 20/26 participants tested there was a therapeutic effect of this feedback based on the integrative experiences in hypnagogia: participants reported increased feelings of psychological wellbeing, improvements in difficult relationships, in college work, and in the ability to concentrate. [229] A future study using only theta feedback found hypnagogia served as a state for reexperiencing and reprocessing past traumatic events: ''It is as though the patient was capable of integrating past traumatic experiences by coping with previously unresolved conflicts represented in the essential anxiety-free images and memories generated during the theta state of consciousness''. [230] This application to PTSD has not been

[227] (Andreas Mavromatis 2010)
[228] (Schacter 1976)
[229] (Schacter 1976; Gruzelier 2009)
[230] (Peniston and Kulkosky 1999)

independently replicated, though a related study has shown the benefits of A/T training for addiction to stimulants. [231]

Results of A/T training to induce hypnagogia extend to creativity benefits as well. Alpha–theta training over a five week course has been successful in producing professionally significant improvements in competitive university ballroom dancing (Raymond et al. 2005a). And Boynton et al. present an 8-week neurofeedback protocol training participants to sustain hypnagogia for extended time periods. They report increased personal creativity, stress reduction, and improved work performance for participants.[232]

In Neuroscience

Hacking Sleep

Much work has been done to alter cognition over the sleep-wake cycle in the neuroscience laboratory, from administration of hormones to electrical stimulation. Infusing the hormone cortisol early in the nighttime blocks sleep's beneficial memory effects on word-pair associates.[233] Cholinesterase inhibitors, which increase acetylcholine levels, similarly block consolidation when administered in slow-wave-sleep.[234] Electrical modification of the brain can similarly modulate the overnight effects of sleep. Application of oscillating electrical potentials to the skull at 0.75 Hz during early NREM sleep has been used to experimentally boost slow oscillations in SWS, resulting in improved memory performance the following day.[235] Applying stimulation at this same frequency further improves behavioral inhibition in ADHD the following day.[236] Magnetic stimulation has been shown to be an effective tool in manipulating sleep stage depth, perhaps a future tool to increase sleep efficiency.[237] As sleep research has given us clues as to which oscillations in sleep are most critical for which function, i.e. sleep spindles being considered critical for memory consolidation, these rhythms can become targets for entrainment: Playing bursts of oscillating white noise during stage 2 and SWS, with noise amplitude modulated at 12 Hz (targeting slow spindles), 15 Hz (targeting fast spindles), can increase the number of spindles in sleep.[238] Even rocking of the bed at a regular ¼ second rhythm can increase the number of fast spindles during sleep, an increase which is correlated with improvements in memory consolidation after sleep.[239]

Hypnopaedia in Action: Learning While Asleep

Studies using sound or somatosensory input in sleep demonstrate that sensory processing continues during sleep and can influence brain oscillations. This opens up an avenue for simple sensory modulations of brain state: In addition to working at the physical level with electrical entrainment, interventions can work at the sensory and symbolic level. Targeted Memory Reactivation (TMR) is the best researched sensory-level intervention to hack sleep mechanisms. [240] Research previously demonstrated correlations between reactivation of specific memories stored in brain networks during sleep and post-sleep endurance of memory storage. In TMR, a cue which has been linked to a learning task is represented during sleep to

[231] (Scott et al. 2005)
[232] (Boynton 2001)
[233] (Plihal and Born 1999)
[234] (Gais and Born 2004)
[235] (Marshall et al. 2006)
[236] (Munz et al. 2015)
[237] (Massimini, Tononi, and Huber 2009)
[238] (Antony and Paller 2017)
[239] (Perrault et al. 2019)
[240] (Rudoy et al. 2009)

drive specific reactivation. Presenting humans with an olfactory cue during NREM sleep that was previously presented during the learning of an object location enhances memory consolidation.[241] TMR can target specific memories for rehearsal even with simple presenting auditory cues during sleep, helping with declarative memories, with skill learning, and with spatial navigation.[242] Re-presenting an auditory or smell cue during sleep can even create stimulus specific enhancement of fear extinction in mice or humans.[243] A recent study suggests that new associations can even be learned via sensory presentation during sleep, as opposed to reactivated: Arzi et al showed significant reduction in cigarette smoking when subjects were presented with a paired cigarette and rotten egg smell, apparently forming a new association between the two. Importantly, this effect was shown following olfactory aversive conditioning during stage 2 and REM sleep but not following aversive conditioning during wakefulness. But what, we wonder, are these subjects dreaming about, and how much does it matter for efficacy?

Hacking Dreams

Successful hypnopaedia begs the question of the role that experience plays in the rehearsal and association processes ongoing in sleep, yet TMR studies rarely, if ever, wake up participants to ask for dream reports associated with cue presentation. To be clear, TMR as it's done in the laboratory is not a matter of guiding a dream, not an ongoing sensory dialogue with the sleeping mind, not interactive or targeted experientially; it is a cue presented to an unconscious, silent subject with learning effects but without reported association to an experience of learning. Presentations of stimuli during sleep without experimental gathering of dream reports leave us with evidence of an efficacy we don't understand at the experiential level. To do controlled experiments on the experiential level, we would need to control experience, and so we come to dream incubation.

The most commonly known method for altering dream content is Lucid Dreaming. In a lucid dream, one becomes aware that they are in a dream, and often gains some degree of control over the content of the dream. It is quite difficult to teach lucid dreaming, with many scientists trying to create a reliable technique for inducing lucidity, but when it works it creates a strange, fantastic hybrid state where we regain our sense of self and control in a dream.[244] Participants who gain lucidity even gain an awareness of the laboratory environment outside of the dream, and can move their eyes to signal to an experimenter that they are lucid.[245] Yet the fact that dreamers have reflective awareness, metacognitive capacity and cognitive control means the lucid dream is drastically different than a classic dream, in terms of experience and brain activation.[246] This means that as a research paradigm, lucid dreams introduce a confound to the controlled study of dreams, wherein it is unclear whether this should be considered as a separate state entirely from the typical organic dream states occurring across a night of sleep.

> " *Wow this was really cool. Because I've been trying to have dreams where I'm in control, like I'm lucid, but I always lose track of them because I fall too deep asleep. But this time, every time I heard the audio, I would come a little bit back, and come a little bit back into control, and then dive back into the story. So I could remember my dreams and be in control.* "

[241] (Rasch et al. 2007)
[242] (Oudiette and Paller 2013; Shimizu et al. 2018)
[243] (Hauner et al. 2013; Wixted 2013)
[244] (Zadra, Donderi, and Pihl 1992)
[245] (La Berge et al. 1981)
[246] (Kahan and LaBerge 1994; Mota-Rolim and Araujo 2013)

Subject 3, Sleep Tree-Incubation, Thesis Experiment
Note that serial interruptions in hypnagogia can induce some specific lucidity features, i.e. cognitive control

Purposeful incubation of specific dream content outside of lucidity has been ongoing for millennia. Fasting, for instance, was a known trigger of vivid dreams among indigenous peoples of North America. Much earlier dream incubation cults such as the Oracles of Trophonius and Amphiaros in Greece, or Egyptian dream temples such as the Thoth temple in Khimunu, used hunger and slept in sacred temples to increase the vividness of dreams and call deities into their sleep.[247] The earliest direct reference to a pre-sleep method for divine revelation dreams is inscribed on the Chester Beatty papyri, found in Upper Egypt and authored c.1350 BC. It describes a method of invoking the wisdom of Besa (or Bes in Egypt), helper of women in childbirth, protector against snakes and other terrors, and god of art, dance and music. It translates as follows:

> "...Make a drawing of Besa on your left hand and enveloping your hand in a strip of black cloth that has been consecrated to Isis (and) lie down to sleep without speaking a word, even in answer to a question. Wind the remainder of the cloth around your neck… come in this very night."[248]

The methods of dream incubation tested in labs today are surprisingly similar to this 3000 year old text: Changing somatosensory stimulation (like cloth wrapping or hunger), and the presentation of pre-sleep stimuli like a hand drawing, have been shown to have some dream incubation effects. Hunger and thirst show incubation effects, though replication is lacking and subject numbers are often low. Dement and Wolpert (1958) collected 15 REM sleep dreams from three subjects who were deprived of fluids for 24 h prior to sleeping in the laboratory on five nights. They found five of the dreams contained thirst-related content, though these did not depict the dreamer as thirsty or in the act of drinking.[249] A similar relationship was found combining pre-sleep thirst and presentation of audio containing liquid related words in REM: Dreams about liquids increased, and curiously, those who had dreams of satisfying their thirst drank less upon awakening than did subjects who had dreams of being thirsty and unsatisfied.[250] A spray of water on the skin, application of a pressure cuff to a specific limb, or even application of electrical pulses to cause muscle contractions in a sleeper have each been shown to affect qualitative dream features, increasing vividness or movement sensations in dreams.[251] While there is clearly a relationship between somatosensory experience during sleep and concurrent dream experience, experimental dream research hasn't yet provided a satisfactory description of how these systematically create or can be used for specific transformations in dream content.

To incubate more specific content than a sensation, empirical studies have used pre-sleep stimuli, much like the drawing of Besa mentioned above. Films presented before sleep have little effect on dream

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[247] ("'The Stuff Our Dreams Are Made Of'" 2011; T. Nielsen and Powell 2015; Foucart 1912; Nichols 1968)
[248] There have been studies on specific foods as dream inducers, though they are not necessarily empirical. Psychoanalyst Ernest Jones named cucumbers as "the article of food that is most looked askance at in relation to Nightmare" (p. 38). The British Cheese Board conducted an internal study to combat popular notions tying cheese to nightmares, and suggested instead that eating Stilton cheese led to vivid dreams while eating cheddar often led to dreams of celebrities: "We hope that people will think more positively about eating cheese before bed,' says Nigel White, British Cheese Board secretary." Reported in T. Nielsen (2012), Dream incubation: ancient techniques of dream influence
[249] (W. Dement and Wolpert 1958)
[250] (T. Nielsen and Powell 2015)
[251] (Tore A. Nielsen 1993)

content, though they can significantly alter the emotional affect of dreams.[252] Presentation of a stressful film, and replaying that film's soundtrack to subjects in REM sleep, slightly but significantly increases incorporations of film scenes into dreams.[253] Static visual images presented before sleep are rarely incorporated into dreams as specific elements of dreams, though pictures presented do produce corresponding affect in morning dream reports.[254] Waking behavioral experiences are not easily detectable in subsequent dreams.[255] Statistically significant effects of pre-sleep manipulation like those seen for measures of qualitative dream features are extremely rare for direct or indirect incubation of dream content.[256]

Pre-sleep rehearsal of current concerns, as opposed to exposure to stimuli, has some efficacy in incubating dreams. Barrett (1993) asked college students to incubate a specific, personally relevant problem of of their choosing. Using the simple incubation method of thinking about the problem for 15 minutes before sleep, participants rated 49% of their dreams as relevant and 34% of them as containing a solution while judges' ratings were 51% and 25%. Saredi et al. (1997) also report that for a small sample of participants in a sleep laboratory study, thinking of a question related to a current problem prior to sleep increased the likelihood that dream content reflected the problem, but that this effect was weakened when dream length was controlled for. Studies like these are extremely helpful, but they fail to separate the effects of waking thought from dream processes: Since participants are allowed to choose personally relevant problems, which they have likely been thinking about for a time period before the experiment, these are not controlled tests on incubation techniques. And since these studies do not control for dream content, and subjects have a wide range of problems to solve, these are not controlled tests on dream content.

The studies thus far offer no way to reliably incubate an experimenter controlled, specific dream theme. Yet one study, a breakthrough in the dream incubation literature and a sensation in the press, stands out. Stickgold (2000) had 27 participants play the game Tetris for 7 hours over 3 days, in the morning and the evening, and collected sleep onset dream reports from each subject over the first hour of sleep. Awakening was done with the Nightcap sleep monitoring system described in Related Work, and reports were collected when participants were attempting to fall asleep as well as after intervals of 15 to 180 s of Nightcap-defined sleep onset. Out of the 27 participants, including amnesiac patients, 17 (63%) reported at least one Tetris-related dream over 3 days. Out of the total reports, 7% contained task-related imagery. Of the 22 non-amnesiac participants, a total 30 reports of Tetris imagery in 418 reports were collected. This study demonstrated that there is a way to incubate specific, experimenter-chosen dream themes in hypnagogia. A follow-up study using the skiing video game Alpine Racer as pre-sleep stimuli showed gameplay directly influenced subjective experiences during sleep onset as well, with reports of task-related imagery in hypnagogia in 24% of post-training reports. The Tetris and Alpine Racer studies of hypnagogic replay inspired the Dormio system, which focuses on dream incubation of sleep onset as well but uses exposure to stimuli within hypnagogia, as opposed to pre-sleep exposure, for theme incubation.

[252] (Rosalind Dymond Cartwright 1969)
[253] (Koninck, de Koninck, and Koulack 1975)
[254] (Carpenter 1988)
[255] (Breger, Hunter, and Lane 1971; Hauri 1970)
[256] (Koulack 2017)

The Dormio Device

Words Make Worlds: Serial Incubation

"The purpose of poetry is to awaken sleepers by something other than a shock."

— Denise Levertov, 1959

The Dormio system consists of a handworn sleep tracker and an associated app, used to communicate with users and record dream reports via laptop or cellphone. The user interaction of the Dormio system crosses multiple stages of consciousness including wake, sleep inertia, semi-lucidity and sleep. The tidal shifts in brain function which occur during sleep do not reverse immediately upon awakening. The properties of the preceding sleep stage linger, leaving participants in a state of sleep inertia. Experimenters have used this brief window of altered brain function to probe the properties of each preceding sleep state.[257] Upon awakening, blood flow is rapidly re-established in the brainstem, thalamus, and anterior cingulate cortex but it can take up to 20 minutes to be fully re-established in dorsolateral prefrontal cortex — this may contribute to heightened suggestibility.[258] Our system takes advantage of this **window of altered, semi-sleeping** brain function, and inserts a dream theme incubation during each inertia-laden awakening, creating a serial dream incubation paradigm.[259]

The Dormio user interaction is detailed below. First, while awake, the user decides what they want to dream about. This can range from a creative problem they are working on to an experience they want to explore or an emotional issue they want a new perspective on. The user launches the Dormio phone app or web app to record a personalized dream prompt message (R1) using their voice, i.e 'Remember to think of X'. The dream prompt will remind the user to dream about a specific topic and will guide their thoughts during hypnagogia. Users then record a dream report message (R2), i.e. 'Please tell me what is going through your mind'. This will prompt the user to report on their experience at regular intervals during hypnagogia. Next, the user selects the desired biosignal calibration period, number of rounds of hypnagogia and depth of hypnagogic experience: shallow (1 minute), medium (1:30 minutes) or deep (3 minutes) for each round. This time period reflects the period of time that users will be allowed to sleep without interruption after the system has signalled descent into hypnagogia. Next, the user puts on the handworn Dormio sensor and lies down to sleep either during a daytime nap, immediately after wakeup from a morning alarm or at the onset of a night of sleep. The use of the system in naps or after morning awakening, as opposed to use immediately before a full night of sleep, does not put normal nightly sleep architecture at risk.

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[257] (Carr and Nielsen 2015; Tassi and Muzet 2000; Noreika et al. 2009)
[258] (Nir and Tononi 2010)
[259] Our dream report system is an adapted, automated version of the serial awakenings paradigm used to collect hypnagogic dream reports with repeated wakeups during sleep onset using either PSG or Nightcap in sleep science paradigms mentioned earlier.

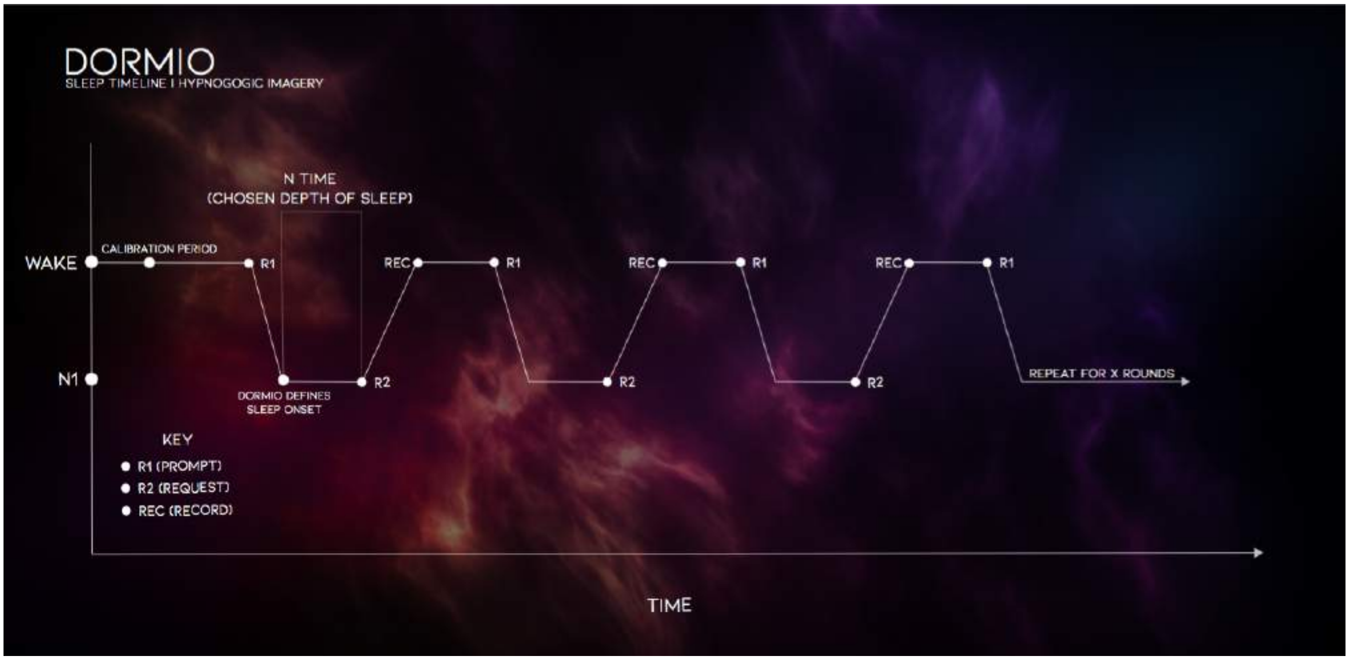

Figure 17. *The Dormio system, combining prompt, request and record features. Figure by* ***Christina Chen***.

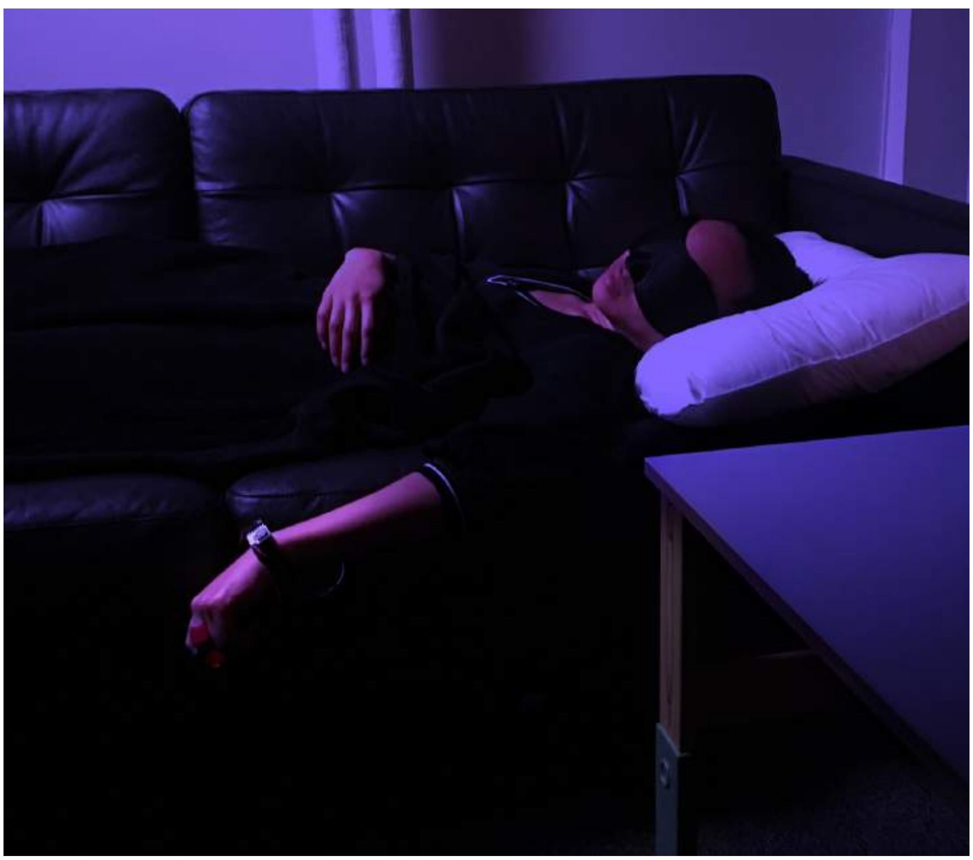
Figure 18. *The Dormio system, in use. Image by* ***Oscar Rosello***.

From the moment the user lies down wearing the hand sensor, the system tracks **heart rate, finger muscle flexion and electrodermal activity**. Subjects are asked to close their hand when they first lie down, and finger flexion lessens as subjects forget or fail at this passive behavioral task as they descend into sleep. Changes in these signals — heart rate, skin conductance and muscle tone — have been historically used as markers of sleep onset, each offering insight into Hori stages of sleep onset, and passive behavioral measures have shown to be unobtrusive sleep onset trackers which offer information in addition to physiological measures.[260] Each of these signals is normalized over a customizable calibration period once the user starts the Dormio session. Once the calibration period is done, the dream prompt message plays once, and subjects begin falling asleep. When the descent into hypnagogia is detected, the Dormio system starts a timer corresponding to how deep the user selected to go into hypnagogia. This timer can be customized to vary over the course of the night, and can do so pseudo-randomly. After this timer elapses, the system plays back the user's voice with the recorded dream request message. This has the function of gently awakening the user and gathering hypnagogic experience data via voice report. After the dream report is gathered, the system plays back the recorded dream prompt to guide dream content. This process is repeated the desired number of times. Finally, the user can wake up to the sound of an alarm and find their stored audio dream reports, or set no alarm and continue sleeping after Dormio interaction finished. Though having your nap interrupted sounds strenuous, even short naps like these which don't involve stage 2 sleep have been shown to improve cognitive function and mood. Just 9 minutes of naptime is adequate for obtaining benefits of a daytime nap.[261] Perhaps this is why subjects have consistently rated the Dormio experience as positive and relaxing.[262]

> *"I started to go down a story path every time the word tree was mentioned, and when I was told that I was sleeping and to think of a tree again I switched back to the tree and took a different path. Very interesting, relaxing, and really made me think."*
>
> Subject 1, Sleep Tree-Incubation, Thesis Experiment
>
> *"Each scene was slightly different with each wakeup. It was like chronological. The first one was animals going here and there around the trees. Then there were people and the cats were going on the trees and not coming back. After the first prompt people are burning down trees. And then in the third one it was a nice garden with a single tree and you were swinging over it with an apple saying 'it was better back then'....Animals and people were all there and doing certain activities. But I was having no control in guiding the dream. It was all spontaneous. I thought I only slept like for 10mins but It was 40-45 mins. I felt I was in an open environment observing things...Yes I was more of an observer looking from a distance. I woke up laughing because I had a very funny dream. About you on a tree."*
>
> Subject 2, Sleep Tree-Incubation, Thesis Experiment
>
> *" My dream was pleasant and mysterious. I never knew what the next part of my dream was going to be. My dream did involve a tree. I was following the roots with*

[260] (Ogilvie 2001; A. Mavromatis and University of Brunel 1983; Casagrande et al. 1997; Prerau et al. 2014)
[261] (Hayashi, Fushimi, and Iizuka 2014)
[262] ("Recuperative Power of a Short Daytime Nap With or Without Stage 2 Sleep" 2005)

someone and the roots were transporting me to different locations. At each location i was trying to find a switch. It was unclear why I had to turn on the switch, but a[t] the final location it a window with a bright light was revealed. I saw a familiar face, but I couldn't place where I'd seen them. In the background, the moon was shining bright and illuminating the face. I was dreaming this while awake and not fully asleep. I could hear myself talking to someone about finding a switch. I could hear my breathing, my footsteps, the wind, and an air conditioner. When I bumped into objects, I can hear the noise of the collisions. I could hear the roots of the tree pulsating with energy as if they were leading me to some location."

Subject 3, Sleep Tree-Incubation, Thesis Experiment

" *This was surprisingly pleasant - I assumed that being drawn closer to sleep and pushed away repeatedly might be frustrating in some capacity. But I really felt like being allowed to explore thoughts in an in-between state was more pleasant than actual sleep, since I can never seem to recall my dreams and this allowed me to consciously think beyond the everyday without feeling like I was consciously pushing myself along very much.*"

Subject 10, Sleep Tree-Incubation, Thesis Experiment

Hypnagogia Detection

One of the main challenges and contributions of the Dormio system is enabling interaction with hypnagogia without the need for PSG sensors which affect sleep quality and comfort. Remember, Hori stages are classically defined via EEG changes, yet there has been broad disagreement and poor inter-rater reliability surrounding classification of hypnagogia with EEG. This is a **definitional grey area**, with 9 stages all classified as a sleep onset process and the line between sleep and wake blurry throughout; picking a point of objective sleep onset along a continuum of change is simply arbitrary. Further, there has been limited work on EEG signatures of hypnagogic phenomenology, and these signals do not reliably indicate experience or onset of subjective sleep.[263] There is evidence that sleep onset imagery occurs in a range of 15 seconds to 5 minutes post sleep onset, and there is evidence that sleep onset imagery exists from early drowsiness into the early minutes of stage 2 NREM sleep.[264] As there is a **wide margin** within which sleep onset imagery will occur, and this system is built to incubate sleep onset imagery, our hand-worn system can tolerate a large temporal margin of error for sleep onset detection and still function to incubate hypnagogic dreams. This version of the Dormio device thus aims simply to detect hypnagogia, or the sleep onset period (SOP), without making claims to detect exact Hori stages or an exact moment of sleep onset.

The Dormio system uses **3 measures of sleep onset in conjunction**. First, users are asked to gently close their hand when they lie down to sleep, allowing the flex sensor to monitor progressive loss of muscle tone via hand opening. This is a **passive behavioral measure of sleep onset**, specifically indexing changes in the Flexor Digitorum Profundus finger muscle, used in the past for reliable SOP detection.[265] Loss of muscle tone is specifically temporally tied to onset of hypnagogic imagery, while more recent papers have

[263] (Tanaka, Hayashi, and Hori 1996; Noreika et al. 2015)
[264] (Rowley, Stickgold, and Hobson 1998; T. Nielsen 2017)
[265] (Kelly, Strecker, and Bianchi 2012; Prerau et al. 2014)

demonstrated that drops in heartbeats per minute (BPM) and shifts in EDA coincide with loss of muscle tone to confirm descent into hypnagogia.[266] These are physiological indicators of sleep onset. Values of each signal are averaged over a customizable calibration time, default of 120 seconds, after the subject lies down. Each signal is assigned an adjustable threshold for deltas in the app, such that Heart Rate delta (BPM) > X or Electrodermal Activity delta > Y or Muscle Flexion delta > Z, wherein a delta of X, Y or Z amount will trigger the 'sleep onset detected' audio interaction. Deltas were determined based on pilot data (n=5) of descent into sleep with wake-ups and self-report of sleep state, i.e. "were you asleep/halfway/awake?". Reports were used to determine sleep stage transitions and associated deltas, employing a past method to validate detection of hypnagogia via assessment of changes in perceived sleepiness and appearance of hypnagogic dream features.[267] For the purposes of this experiment, Heart Rate (BPM) delta > 5 beats per minute or Electrodermal Activity delta > 4 or Muscle Tone (Flex) delta > 8 were used, determined based on pilot data of physiological signals tied to reports of sleepiness and hypnagogic phenomenological features. BPM units for delta calculation are beats per minute, while Electrodermal Activity and Flex units are raw analog-to-digital units which index changes in conductance (μS) and resistance (KΩ) respectively. Further, during experiments, subjects were asked upon each wakeup "were you asleep/halfway/awake?", for subjective confirmation of sleep onset. For users at home with the iOS app and web app, we also developed a semi-supervised anomaly detection method to recognize sleep onsets based on the Histogram Based Outlier Score (HBOS) method.[268] Histograms are calculated for the three physiological signals over the calibration time, each histogram representing the distribution of the awake state. Then, 15-second time windows are continuously compared against the histograms, to generate a Histogram Based Outlier Sleep Score (HBOSS) which is used to demarcate sleep stage transitions. HBOSS allows for differential weighting of each signal, if one seems abnormal or more informative in a specific individual. Based on pilot data, HBOSS is highly correlative to sleep onsets detected by a human sleep scorer from the Dormio signal record.

[266] (Penzel et al. 2003; Herlan et al. 2019; Ogilvie 2001; Carskadon and Dement 2005)
[267] (Rowley, Stickgold, and Hobson 1998; Ogilvie 2001)
[268] (Munir et al. 2019); "Histogram-based outlier score (hbos): A fast unsupervised anomaly detection algorithm." *KI-2012: Poster and Demo Track* (2012): 59-63

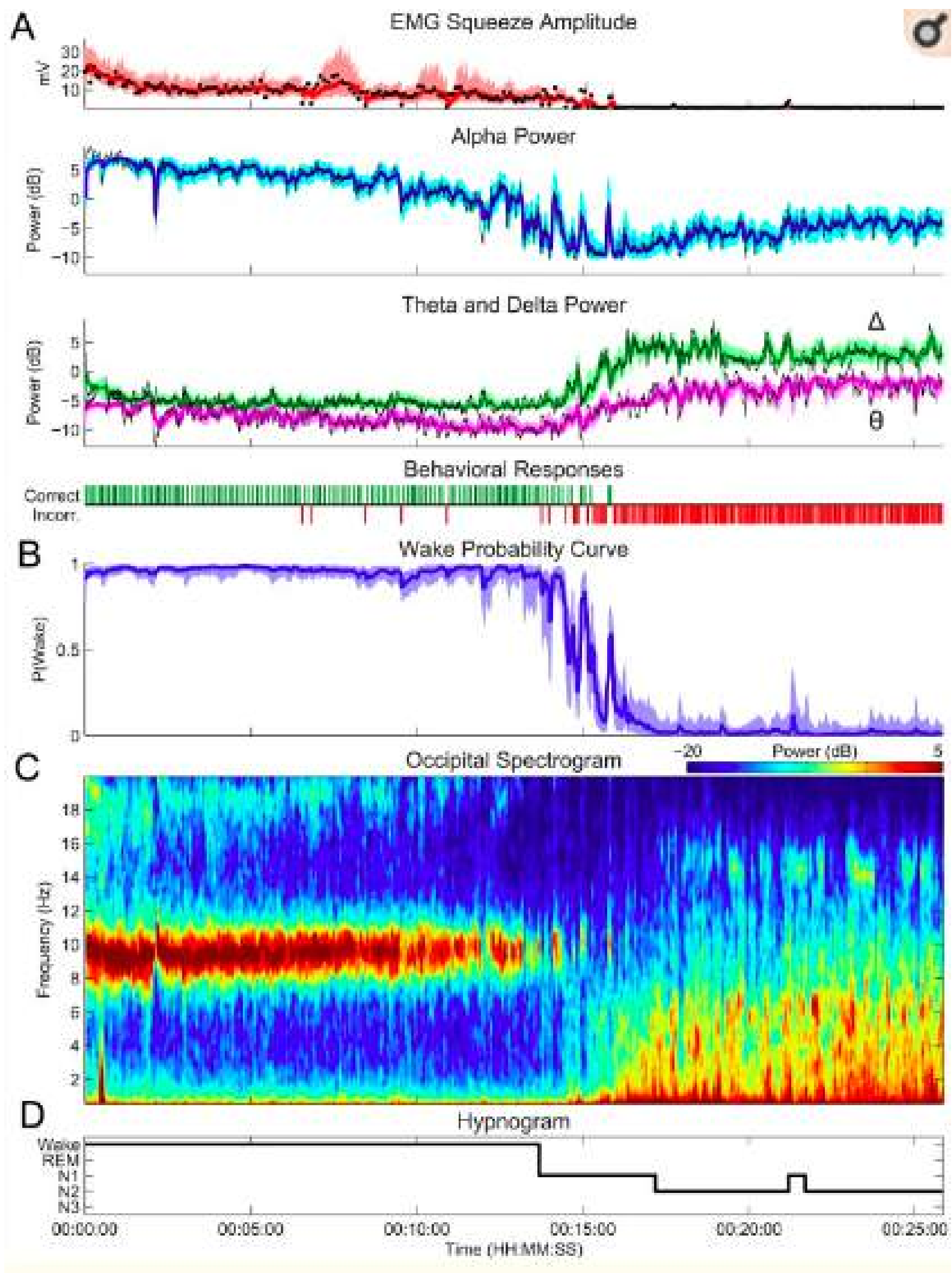

Figure 19. *Illustration of the correspondence between passive behavioral measures of FDP (finger flexion muscle) EMG squeeze amplitude and EEG dynamics at sleep onset. (A) The simultaneously observed EMG and EEG observations, and behavioral responses from the experiment are used to estimate the wake probability curve (B), which shows Pr(Wake), the probability of wake given the EEG and EMG data, over time. The wake probability curve agrees well with features of the EEG spectrogram (C) and the clinical hypnogram (D). Image from Prerau et al 2014.*

Hardware

Form Factor

We designed our own custom 30 x 15 mm board using Autodesk Eagle and fabricated it in-house using a Modela MDX-20 3-axis milling machine. To handle sensor input, logic and networking we used an RFD22301 module, a Nordic nRF51 microcontroller with integrated Bluetooth based on the ARM Cortex-M0 core. This board sits on the user's wrist. The Dormio system is designed to be free of wires for comfortable sleep. We embedded a 3.7V lithium-ion battery to power the Dormio glove for over 20 hours of uninterrupted monitoring. In addition, all the communication between the glove and the OpenSleep iPhone application relies on Bluetooth Low Energy (BLE).[269] The Dormio glove is designed to be breathable, lightweight and comfortable. We fabricated a series of adjustable nylon straps around the wrist, middle and index fingers that hold the sensors and PCB in place while exposing the hand to air for cooling. Each of the three Dormio sensors is sampled at 100hz. The user's heart rate is monitored by means of the Adafruit's Pulse Sensor Amped on their middle finger, muscle tone is tracked using a voltage divider composed of a resistor and a 4.5" Sparkfun flex sensor wrapped around the index finger, and EDA is monitored using a constant voltage source, a voltage divider and a low-pass filter to measure conductance between two electrodes placed on the bottom of the wrist.

Figure 20. *The Dormio circuit design*

[269] Hardware design led by Tomás Vega, the form factor a collaboration with Oscar Rosello

Figure 21. *The Dormio PCB and handworn system, dorsal side. Photo credit* ***Oscar Rosello***

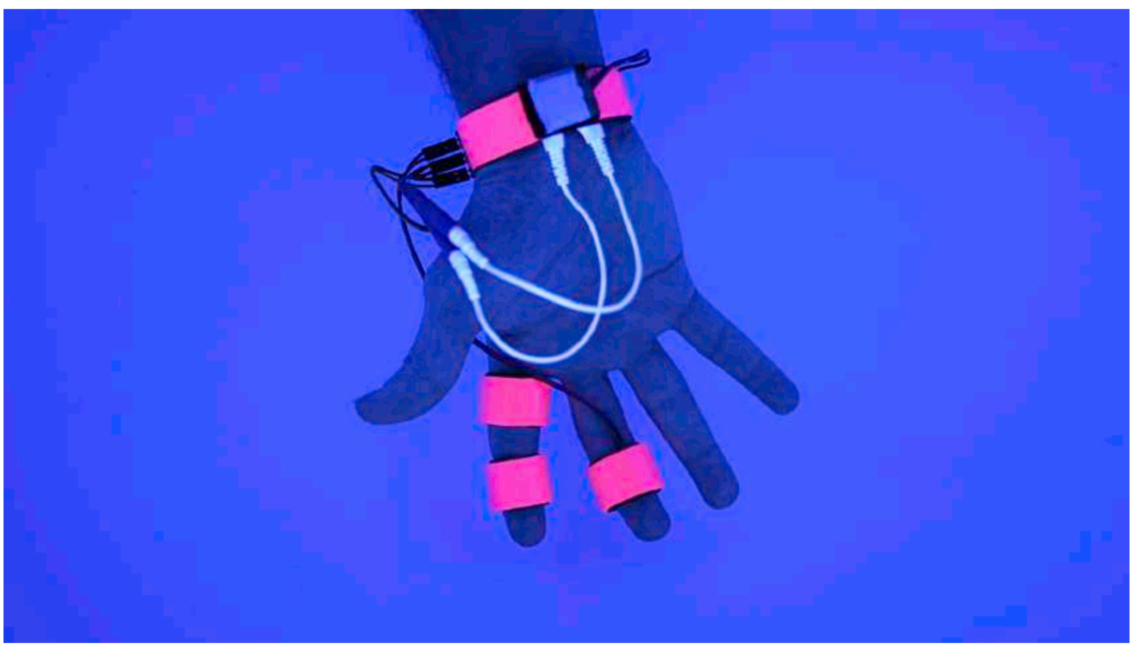

Figure 22. *The Dormio PCB and handworn system, palmar side. Photo credit* ***Oscar Rosello***

Software

iOS App

Dormio App

The Dormio iPhone app, together with the Dormio glove, provides an interface for users to control their hypnagogic experiences **from their smartphones.** The interface allows users to set up the system and customize it according to the desired dream theme. There are features for recording the dream prompting message and the dream report request, a text-field for inputting the desired number of hypnagogic rounds and the signal deltas to determine wakeup, a combo-box for choosing the desired depth into hypnagogia, and a toggle button to initiate the interaction.[270] There is further a silence detection feature, so that recording does not continue when unnecessary. The app has **two modes, signal based and timer based.** The signal based mode is for people with Dormio hardware, and does recording and prompting based on signal deltas. The timer based mode is for people who do not have the Dormio hardware, and bases interaction only on user estimates of sleep onset latency. A drop detection feature is included, so people can hold their phone and use the equivalent of the 'Steel Ball Technique' to determine sleep onset latency.

Figure 23. *Screenshots of the Dormio application. Biosignals are displayed live from the Dormio sensor (left). After the user is awake, they can access and share a list of their dream recordings (right).*

[270] iOS design was done in collaboration with Eyal Perry and Matthew Ha

Web App

OpenSleep Biosignal Interface

For those who do not have an iPhone, the Dormio web app enables easy hypnagogic interaction online via laptop or desktop. The Dormio web app also has two modes, signal and timer based, and captures audio and biosignals from each user. Because bluetooth connectivity and audio recording function differently on the web than on iOS, a separate Dormio software system is necessary. To gather and store sensor data, the Dormio Web App makes use of OpenSleep, a framework built for biosignal tracking and analysis. OpenSleep communicates wirelessly with the Dormio glove, using the CoreBluetooth framework to receive heart rate, muscle tone, and electrodermal activity via BLE. OpenSleep streams signals to the Dormio web UI, which monitors sleep, visualizes time-stamped sensor data and logs biometric information and audio data. The back-end of OpenSleep Desktop is written using Node.js. To receive the data sent from the glove, we use Noble, a Node.js Bluetooth Low Energy (BLE) central module. We handle server communication with the client using socket.IO, a real-time bidirectional event-based communication framework. The UI is a web application written in JavaScript, using client-side socket.IO to communicate back and forth with the server. The client listens for the streaming of the sensor values and plots the data in real-time using D3.js. Group, gender, age, dream theme, audio recorded and biosignals are logged into a zip file when each session is ended.[271]

Figure 24. *Dormio Timer based website. UI led by* ***Christina Chen***

[271] OpenSleep development led by Tomás Vega. Dormio Web UI has been a collaborative effort with Eyal Perry, Matthew Ha, Tomás Vega and Christina Chen.

Data Analysis Platform

To give users a sense of session dynamics and their own deltas, we have built a custom data analysis platform. This platform is connected to the server which the Dormio iOS app can automatically upload to, if users choose to upload data. Alternatively, it can accept local files which the Dormio iOS app or Web App each save. It will parse and plot these, along with markers for wakeup and report times, so users can see biosignal changes and corresponding changes in phenomenology.

Experiments

Pilot Experiment, First Dormio Iteration[272]

System

The first iteration of Dormio was built to awaken subjects solely based on changes in their flexor digitorum profundus (a muscle in the forearm that flexes the fingers) flexion. This method, as described earlier, is a remarkably simple yet robust signal of descent into hypnagogia. Our interest was in testing whether we could target hypnagogia for dream theme incubation using this detection strategy and an audio interface, and in turn engender a creative boost related to incubated dream themes. Given that people lose muscle control when entering stage 1 sleep,[273] we designed an Arduino-based glove to signal to the Dormio system when users were no longer able to hold a closed fist. With an embedded force sensitive resistor in the palm, users can comfortably touch the sensor during their wakeful state and then, when their hand opens and force ceases upon sleep onset, send a signal of 'no-touch' back to the system. With a constant feed of data on muscle control, the first Dormio system used the conversational robot Jibo to alert users whenever they lost sensor contact (as opposed to delivering alerts via the Dormio iOS or Web App), to prevent them from going into NREM 2.

To do this correctly, Dormio must rouse users lightly, saying "[Name(x)] you are falling asleep" at the correct time — not missing Hypnagogia by prompting either too early, too late or too loudly — and correct volume — loud enough to rouse participants from their descent into deeper sleep, but not so loud as to shock them awake and make reentry into hypnagogia difficult. After alerting users they are falling asleep, Dormio says "remember to think of [dream cue (a)]", then "tell me, what are you thinking about" and finally "can you tell me more?", with a hard-coded 2-minute delay between prompts. Dormio is able to speak with users in Hypnagogia about any pre-programmed prompt, using either text-to-speech generation (as was done in the pilot experiment) or a pre-recorded audio cue in the user's voice.

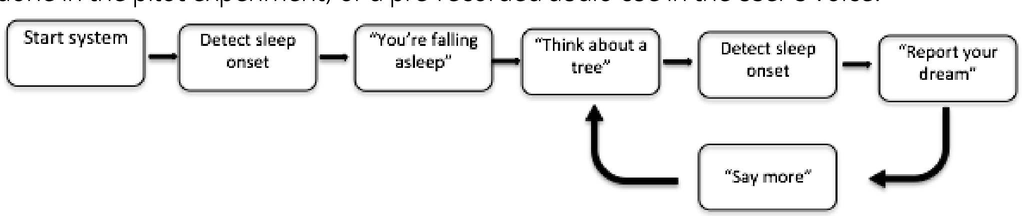

Figure 25. *An illustration of the Dormio audio interaction, Iteration 1. Image credit Robert Stickgold*

[272] The pilot experiment was done in collaboration with Ishaan Grover and Pedro Reynolds-Cuéllar
[273] (Ogilvie 2001)

This tracker enables a closed-loop system to present dream direction stimuli and dream report prompts based on flexion changes, without the need for pre-sleep training, expensive sensor equipment or supervising sleep staging technicians. A Muse EEG is included in the system, communicating with the computer, purely for data collection purposes and post-sleep validation of staging by Dormio. This hand-worn sleep tracker thus opens up possibilities for simple, mobile, cheap testing of dream direction with audio. Figures 2 shows the design of the glove used in our experiments.

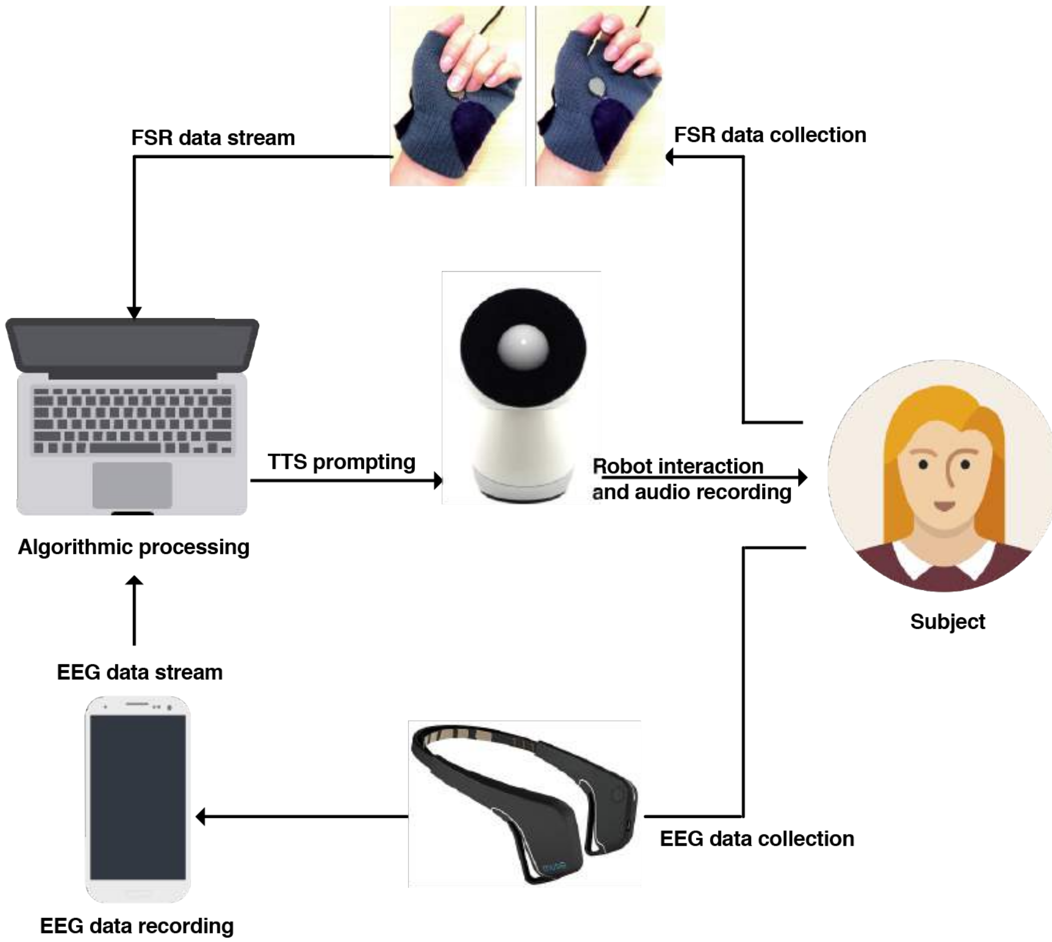

Figure 26. *An illustration of the Dormio system devices, Iteration 1. Image credit* Pedro Reynolds-Cuéllar

Methods

We enrolled 8 graduate students (4 male, 4 female) from the Greater Boston Area as participants for a within-subjects design experiment. The average age of the participants was 23.8 yrs (SD 1.76). Participants arrived at the laboratory in the evening (between the hours of 5:00pm and 9:00pm) and were given a consent form to read and sign. Consent form and experimental procedures were approved by the MIT Institutional Review Board, The Committee on the Use of Humans as Experimental Subjects. After subjects signed the consent form, they were instructed to lie down in a testing room bed. Participants were told the test was investigating the relationship between rest and creativity, and that they would engage in both active rest (lying down awake with eyes closed) and sleep. Experimenters remained in the room with subjects for safety, staying out of sight behind a partition wall after subjects lay down, and returned to deliver instructions after wakeup. Subjects were informed that upon wakeup with prompt words they could experience something akin to hallucinations and should not worry, simply stay calm and still and inform experimenters of any discomfort.

Prompt words for each condition (either "A Rabbit" or "A Fork") were matched based on their values of affective arousal, according to the Affective Norms for English Words.[274] Words were further counterbalanced with conditions, such that no consistent word-condition association could skew task performance or incubation results. Two participants (both male) explained they were not tired enough to fall asleep during the experimental condition. Their data are excluded from our analysis and results. The experiment took 2 hours from start to finish.

In the control condition (n=6) of active rest, participants were asked to answer a pre-condition survey, lay down with their eyes closed, remain still and awake and think of a given prompt word for a span of 8 minutes. Participants were asked to focus on any ideas or images that came up while lying down. While lying down, the participant was prompted three times by the robot on what word to think about ("remember to think of a rabbit/fork"), matching number of prompts across conditions, and asked to dictate a report of what they had been thinking before each prompt was given. Once 8 minutes ended, the robot asked participants to open their eyes and participants were given a pen and paper. Participants were then presented with the Alternative Uses Task (AUT),[275] a classic test of creativity related to divergent thinking abilities, and given 2 minutes to write alternative uses for the specific word they were prompted with; i.e. alternative uses for a fork. Participants were then asked to perform a creative storytelling task, adapted from the Baer's Consensual Assessment Techniques (CAT) for creativity, telling a story using the prompt word.[276] Participants were informed that there was no time deadline for this task, but an alert would be provided after 5 minutes of writing, and that they could make use of any media they preferred (drawing, writing). Total story writing time was recorded across both conditions.

For the experimental condition (n=6) of hypnagogic sleep, participants repeated the same protocol but were wearing the Dormio system and were instructed to fall asleep. Participants were asked to focus on any ideas or images that came up while lying down. Once the robot prompted them to go to sleep, the system started tracking the participant's hand pressure over the FSR sensor, as well as recording EEG signals. Once a loss of muscle control was picked up by the system, a 3-minute timer was triggered after which the robot would alert participants they were falling asleep. This 3-minute window was chosen to ensure full sleep onset transition, and because previous work with serial awakenings has shown hypnagogic imagery can continue into early stage 2 sleep. Within this 3-minute window, the system continued EEG data capture and tracking sleep spindles. After first detecting and alerting participants of sleep onset, the system reminded participants of the prompt word, asked them to verbally report the thoughts they were currently having, and recorded audio. Once subjects finished speaking, the robot instructed them to hold the glove again and prompted them to go back to sleep. This loop of events was repeated three total times in order to confirm the system enabled entering and exiting sleep multiple times. At the end of the last loop, the robot instructed the participant to wake up fully. Immediately after removing the Dormio system, participants were tested again using the AUT test, as well as asked to write up a story in the same way they did in the control condition.

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[274] (Ogilvie 2001; Stevenson, Mikels, and James 2007)
[275] (Joy Paul Guilford 1967)
[276] (Baer 2008)

Results

Enabling Hypnagogic Dream Access and Inception

The primary objective with this study was to demonstrate a successful interface for accessing hypnagogic cognition. 100% (6/6) of our subjects remembered and reported seeing[277] the prompt word during their dream state, showing successful incubation and recall of stimuli into said dream state. This allows subjects to actively reflect on their semi-lucid Hypnagogic cognition, allowing for a 'conversation' across levels of consciousness detailed in verbal reports. Each subject had 3 recorded losses of muscle control, prompting 3 audio cues from Dormio. 83.33% (⅚) of the participants reported an emotional experience in hypnagogia, and 83.33% (⅚) reported an intellectual experience in hypnagogia. Though prompting was exclusively in audio, thematic hypnagogic experiences were reportedly multimodal.

> *"**Dormio:** You're falling asleep. Think of a fork, a fork…Tell me, what are you thinking?*
> ***Subject:** A fork in a supermarket and I'm trying to use it to cook burgers on the seaside and my friends are there and it's very comfortable and it's a metal fork. One fork.*
> ***Dormio**: Can you tell me more?*
> ***Subject**: The house…It's a house I've been in. And a sink, and there are forks in the drawers but there's only one fork im using. And there's a charcoal grill it's making beef burgers and we bought the forks at the supermarket and there's a lot of smoke.*
> ***Dormio**: Ok you can start falling asleep again..Please tell me, what are you thinking about?*
> ***Subject**: A speech about a fork. A monkey is holding it the eagle is carrying it across the trees. It's a wooden fork. And the family is happy to see the fork. And they're putting it in a pumpkin. And the secret agent is using the fork to go into the headquarters. People in sunglasses are taking the agent out. And the agent throws the fork into a tree*
> ***Dormio**: Can you tell me more?*
> ***Subject:** The fork is on the ground. And a child picks it up and throws it to a bird. And the bird lays an egg with a fork….in it. And there's a caterpillar.*
> ***Dormio**: Ok you can start falling asleep again…You're falling asleep, remember to think of a fork…Tell me, what are you thinking*
> ***Subject:** A fork the size of a lightbulb. And there was a city in the lightbulb. The fork is found under a sink. There is a maze in the fork. And the water from the sink is flowing through the maze. And it gets filled up.*
> ***Dormio**: Can you tell me more?*
> ***Subject:** A fork comes in plastic tubes in a waterfall. And it flows into space. And they're on the moon, and the fork is planted as a flag. The sun grows bigger. The maze is made of grass and shaped like a brain. There are cats in the maze, and spiders and the spiders – they're legs are made of metal and red and brown. And they have ears, and someone scratches the ears with a fork. And the fork is used to scoop ice cream into a styrofoam cup."*
>
> Subject 4, 'Fork' Incubation Condition, Pilot Experiment, verbal reports given at each awakening

[277] Subjects reported "seeing" imagery, but we did not ask them to clarify the distinction between seeing, hallucinating, imagining, simulating, or thinking of visuals.

Figure 27. Animation of the above dream report created for *BBC Click*. Credit BBC.

"I would be reminded to think of a rabbit and each time was like the new beginning of a story with very different rabbit characters. For example, my childhood pet rabbit, an aluminium rabbit head, a dissected rabbit, a warren of rabbits thumping the ground rhythmically."

Subject 1, 'Rabbit' Incubation Condition, Pilot Experiment

User Experience with the Dormio System

Subjects rated their comfort with the conversational interface on average 4.5/5 (SD ± .5), from 1 "uncomfortable" to 5 "very comfortable", while two subjects noted that the presence of researchers supervising in the room, made them less comfortable. It is further important to note that 2 subjects commented that keeping their hand closed for force sensing made falling asleep more difficult, and that they found the robotic voice had a jarring tone. These reports open up opportunities for future interaction improvements.

Story Results

Subjects wrote for a mean time of 530.33 (±S.D. 169.19) seconds in the Sleep condition and a mean time of 371.5 (±S.D. 154.18) seconds in the Wake condition. The mean story time was significantly greater in the Sleep than Wake condition ($p=0.01$, $t = 4.0494$, $df = 5$). This may be indicative of increased motivation or enjoyment of creative storytelling. 4/6 subjects expressed their story in mixed media (drawing and writing) after hypnagogia, versus 6/6 choosing to use only one medium (writing) after the control condition. The above statistics are proxies for increases in creativity. We recognize the lack of standardized measures for creative story assessment in this study as an opportunity for improvement in this experiment, and used extensive and validated creativity rating methods for the larger Thesis Experiment

Alternative Uses Task Ratings

To score creativity of idea generation in the AUT test, we used scoring methods from the clearest comparable paper.[278] In this study, researchers investigated creativity augmentation in REM sleep, and relied on an AUT to assess creative idea generation. Following this model, two human raters were trained

[278] (Baer 2008; Ritter and Dijksterhuis 2014)

with an elaborate explanation of the concept of creativity, centered around novelty of ideas, and the raters were provided with information about the scoring system. Each condition-blind rater then performed a 10-minute practice phase with feedback before rating experimental data. Each rater scored the creativity of each individual item on a five-point Likert scale (from 1 = 'not at all creative' to 5 = 'extremely creative'). For the AUT the measure of interest was each participant's average creativity score (mean rater score) and number of ideas generated.

Alternative Uses Task Results

Subjects demonstrated improved performance on the classic Alternative Uses Test of creativity, with the experimental hypnagogia condition yielding 18% more alternative uses than the control condition. 5/6 subjects received higher mean creativity ratings from two independent raters in the experimental conditions, but mean creativity ratings were not significantly higher in the Experimental conditions than in the Control conditions ($p=0.64$, $t = 0.4928$, $df = 5$).

Self-Reported Creativity

3/5 subjects reported feeling less inhibited during hypnagogia (1/6 did not answer this question) and 4/6 subjects saw ideas generated in Hypnagogia as creative.

Preliminary Sleep Staging Algorithm

We further proposed a preliminary algorithm for sleep stage detection built with the MUSE EEG dataset gathered in this pilot study. EEG data has been used as a reliable measure of the depth of drowsiness, with bursts of alpha activity common at sleep onset (typically 8-12 Hz) and sleep spindles (typically 12-16 Hz) marking the end of Hypnagogia and beginning of unconsciousness.[279] Frontal sleep spindles which we would expect with a forehead-worn MUSE EEG are slower, typically ranging from 11-13 Hz, and automatic spindle detection algorithms tend to look in wider frequency windows than expected spindles. [280] Our preliminary algorithm uses a variety of existing techniques from the automatic sleep spindle detection literature, particularly Molle[281] and Devuyst.[282] We use data from EEG channel TP-10, located behind each subject's right ear.

The algorithm uses a band-pass filter with cutoff frequencies from 9-12 Hz, an approximation of the frequencies expected for short alpha bursts in sleep onset and frontal sleep spindles. The algorithm subsequently computes the Root Mean Square (RMS) value $RMS_{9\text{-}12}$ of the filtered data with a short overlapping moving window of 100 milliseconds. The algorithm also uses a band-pass filter from 0.5-40 Hz and computes a similar RMS value $RMS_{0.5\text{-}40}$ with a moving average window of 1 second. Changes in alpha frequency are now detected by thresholding the $\frac{RMS\ 9-12}{RMS\ .5-40}$ value, and looking for a consistent detection for at least another 1 second. Thus, the algorithm takes two parameters: threshold of parameters values and the number of seconds after which the algorithm discards spindles. The algorithm discards any detected spindle that lasts more than 2 seconds as spindles are known to last approximately .5 to 1.5 seconds. In our Muse dataset, we only detected spindles after Stage 2 onset as measured by loss of muscle tone, which is what we would expect. But before validation of this algorithm with a more extensive PSG system, this spindle detection method remains purely exploratory.

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[279] (Noreika et al. 2015; Tanaka, Hayashi, and Hori 1996)
[280] (Zygierewicz 1999)
[281] (Mölle et al. 2002)
[282] (Devuyst et al. 2011)

Takeaways

We were surprised, and extremely pleased with the results and reception of this original experiment. It seemed we had hit on a feasible strategy for dream incubation. We received inquiries from sleep scientists, artists, biohackers, hypnotists, lucid dreamers and more. A reliable protocol for dream incubation potentiates a controlled experiment on dream content, and so we designed the follow-up experiment to be just that. While some of the pilot study findings suggest greater creativity after the presentation of target words in hypnagogia vs. wake, we had to test whether this system really worked!

While the pilot experiment offers initial insights and serves as a model for more thorough experimentation on serial dream incubation, it nevertheless **has serious limitations**: limited subject number, lack of an unincubated hypnagogic control condition, device limitations, and limited physiological data. The limited subject number make for weak statistics on the first experiment, and as such leaves us unsure of our dream capture/control results. The lack of a hypnagogic control condition leaves us unsure of whether boosts in creativity seen in the pilot experiment are a product of specifically dreaming of themes which are later incorporated in creativity testing, or of simply passing through hypnagogia. The complaints about the comfort and voice interface of the prototype Dormio system need to be solved. And as muscle atonia was the sole signal used in the pilot experiment, no datasets were assembled on EDA and HR changes in sleep onset and their related phenomenology.

Thesis Experiment

The thesis experiment adds a significant number of subjects (n=50), adds a hypnagogic control condition and unprompted wake condition, allows for continuous dataset capture with a multi-sensor device, and has a more in depth set of creativity tasks combining objective and subjective performance analyses. The goal of this study is testing Dormio for **effective incubation of specific dream themes, effective dream recall, and creativity augmentation.**

System

Device Updates from Dormio V1

The Thesis experiment was done with the updated Dormio hardware and software system, described in the 'Words Make Worlds' section. Multiple improvements were made from the pilot Arduino + Jibo system. To address bulkiness concerns, we reduced the size of the new board to be 8x smaller than the prototype board. We replaced the 68.6 x 53.3 mm Arduino Uno microcontroller with a custom 30 x 15 mm board. This microcontroller has 128kb of Flash and 8kb of RAM. The new board now sits on the wrist instead of the dorsal side of the hand. The updated Dormio system is free of wires for comfortable sleep, compared to the computer-tethered Dormio 1.0 prototype.

The first Dormio prototype consisted of a single sensor pressure sensing glove and conversational robot. The pilot user study (n=6) indicated multiple issues related to usability during sleep. The main concerns collected after the user study were: (1) unpleasant voice interface, (2) unnecessary use of a conversational robot, (3) a bulky, wired glove that limited mobility and required a fully closed fist for pressure sensing. The current system has been remodeled based on findings from the original Dormio pilot study. We have designed the voice interface to be more pleasant, removed the conversational robot, and included a wireless, lightweight glove to detect hypnagogia without a tightly closed fist.[283]

Methods

We enrolled 50 participants to participate in a daytime napping study. Participant mean age was 26.71 ± S.D. 7.86 yrs, 26 male and 24 female. Participants arrived at the laboratory in the afternoon between the hours of 12:00 pm and 4:00pm, optimizing for the postprandial increase in sleepiness. Subjects were given a consent form to read and sign. Consent form and experimental procedures were approved by the MIT Institutional Review Board, The Committee on the Use of Humans as Experimental Subjects. One subject did not follow the requirements of their experimental condition and was eliminated, leaving a total n=49.[284] Participants were told the experiment investigated the relationship between rest and cognitive flexibility, that they would engage in active rest or a nap, and were offered a sleep mask as compensation for the study. After reading and signing consent forms, subjects completed a series of questionnaires including creative self-efficacy, demographic information, and information on sleep quality. All participants wore the Dormio system, regardless of condition. Experimenters remained in the room with subjects, out of sight as participants had eyes closed in awake conditions and wore an eye mask in sleeping conditions.

Instructions

The wording of instructions given to subjects in administering sleep and dream studies is crucial. Since we worked with subjects in periods of semi-lucidity where executive control is transient, metacognitive ability is declining, and dream amnesia is common upon wakeups, we had to design the right question to capture a dream experience before it disappeared. As an example, when REM sleep was initially distinguished from NREM sleep in the 1950's, it was reported that 74–80% of REM sleep awakenings produced vivid dream recall, compared to only 7–9% of NREM awakenings.[285] [286] But just changing the wording of the question from "tell me if you had a dream" to "tell me anything that was going through your mind just before you woke up," reports of conscious experiences in NREM sleep jump up to range between 23% and 74%.[287] Because of the importance of word choice here, all instructions and any audio played to subjects across conditions are included below. Experimental instructions were delivered by an experimenter, while audio prompts from the Dormio were delivered via pre-recorded human voice.

Condition 1, Sleep Tree-Incubation: involved a prompted hypnagogic nap, wherein we used the Dormio system to incubate the dream theme 'Tree'. Upon lying down, the Dormio web app instructed these participants to "*think of a Tree*". Once entry into hypnagogia was determined by the system, a variable timer was triggered. This timer instigated wakeups from 1:00 to 5:00 minutes after hypnagogia detection, to allow participants an experience of different depths of sleep. At the end of this timer window, the computer audio alerted participants they were falling asleep ("*You're falling asleep*") and asked participants to vocalize the thoughts they were currently having ("*Please tell me, what's going through your mind*"), and recorded audio. Once subjects finish speaking, the system asked about their sleep state ("*And were you asleep?*"), to which subjects responded 'Awake', 'Halfway' or 'Asleep'. The system then instructed them to think of the dream prompt ("*Remember to think of a tree*") and to go back to sleep ("*You can fall back*

[283] Updates were led by Tomás Vega, in collaboration with Oscar Rosello and Aby Jain.
[284] One subject in the Sleep Tree-Incubation condition (Condition 1) was unable to sleep.
[285] (W. Dement and Kleitman 1957)
[286] (William Dement and Kleitman 1957)
[287] (Rechtschaffen 1973)

asleep now"). This loop of events was repeated for a total experiment time of 45 minutes, enabling entering and exiting Hypnagogia multiple times. At the end of the last loop, the experimenter instructed the participant to wake up fully.

Condition 2, Sleep No-Incubation: involved an unprompted hypnagogic nap, wherein we used the Dormio system solely to extend the hypnagogic period into multiple serial onsets and to capture dream reports. The Dormio system functioned as it did in Condition 1, except "Remember to think of a Tree" was switched out for "Remember to observe your thoughts".

Condition 3, Wake Tree-Incubation: involved a prompted period of time-matched wake. Subjects sat upright with head unsupported (so the experimenter could survey for muscle tone loss, which would indicate sleep onset), eyes closed, and were instructed to stay awake. The Dormio web app instructed these participants to "think of a Tree". Once 7:00 minutes had passed, approximating sleep onset time, a variable timer was triggered from 1:00 to 5:00 minutes. At the end of this timer window, the computer audio alerted participants and asked them to vocalize the thoughts they were currently having ("Please tell me what's going through your mind"), and recorded audio. Once subjects finish speaking, the system instructed them to think of the prompt ("Remember to think of a tree").

Condition 4, Wake No-Incubation: involved an unprompted period of time-matched wake. Subjects sat upright with eyes closed. The Dormio system functioned as it did in Condition 3, except switched out "Remember to think of a Tree" for "Remember to observe your thoughts".

	Tree-Incubation	No-Incubation
Sleep Condition	1	2
Wake Condition	3	4

Table 2. Group numbers assigned to experimental conditions

Instructions for Condition 1: *"This experiment is investigating the relationship between mental rest and cognitive flexibility. Varied imagery, memories, words, or bodily feelings may come up throughout the experiment. The aim of this exercise is to observe them, stay with them, follow them lightly and see where they go. One thing not to worry about is questioning whether you are asleep. This period in between sleep and wake feels to some people like sleep, to others just like relaxation or mind wandering. All are completely fine, just watch your mind and relax. Sleep cannot be forced, just allowed. Head towards sleep, but don't worry at all where you are in it, just relax.*

After you lie down, you will be asked to think of a theme. Relax, hold that theme in your mind. A few times, you will be told you are falling asleep and reminded of the dream theme. These prompts are not to wake you up fully, just to make sure you do not descend into deep sleep, and to keep you aware so that you can keep observing your mind. Just stay still when the prompts come. Again, we're interested in your thinking in this semi-lucid period. Whenever you are prompted to report, please just vocally report what was going through your mind, and report whether you think you were asleep, by either saying awake, halfway or asleep. Then relax and drift towards sleep again."

Instructions for Condition 2: *Same until: "After you lie down, you will be asked to observe your thoughts. Relax, and see where your thoughts go. A few times, you will be told you are falling asleep and reminded to observe your thoughts. These prompts are not to wake you up fully, just to make sure you do not descend into deep sleep, and to keep you aware so that you can keep observing your mind. Just stay still when the prompts come. Again, we're interested in your thinking in this semi-lucid period. Whenever you are prompted to report, please just vocally report* *what was going through your mind, and report whether you think you were asleep, by either saying awake, halfway or asleep. Then relax and drift towards sleep again."*

Instructions for Condition 3: *"This experiment is investigating the relationship between mental rest and cognitive flexibility. Varied imagery, memories, words, or bodily feelings may come up throughout the experiment. The aim of this exercise is to observe them, stay with them, follow them lightly and see where they go. One thing not to worry about is questioning whether you are mind wandering or focused. All are completely fine, just watch your mind and relax. After you close your eyes, you will be asked to think of a theme. Relax, hold that theme in your mind. A few times, you will be told to observe your thoughts and reminded of the theme. These prompts are just to keep you aware so that you can keep observing your mind. Just stay still when the prompts come. Again, we're interested in your thinking in this period of mental rest. Whenever you are prompted to report, please just vocally report what was going through your mind. Then relax and let your mind drift again."*

Instructions for Condition 4: *Same until*: *" After you close your eyes, you will be you will be asked to observe your thoughts. These prompts are just to keep you aware so that you can keep observing your mind. Just stay still when the prompts come. Again, we're interested in your thinking in this period of mental rest. Whenever you are prompted to report, please just vocally report what was going through your mind. Then relax and let your mind drift again."*

Creativity Tests

Before all conditions of nap or wake, subjects filled out a self-assessment of creative and flexible thinking. After the condition of nap or wake, participants were given 3 separate creativity tasks. For all tasks, participants were explicitly told to be creative. Explicit instructions to be creative have been consistently shown to influence creativity across a wide variety of tasks, including divergent thinking.[288]

First was the Creative Story-Writing Task, a measure of creative production. All participants (across all conditions) were instructed to write a creative story including the word 'Tree'. Participants were instructed to use their imagination and to be creative. Participants wrote responses by hand, and were told writing was necessary but drawing was additionally allowed. Subjects were told no time limit was given, but every 5 minutes that passed was announced so subjects could have a sense of time, and total writing time was recorded.

Second, participants completed the classic Alternate Uses Task (AUT). Participants were given three minutes, and asked to "list all the creative, alternative uses you can think of for a tree." All responses were written by hand. The AUT has been widely validated as a measure of creativity which specifically indexes divergent thinking abilities, and has been shown to be correlated with and predictive of real-world creative achievements.

Third, the Verb Generation Task (VGT) was given to participants. The verb generation task is a classic cognitive neuroscience measure of language production and semantic processing abilities, adapted to serve as a measure of creative abilities. In the task, a noun is presented and the participant is instructed to say a verb out loud—simply, the first verb that comes to mind in response to the noun. Our version of the task is quite similar, except that responses are typed rather than spoken, subjects were instructed explicitly to generate creative verb associations, and nouns given were all semantically related to 'Tree' [289] .

[288] (Prabhakaran, Green, and Gray 2014)
[289] VGT nouns given: Leaf, Sunshine, Bird, Plant, Shadow, Tree, Frog, Swing, Forest, Wind, Mountain, Rope, Tea, Pot, Roots, Squirrel, Book, Seed, Apple, Grass, Branch, Water, Shovel, Stick, Nest, Flower, River, Hole, Dirt, Syrup, Chair

Although the Creative Storytelling Task and Alternate Uses Task assess participants' creative abilities and are popular indices of individual differences in creativity, they rely on subjective assessment by groups of raters. Semantic distance values measuring distance between noun-verb pairs in the VGT serve as a strongly objective measure that is not subject to the potentially shared biases of raters. Semantic distance here is a measure of the unusualness of the verb in the context of the given noun; note that the set of nouns were the same for all participants.

After completing this battery of creativity assessments, subjects completed a series of questionnaires, including descriptions of dreams, self-assessment, and their user experience.

Hypotheses

- Dormio is an effective dream incubation device: >50% of awakenings will have direct incorporation of auditory prime 'Tree'. A direct reference is defined as an unambiguous mention of "tree" (such as tree, forest, branch, or root) while indirect references are sensations, objects, locations, or themes related to "tree" (such as wood, grow, plant, or paper). Adapted from the Alpine Racer sleep onset study described above. [290]
    - Incubation is more effective in Tree-Incubation versus No-Incubation condition AND Sleep vs. Wake (increased suggestibility).
- Dormio is an effective dream capture device: >90% of awakenings will lead to recalled content
- Dormio is able to extend hypnagogia to multiple hypnagogic experiences in one nap period and subjects will report >1 hypnagogic dream report per nap opportunity.
- Dormio is a comfortable, usable system which does not hinder sleep: we hypothesize high subjective comfort ratings and >80% of subjects able to fall asleep wearing the Dormio system
- Dormio can augment creativity on specific incubated dream themes. We hypothesize a significant effect of both sleep and incubation, i.e. significant creativity increases for Sleep vs. Wake AND significant creativity increases for Tree-Incubation vs. No-Incubation condition.
    - We expect a combined positive effect of sleep and incubation for creativity task performance in sleep + incubation (Condition 1). Performance improved in:
        - Story
            - Consensual Subjective Ratings of Overall Creativity
            - Consensual Subjective Ratings of Use of Imagery in Creative Storytelling
            - Consensual Subjective Ratings of Narrative Cohesion/Plot Continuity
            - Consensual Subjective Ratings of Fantasy
            - Consensual Subjective Ratings of Descriptiveness
            - Consensual Subjective Ratings of Semantic Flexibility
            - Consensual Subjective Ratings of Emotiveness
        - AUT
            - AUT Semantic Distance 'Tree' vs. Use Generated
            - Number of Alternative Uses generated
            - Elaboration of Alternative Uses
            - Consensual Subjective Ratings of AUT Snapshot
            - Consensual Subjective Ratings of AUT Individual Uses

[290] (Wamsley et al. 2010)

- VGT
    - Semantic Distance Noun prompt vs. Verb Generated
    - VGT Elaboration by Instance Generated
    - VGT Elaboration by Subject

Sleepiness takes up to 0.67 hours to be replaced by full waking subjective alertness, and 1.17 hours to be replaced by full waking cognitive performance, with both increasing continuously in periods following awakening.[291] We would thus expect a most pronounced effect of hypnagogia on creativity for Stories > AUT > VGT, as tasks were presented in that order post wakeup.

Exploratory Measures

This study will yield additional outcomes of interest which are not core to this analysis, including open-source datasets for future use and exploratory correlation matrices. For these measures, we do not have enough past literature to have strong pre-hoc hypotheses.

- Within-group comparisons between subjects with high vs. low dream incubation on creativity task performance. The core question of this experiment is whether incubation vs. no incubation confers a benefit for creative performance. This follow-up question asks whether, additionally, the degree of dream incubation (proportion of dream reports containing tree) confers a creative benefit.
- An exploration of correlations between objective linguistic features of the story as measured by Coh-Metrix and Consensual Creativity ratings.
- An extensive, open-source dataset on sleep onset signals for EDA, HR and Muscle Tone + pilot machine learning methods trained on this dataset for identifying hypnagogia
- An extensive dataset on the phenomenological spectrum during hypnagogia, for future analysis of variations in report length, visual content, and dream theme content.
- An extensive dataset on the dream report variability correlated with number and order of wakeups.

[291] (Jewett et al. 1999)

Results[292]

Dream Incubation

We performed serial wakeups on 25 sleep subjects and got 136 total dream reports, 67 from the Sleep Tree-Incubation condition and 69 from the Sleep No-Incubation condition. We gathered a total of 104 waking reports from awake subjects, 56 from the Wake Tree-Incubation condition and 48 from the Wake No-Incubation.[293]

Condition 1, Sleep Tree-Incubation: Out of 67 total verbal dream reports, 45 (67%) contained direct references to 'Tree'. Across these 67 reports, there were 91 total references to 'Tree', with 77 direct references and 14 indirect references.

Condition 2, Sleep No-Incubation: Out of 69 total verbal dream reports, 1 (1.4%) contained direct references to 'Tree'. Across these 69 reports, there were 2 total references to 'Tree', with 1 direct reference and 1 indirect reference.

Condition 3, Wake Tree-Incubation: Out of 56 total verbal waking reports, 29 (52%) contained direct references to 'Tree'. Across these 56 reports, there were 70 total references to 'Tree', with 51 direct references and 19 indirect references.

Condition 4, Wake No-Incubation: Out of 48 total verbal waking reports, 0 (0%) contained direct references to 'Tree'. Across these 48 reports, there were 0 total references to 'Tree'.

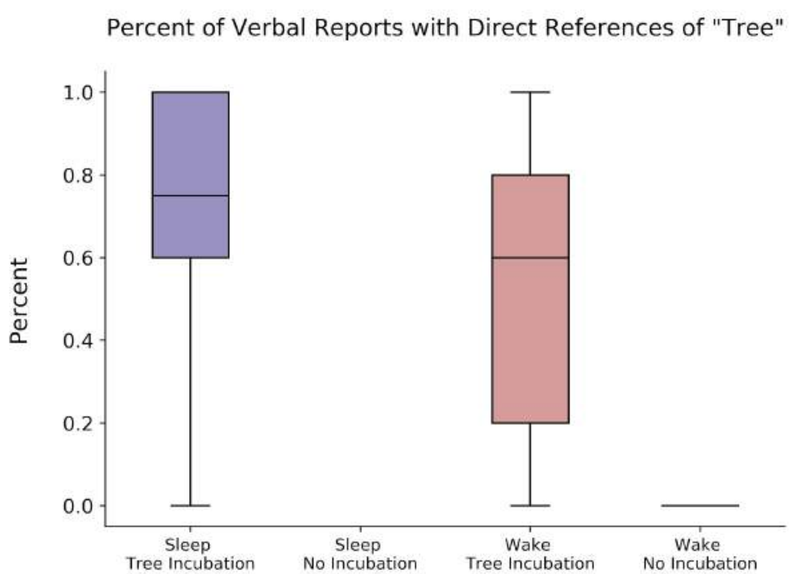

Figure 28. The percent of direct references to 'Tree' in verbal reports

[292] If you just care about creativity test results, feel free to skip ahead to the summary right before the Discussion.
[293] Note that awake subjects were asked for 4-5 mentation reports, depending on experiment timing. Sleep reports depend on the timing of sleep onset with each awakening within a 45 minute nap opportunity, are more variable, and generated a greater number of total reports.

The percent of “tree” direct references varied significantly by group (Kruskal Wallis H test; H=29.69, p=1.60e-06). A Mann-Whitney U test indicated that the inclusion of direct references to ‘Tree’ in reports was significantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation=0.62 ± 0.35, No-Incubation=0.01 ± 0.03, *U*=527.0, p=4.295e-07). Additionally, inclusion of direct references to ‘Tree’ in reports was significantly greater in the Sleep Tree-Incubation condition as compared to the Sleep No-Incubation condition (Sleep Tree-Incubation=0.7 ± 0.35, Sleep No-Incubation=0.01 ± 0.05; *U*=131.0, p=0.001). Inclusion of direct references to ‘Tree’ in reports was significantly greater in the Wake Tree-Incubation condition as compared to the Wake No-Incubation condition (Wake Tree-Incubation=0.52 ± 0.36, Wake No-Incubation=0 ± 0;*U*=132.0, p=6.160e-05).

Dream Recall

All sleeping subjects (25/25) were able to recall ≥ 1 hypnagogic dreams. 1 subject reported difficulty speaking while in hypnagogia, but uttered short phrases and elaborated on each after wakeup. All awake subjects (24/24) were able to report ≥ 1 instance of waking mentation.

Phenomenology

Sleep Tree-Incubation

Hypnagogic mentation with Tree-Incubation revealed inclusion of the Tree theme into episodic memories, current concerns, and dream narratives. We observe dream reports appear to increase in bizarreness and immersion with each subsequent wakeup, but consensual rating of bizarreness were not performed. Further, multiple subjects reported that continuously observing transformations in thoughts regarding ‘Tree’ was useful as a way to observe the onset of sleep, and at times induce lucid sleep onset dreams.

> *“1: Trees, many different kinds, pines, oaks*
> *2: Who I'm going to have over for dinner on Saturday, and occasionally trees, and how I'm not falling asleep*
> *3: A tree from my childhood, from my backyard. It never asked for anything.*
> *4: Trees splitting into infinite pieces*
> *5: I'm in the desert, there is a shaman, sitting under the tree with me, he tells me to go to South America, and then the tree…”*
>
> Subject 11, Sleep Tree-Incubation, verbal reports given at each awakening
>
> *“My dream was pleasant and mysterious. I never knew what the next part of my dream was going to be. My dream did involve a tree. I was following the roots with someone and the roots were transporting me to different locations. At each location i was trying to find a switch. It was unclear why I had to turn on the switch, but at the final location ia window with a bright light was revealed. I saw a familiar face, but I couldn't place where I'd seen them. In the background, the moon was shining bright and illuminating the face. I was dreaming this while awake and not fully asleep...I could hear myself talking to someone about finding a switch. I could hear my breathing, my footsteps, the wind, and an air conditioner. When I bumped into objects, I can hear the noise of the collisions. I could hear the roots of the tree pulsating with energy as if they were leading me to some location.”*
>
> Subject 3, Sleep Tree-Incubation, post-sleep report

It helped me understand more about what I can do with hallucinations, I've never spent this much time unconstrained and free, it helps me see more in the world. I started with a tree but actually I can walk everywhere with this task, I can walk into the lego office and see it covered in trees, I can walk into my own building and see my professor turn into a tree, it became supremely absurd but that made me see all ways I can use a tree in ways I never imagined before, so now I can see the trees with a new sort of eyes because I will maybe continue challenging myself on the task... Just now it was as if my scenes I was seeing change every once a second so that new ways to use a tree come up every second and I couldn't even keep up, I couldn't use my language and still see and imagine but it would be super fun and I will talk with a virtual robot at home to work on ideas. That was eye opening. I think it's really really useful for creativity...at the beginning of my dreaming experience I was seeing scenes that were the same size and functionality of real trees, but then the second time I was much bigger than the trees and I could eat them like finger food. You wouldn't come up with that idea at the beginning, but this time I had hundreds of them. The hope is to break out of the banal stories. Which is why I liked this experiment. I'm afraid when I walk out that I will see everything changing like fantasies. But yeah why not. Who says that I must live in the world that everyone is living in? I could write it as if I'm living in a novel.

Subject 6, Sleep Tree-Incubation, post-sleep report

"I particularly remember feeling that my consciousness was almost entirely untethered when I thought about the subject of my post-sleep story about a tree - when a person began exploring the freedom of space through tree imitation, before collapsing in a twisted heap and fully becoming a tree. Then, they proceeded to explore four dimensions - which was thoroughly confusing but a lot of uninhibited fun."

Subject 12, Sleep Tree-Incubation, post-sleep report

"I'd start with a tree, I'm like thinking of a tree, for the first few minutes I didn't really go anywhere with the tree, I was just looking at it, it was like really colorful, but each time it woke me up, the path and depth in terms of how much it became a story went deeper. I started to go down a story path every time the word tree was mentioned, and when I was told that I was sleeping and to think of a tree again I switched back to the tree and took a different path. Very interesting, relaxing, and really made me think...I felt much more creative than usual. I never really think of myself as a creative person but it felt easier to think of abstract things and stories, like it just came to me."

Subject 1, Sleep Tree-Incubation, post-sleep report

Sleep No-Incubation

Hypnagogic mentation revealed a range from flashing imagery to fully immersive narrative scenes. Reports often reflected low cognitive control, disinhibition, labile personal agency, acceptance of implausibility, temporal, spatial and proprioceptive distortion.

> *"1: The desert*
> *2: I was thinking about how someone else would have to fall asleep here*
> *3: the sea, sharks, lots of movement*
> *4: clouds, and movement and*
> *5: the mothering feeling…in the middle…safe*
> *6: I lost it! I wasn't thinking of anything. "*
>
> Subject 37, Sleep No-Incubation, verbal reports given at each awakening
>
> *"I feel like my story was far more open and interesting than it would have been regularly, and that the thoughts I had flowed into each other much more easily than what otherwise might have been."*
>
> Subject 28, Sleep No-Incubation, post-sleep report
>
> *"I think it would be good to think about ideas for art in this state because everything feels looser and your mind goes places it might not go otherwise. Even reflecting on your day feels good because the thoughts don't seem permanent…my thoughts kept jumping around so I didn't really have a normal sense of time. I don't think I really had any sense of time. It felt shorter than 45 min when the experiment ended…I let myself think about anything I wanted to and my mind felt very relaxed because I was sort of asleep. It definitely felt different from my normal cognitive state. I think I could see my whole self at some points, so kind of like an out of body experience."*
>
> Subject 29, Sleep No-Incubation, post-sleep report
>
> *"I feel more at ease. And as compared to earlier today - when I couldn't even read more than a few pages without feeling distracted - I feel calm. I feel creative. The writing activity especially was very calming, and makes me feel like that sort of random thought exercise can be a source of inspiration for me moving forward. I just feel more in tune with my experiences and memories - and feel like I want to be more artful… I definitely didn't feel like I had been asleep for 45 minutes. I felt it was more likely around 10-15 minutes. So in that sense, dreams felt a lot slower to me. I didn't really imagine my body. At some points it felt like I wasn't even there, and I was just a pair of eyes observing the memories and world around me - without necessarily physically being there. It's like I was just a visitor, looking at my life as if it were in an enclosure. Life is very beautiful, but sometimes when we get lost in the minutia of daily activities - we forget that. I felt like I was seeing a highlight reel of peculiar memories, and it really made me want to be more reflective about my life and really decide what I do on an everyday basis with*

intention and purpose. I just felt much more relaxed during the experience. I didn't feel inhibited by any of the constraints I feel when I have to convey experiences with actual words - it felt like I could communicate without any sort of language (verbal or otherwise) - I just understood everything around me for what it was."

Subject 33, Sleep No-Incubation, post-sleep report

"I went from imagining something that I thought might induce a dream, to beginning to dream about that imagined thing. Then, there would be a transition from imagined experience to dream, sometimes that was continuous, and sometimes not continuous at all. When not continuous, my mind would jump from what I had been imagining to something entirely different, and this lack of control indicated to me that I was dreaming. I never lost full awareness of where I was, such that when I was woken I was not surprised to find myself in this reality...However, I seemed to have some kind of creative inspiration while I wrote that seemed somewhat self directed similar to how dreams are. Certainly, I thought of some strange things that I would never have thought about were I not somewhat asleep. I had a dream that I was hovering through the air, and throwing what were like miniature bombs to the ground that would explode into literal mushrooms, not mushroom clouds. I consider ideas like these to be creative."

Subject 35, Sleep No-Incubation, post-sleep report

"I had a lot of strong images and some narrative stuff- didn't experience any big hypnic jerk but I guess some little ones. My mind wandered a fair amount from physical locations that were made up to ones that resembled ones I knew. I remember a rather horrifying story from the experience of a train with a pigs face and a piglet who was talking to me and saying I didn't understand what it was like for my mother to be taken away. There was a period of time in which there was narration that sounded a lot like an oliver sacks book and like his voice and i had some v mild hallucination type things of colors fluctuating in a thermal-imagey type way. I daydreamed about things I wanted to do in the coming weeks. I saw myself turn around, wearing a veil. I saw maxwelton and bone caves with swingsets at the entrances, and my friends who I just went on a caving trip with sitting in them. I imagined several strange and implausible things and honestly can't remember 90% of them just bc the images went by so quickly"

Subject 36, Sleep No-Incubation, post-sleep report

Wake Tree-Incubation

Waking mentation revealed a range of imagery with low immersion. Reports often pulled from episodic memory or involved prospective planning, and revolved around current concerns or cultural references where trees played a central role.

"1: i'm thinking about an X Files episode where a creature ties people to trees
2: thinking about climbing a tree and reading at the top of it
3: i'm thinking about walking through orange and almond groves

4: the adventure I'm going to have this weekend
5: i'm thinking about the tree that the peach grew on in james and the giant peach"

Subject 19, Wake Tree-Incubation, verbal reports given at each prompting

"I had a mostly pleasant experience. During the first portion, I found my mind mostly wandering between the task at hand (thinking about trees) and thinking about the study overall and thinking about my heartbeat/breathing...I thought about the word t-r-e-e and I would recall past experiences when I was around trees. It was interesting how I often think of trees as secondary items that are in the environment around me but not really primary. I can't say the thoughts I had were creative.

Subject 23, Wake Tree-Incubation, post-hoc report

Wake No-Incubation

Waking mentation without incubation revealed low imagery, low immersion, high cognitive control, high reference to current concerns and future planning, and high references to the ongoing study and lab environment.

"*1: Oh I'm just awake*
2: Thinking about what I have to do tonight
3: I was thinking about the election
4: I was thinking about the itch on my ear
5:I was thinking about thinking about what I should be thinking about"

Subject 42, Wake No-Incubation, verbal reports given at each prompting

"My thoughts were about recent events including the experiment itself. I thought about what I should think about and tried to guess what would trigger the device. I also felt a sense of tightness in my stomach and wondered if it's because I was overly concentrated on my thoughts. I wasn't really trying to be creative. I felt more of what my body is feeling than if I had my eyes open."

Subject 48, Wake No-Incubation, post-hoc report

Sleep Physiology Results

Dormio-defined sleep onset time averaged 10.31 (±S.D. 6.39) minutes. Biosignals collected from subjects across conditions reveal the Dormio sensor picks up signals of sleep onset described by previous literature: between the onset of the experiment and the first report, deltas in HR, EDA and Flexion are greater for reports of Sleep (collapsing reports of 'halfway sleep' and 'sleep'[294]) than for reports of Wake. Directionality of deltas (+/-) across Sleep and Wake are displayed below. Blue dotted lines denote deltas which 80% of Sleep wakeups fall below, i.e. a wakeup threshold where 'Asleep' is an unlikely report. Red dotted lines denote deltas which 80% of Sleep wakeups fall above, i.e. a wakeup threshold where 'Awake' is an unlikely report. These thresholds are included as wakeup guidelines for future experimenters.

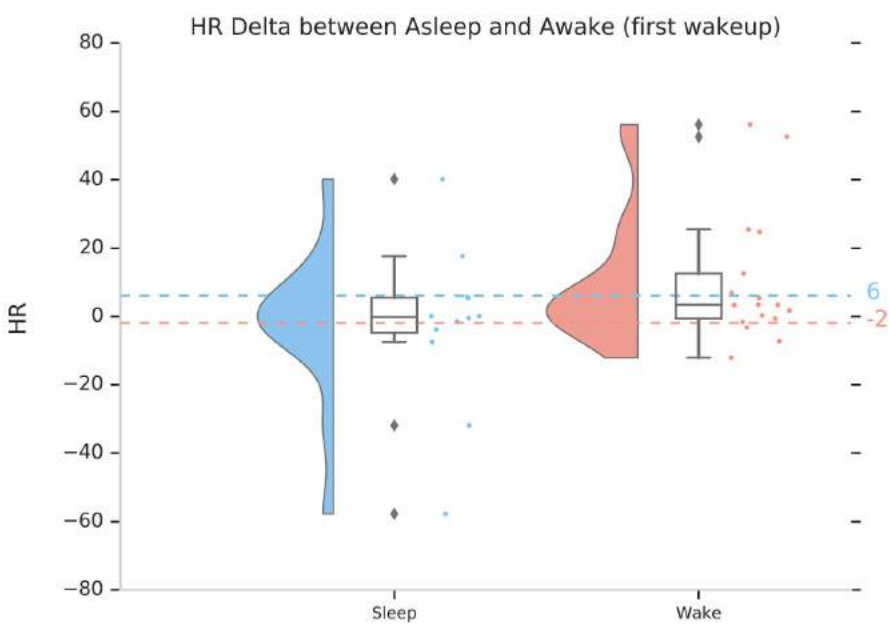

Figure 29. Delta in heart rate between experiment onset and first report of sleep or wake. HR Mean Sleep: -2.89 ± 22.94. HR Mean Wake: 10.01 ± 18.7. 80% of Sleep reports below 6, 80% of Wake reports above -2.

[294] As a report of any level of sleep, even halfway, is likely to occur within the sleep onset period (Ogilvie 2001; Noreika et al. 2015)

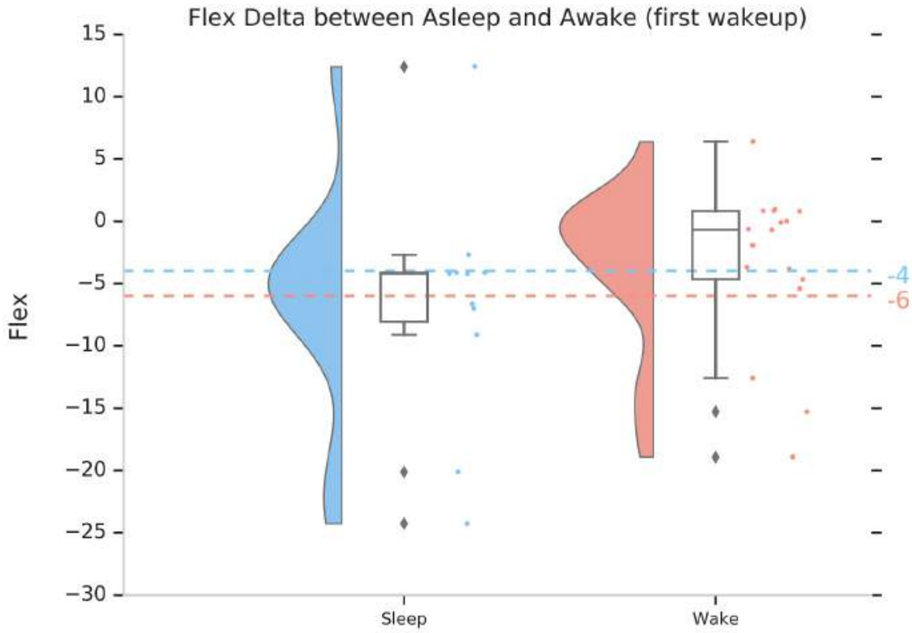

Figure 30. Delta in FDP muscle flexion between experiment onset and first report of asleep or awake. Flex Mean Sleep: -6.74 ± 9.05. Flex Mean Wake: -3.42 ± 6.32. 80% of Sleep reports below -4, 80% of Wake reports above -6.

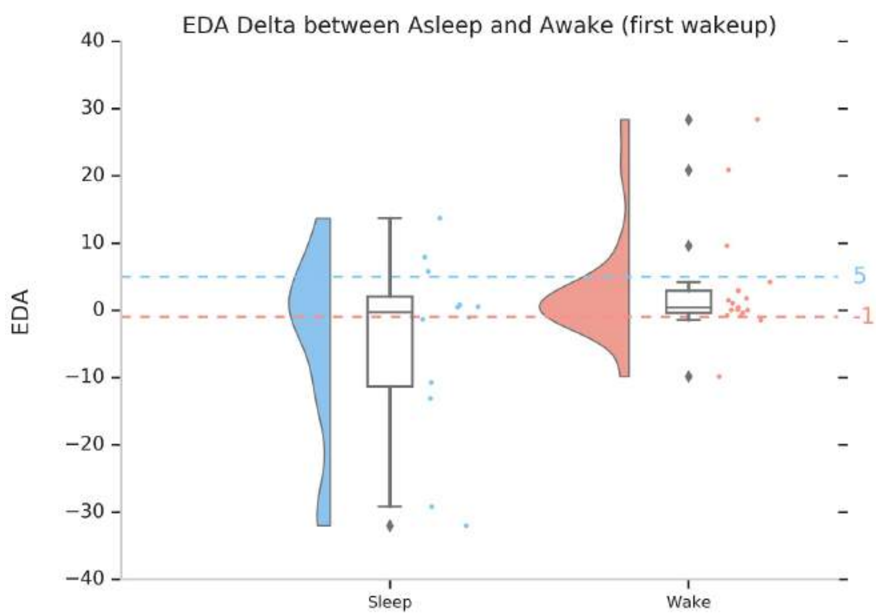

Figure 31. Delta in electrodermal activity between experiment onset and first report of sleep or wake. EDA Mean Sleep: -4.88 ± 13.44. EDA Mean Wake: 3.36 ± 8.64. 80% of Sleep reports below 5, 80% of Wake reports above -1.

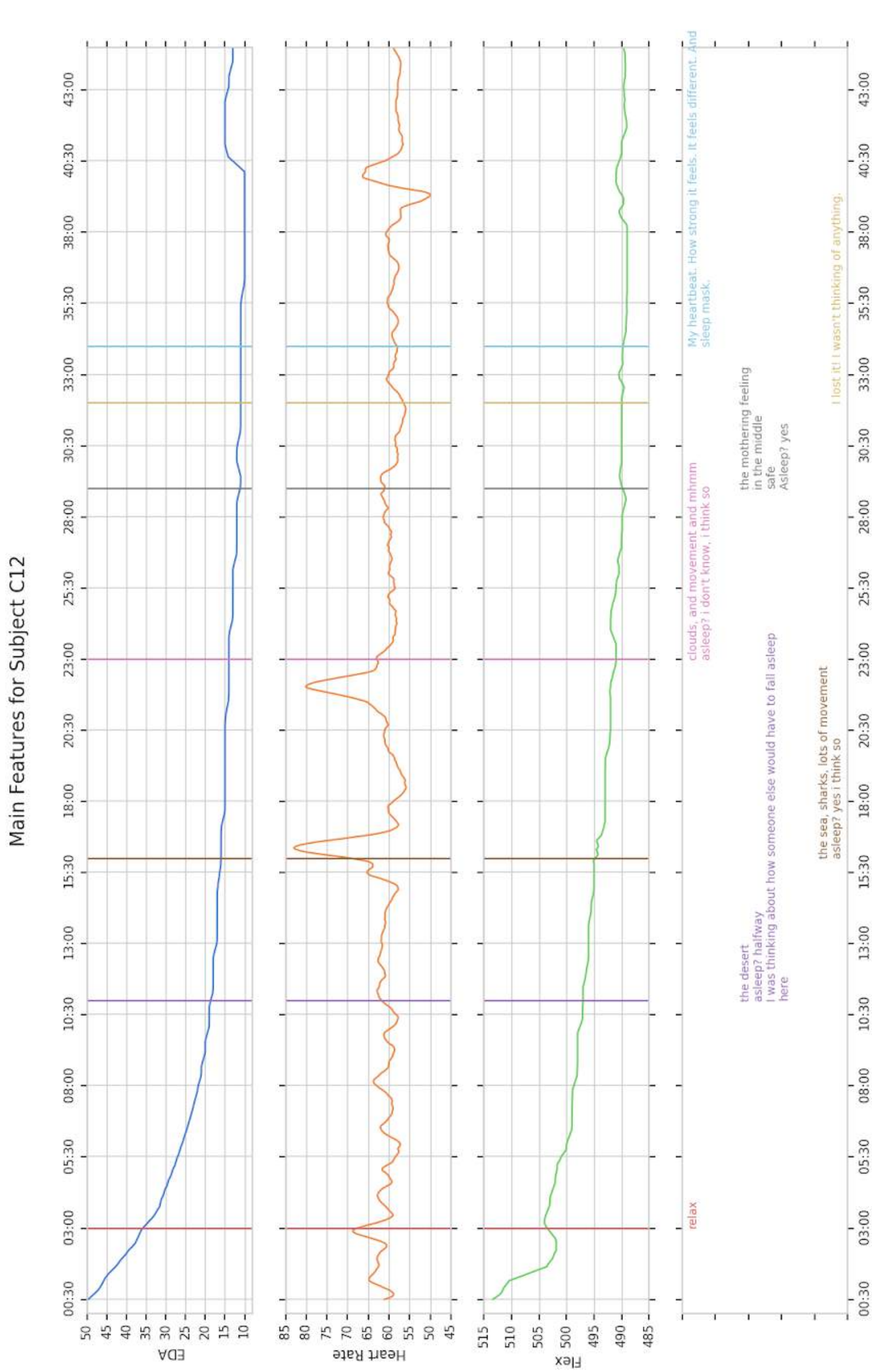

Figure 32. *Biosignal plots for Subject 37 45 min. nap period, with lines indicating wakeups and color-coordinated verbal reports*

System Comfort

Subject rated the comfort of the Dormio experience on a scale from 1 "Not Comfortable" to 5 "Very Comfortable." Subjects in the Sleep Tree-Incubation rated mean comfort 4.43 (± S.D. 0.85). Subjects in the Sleep No-Incubation rated mean comfort 4.42 (± S.D. 0.67). Subjects in the Wake Tree-Incubation rated mean comfort 4.08 (± S.D. 0.9). Subjects in the Wake No-Incubation rated mean comfort 4.25 (± S.D. 0.87).

Creativity Test Results

Data Conversion and Storage

The raw written (Creative Story-Writing Task and Alternate Uses Task) and typed (Verb Generation Task) response data were pre-processed prior to analysis. Firstly, all written responses were scanned and saved using the ScannerPro iPhone app. Next, the written responses were converted into typed text. All responses were saved in a Google Sheets spreadsheet.

Preprocessing

Since only correctly spelled words can be converted into vector representations using GloVe (a tool defined below), the first step in pre-processing was using the spell-check function in Google Sheets to correct instances of misspelled words. Secondly, a few acronyms (such as "ASMR") were expanded into their component words ("autonomous sensory meridian response"). Thirdly, any numbers written as digits (such as "2") were changed into the corresponding word (such as "two). Without these changes, some parts of responses would not have been able to be converted into vector representations.

The edited response data was then further preprocessed using a Python script. In AUT and VGT responses, all punctuation was removed and all text was made lowercase. The story responses were left unchanged except for standardizing the space between sentences to be 1 space. These responses were then put into a Pandas Dataframe and saved as both a CSV and a pickle file.[295]

GloVe

GloVe (short for Global Vectors for Word Representation) is an unsupervised learning algorithm for obtaining vector representations of words.[296] GloVe is trained based on a co-occurrence matrix and outputs word vectors that capture meaning in vector space. Using GloVe, we can predict co-occurrence ratios of words and thus quantify how semantically similar or distant two words are. GloVe outperforms other current methods for quantifying semantic similarity, including the commonly used word2vec, on several word similarity tasks[297]. We used a 300-dimensional word vector space from a GloVe model trained on 6 billion words and their aggregated global word-word co-occurrence statistics. To calculate semantic distance between two word vectors, a SciPy function for calculating Cosine distance (scipy.spatial.distance.cosine) was used (see SciPy.org, Jones, Oliphant, Peterson).

[295] The CSV and pickle file contained additional data from subjective creativity ratings of these responses and data from both the pre- and post-questionnaire processed in the same Python script.
[296] (Pennington, Socher, and Manning 2014)
[297] (Pennington, Socher, and Manning 2014)

Kruskal Wallis H test

The Kruskal Wallis H test is a rank-based nonparametric test that can be used to determine if there are statistically significant differences between groups of a continuous independent variable. This test is often used prior to a post-hoc multiple-comparisons analysis. Follow-up multiple comparison analyses use a Mann-Whitney *U* Test without Bonferroni corrections. [298] We did a multiple comparison analysis regardless of the result of Kruskal Wallis H Statistic Test, and have noted throughout the results where Kruskal Wallis justified the multiple comparison and where it did not. We include both Kruskal Wallis justified and unjustified multiple comparisons based on past work by Hsu: "An unfortunate common practice is to pursue multiple comparisons only when the null hypothesis of homogeneity is rejected." [299]

Mann-Whitney ***U*** Test

The Mann–Whitney U test (also called the Wilcoxon rank-sum test or Wilcoxon–Mann–Whitney test) is a nonparametric test of the null hypothesis that it is equally likely that a randomly selected value from one sample will be less than or greater than a randomly selected value from a second sample. Unlike the t-test it does not require the assumption of normal distributions. It is nearly as efficient as the t-test on normal distributions. This test can be used to determine whether two independent samples were selected from populations having the same distribution. This test is used for pairwise or multiple comparisons. Typical for analysis of a 2 x 2 experimental design, we did pairwise comparisons to understand main effects of State (Sleep vs. Wake, i.e. Conditions 1 + 2 vs. Conditions 3 + 4) and Incubation (Tree-Incubation vs. No-Incubation, i.e. Conditions 1 + 3 vs. Conditions 2 + 4). We then did follow-up comparisons across all conditions to understand interactions, i.e. Condition 1 vs. 2 vs. 3 vs. 4.

[298] (Conover 1971; Hsu 1996; 2004; Daniel 1990)
[299] (Hsu 1996; "Relationship between Overall ANOVA and Multiple Comparisons Tests" n.d.)

Creative Storytelling Task

Subjective Rating Categories

Stories were provided to raters as scans, for viewing imagery and hand written words, and as typed text in case handwriting proved difficult to read. Three condition-blind raters assessed participants' stories on the following eight dimensions:

1	Overall Creativity	*the extent to which the participant told a unique story that "came alive" (story does not need to be cohesive or have a plot)*
2	Imagery	*the extent to which the image contributes to the creativity of the story*
3	Narrative Cohesion / Plot Continuity	*the extent to which the story has a continuous plot*
4	Fantasy	*the extent the story transports you to a world which is not our own, using things like imagination, visualization, etc.*
5	Descriptiveness	*the extent to which the participant added additional details*
6	Semantic Flexibility	*uniqueness of incorporation of topic "tree" into the story*
7	Emotiveness	*the extent to which the participant used words that convey emotion and shifts of emotion*
8	Humor	*the extent to which the participant incorporated clever, witty, and/or amusing elements into the story* [300]

Subjective rating dimensions were adapted from Prabhakaran (2014). Raters assessed each of these dimensions on a 7-point Likert scale (1–7), with 1 reflecting a low rating and 7 reflecting a high rating. For imagery, a participant who chose not to draw was given a rating of 1. After each rater finished, ratings were assessed for discrepancies $\geq$ 3 points. In line with the Consensual Assessment Technique, raters then discussed differences until an $\leq$ 2 consensus was reached. Then, a mean across the three ratings was taken for each subject for each rating dimension.

[300] You will not see any figures printed below for Humor or Emotiveness because there were null results on all comparisons.

Creative Story Examples

They were sitting under the tree listening to the leaves rustle. The tree was trying to tell them something. It was as if the tree was revealing it's secrets and life ~~store~~ stories. They were suddenly transported underground where the tree's roots expanded almost infinitely, in every direction. The tree instructed them to follow a path which led them to an abandoned. Although abandoned, this kitchen seemed to paused in time. There were pots on the stove, dishes in the sink, and spices on the counte'r. It felt like whomever was in this kitchen previously gotup and just left. The purple walls of the kitchen were covered in the roots. The roots wound ~~and is up~~ in all directions on the walls. Roots were dangling from the ceiling like chandeliers. After taking in the surroundings they began to search for a switch. They felt prompted to flip the switch to turn something on. They found along one of the walls behind a counter with some dirty dishes and a roll apaper towels. The switch opened a window hidden amongst the roots. It was entirely covered that it seemed like a wall. The window was suddenly illuminated by light and the moon was seen in the distance. As their eyes adjusted to the sudden brightness a face emerged in front of the moon. The face was familiar, but the presence was strange. They had never seen ~~the~~ this face before, but yet they remained put, waiting for the face to say something. However, the face only stared, as if waiting for them to speak, ~~or even~~ None said anything, but they felt the face communicating with them. It's deep green eyes, longing ~~for~~ to break the silence. The face was slowly over taken by tree roots like pulsing veins. They were transported back to the tree. This time they sat in the branches amongst the trees. They continued to listen to the leaves rustling reflecting on their ~~its~~ trip to the trees roots and the face. This time anytime they looked at the leaves, the deep green eyes of the face looked back at them. Together, in silence, they listened and waited for the tree to transport them again.

Figure 33. Story written by Subject 3, Sleep Tree-Incubation condition. This story received mean ratings of: 6.66 (Overall Creativity), 6.33 (Plot Continuity), 6 (Fantasy) 6.33 (Descriptiveness), 6.66 (Semantic Flexibility), 1.33 (Humor), 5.33 (Emotiveness), 1 (Imagery)

Figure 34. Story written by Subject 10, Sleep Tree-Incubation condition. This story received mean ratings of: 5 (Overall Creativity), 4 (Plot Continuity), 3.66 (Fantasy) 3 (Descriptiveness), 4.66 (Semantic Flexibility), 1 (Humor), 2 (Emotiveness), 5.33 (Imagery)

Creative Storytelling Task Results

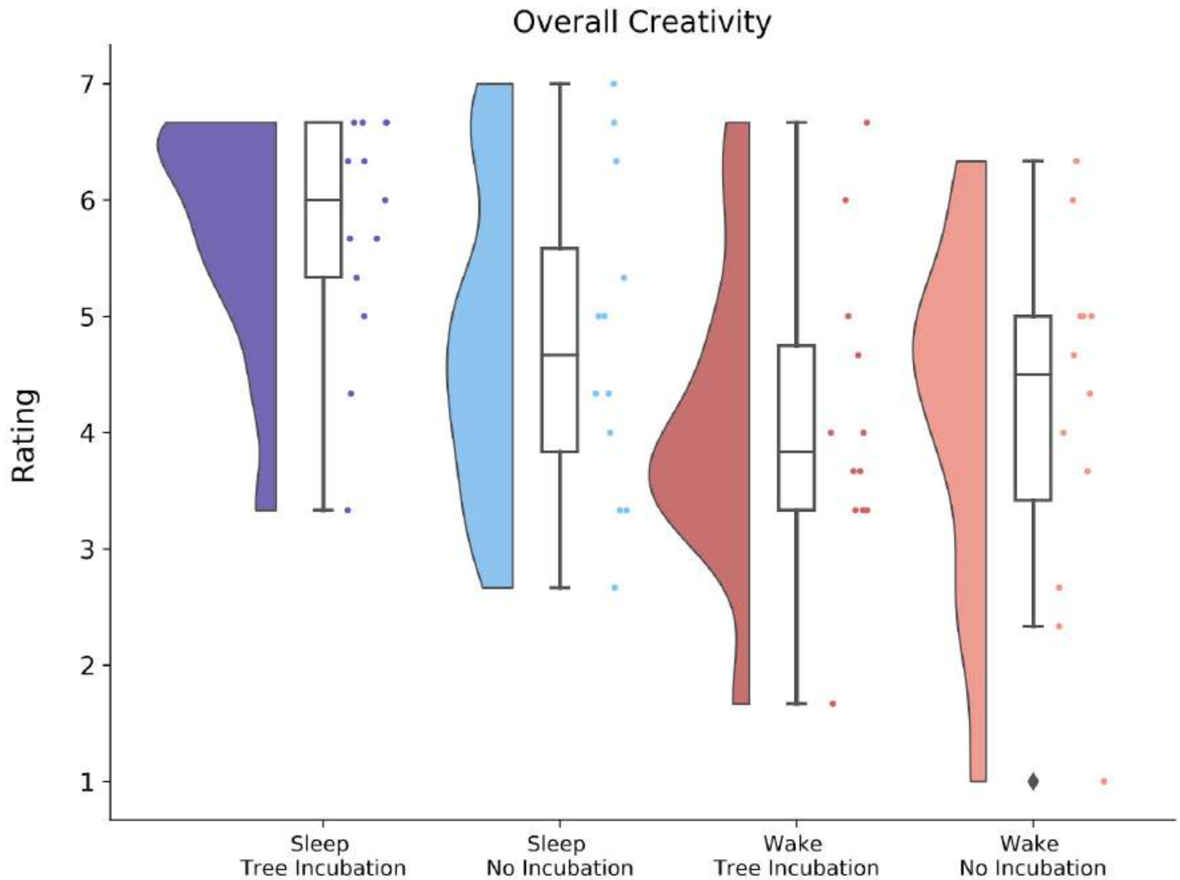

Figure 35.

Overall creativity varied significantly by group (Kruskal Wallis H test; H=10.7, p=0.014). A Mann-Whitney U test indicated that the Overall Creativity ratings were significantly greater in the Sleep vs. Wake condition (Sleep=5.24 ± 1.26, Wake=4.14 ± 1.38; *U*=436.0, p=.003), and were insignificantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation=4.96 ± 1.39, No-Incubation=4.39 ± 1.41, *U*=354.0, p=0.141). Furthermore, ratings were significantly greater in the Sleep Tree-Incubation group (Sleep Tree-Incubation=5.74 ± 0.99) as compared to the Sleep No-Incubation group (Sleep No -Incubation=4.64 ± 1.29; *U*=110.0, p =.0397), the Wake Tree-Incubation group (Wake Tree-Incubation = 4.11 ± 1.27, *U* = 128.0, p =.003), and the Wake No-Incubation group (Wake No-Incubation = 4.17 ± 1.48, *U* = 128.0, p =.003).

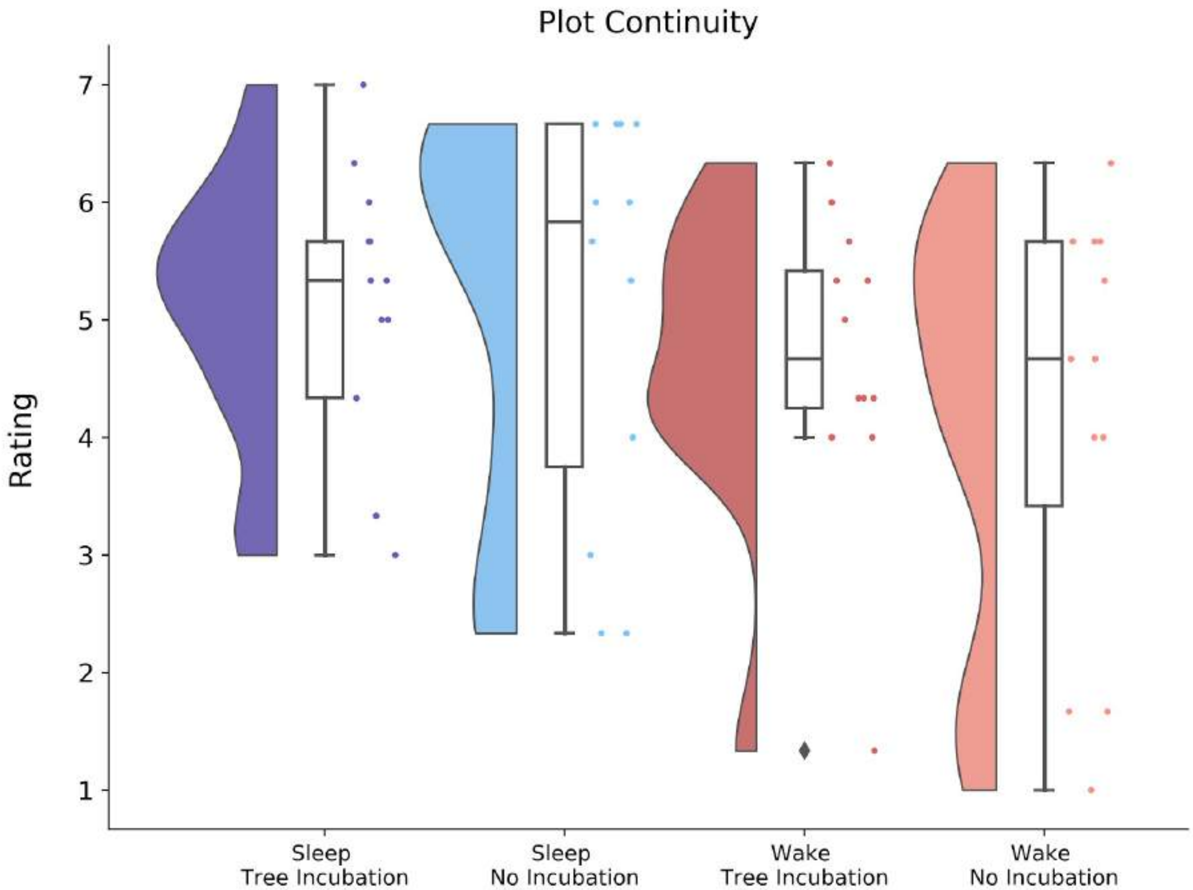

Figure 36.

Plot Continuity varied insignificantly by group (Kruskal Wallis H test; H=3.15, p=0.369). A Mann-Whitney indicated that the Plot Continuity/Narrative Cohesion ratings were significantly greater in the Sleep vs. Wake conditions (Sleep=5.04 ± 1.38, Wake=4.43 ± 1.53; *U*=383.0, p=0.048), but were insignificantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation=4.89 ± 1.19, No-Incubation=4.57 ± 1.74; *U*=298.0, p=0.524).

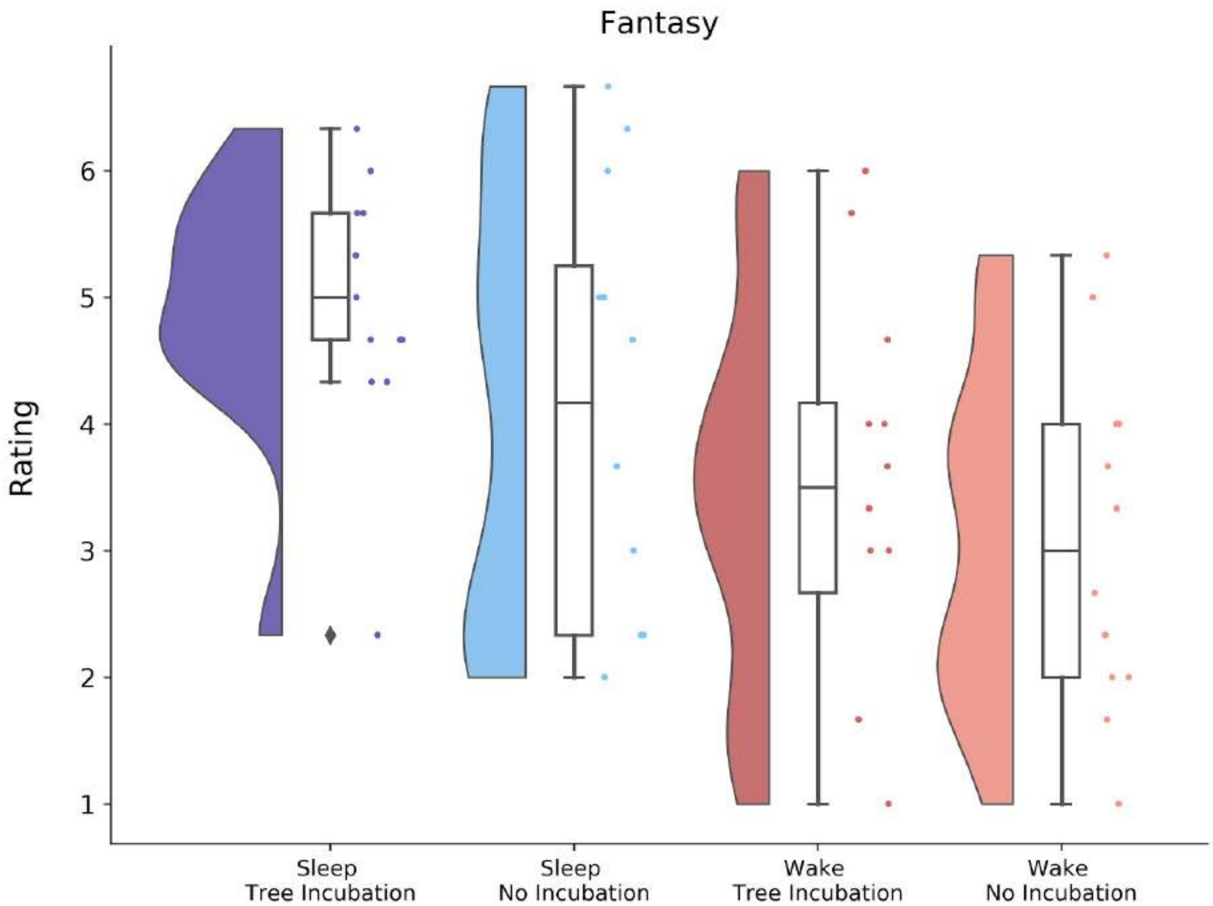

Figure 37.

Fantasy varied significantly by group (Kruskal Wallis H test; H=10.51, p=0.015). A Mann-Whitney U Test indicated that the Fantasy ratings were significantly greater in the Sleep vs. Wake condition (Sleep=4.46 ± 1.40, Wake=3.28 ± 1.41; *U*=443.0, p=.002), and were insignificantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation=4.24 ± 1.44; No-Incubation=3.46 ± 1.50; *U*=372.0, p=0.074). Furthermore, Fantasy ratings were significantly greater in the Sleep Tree-Incubation group (Sleep Tree-Incubation = 4.95 ± 0.97) as compared to the Wake Tree-Incubation group (Wake Tree-Incubation =3.47 ± 1.48; *U*=124.0, p=.006) and the Wake No-Incubation group (Wake No-Incubation=3.08 ± 1.3; *U*=136.0, p=.0086).

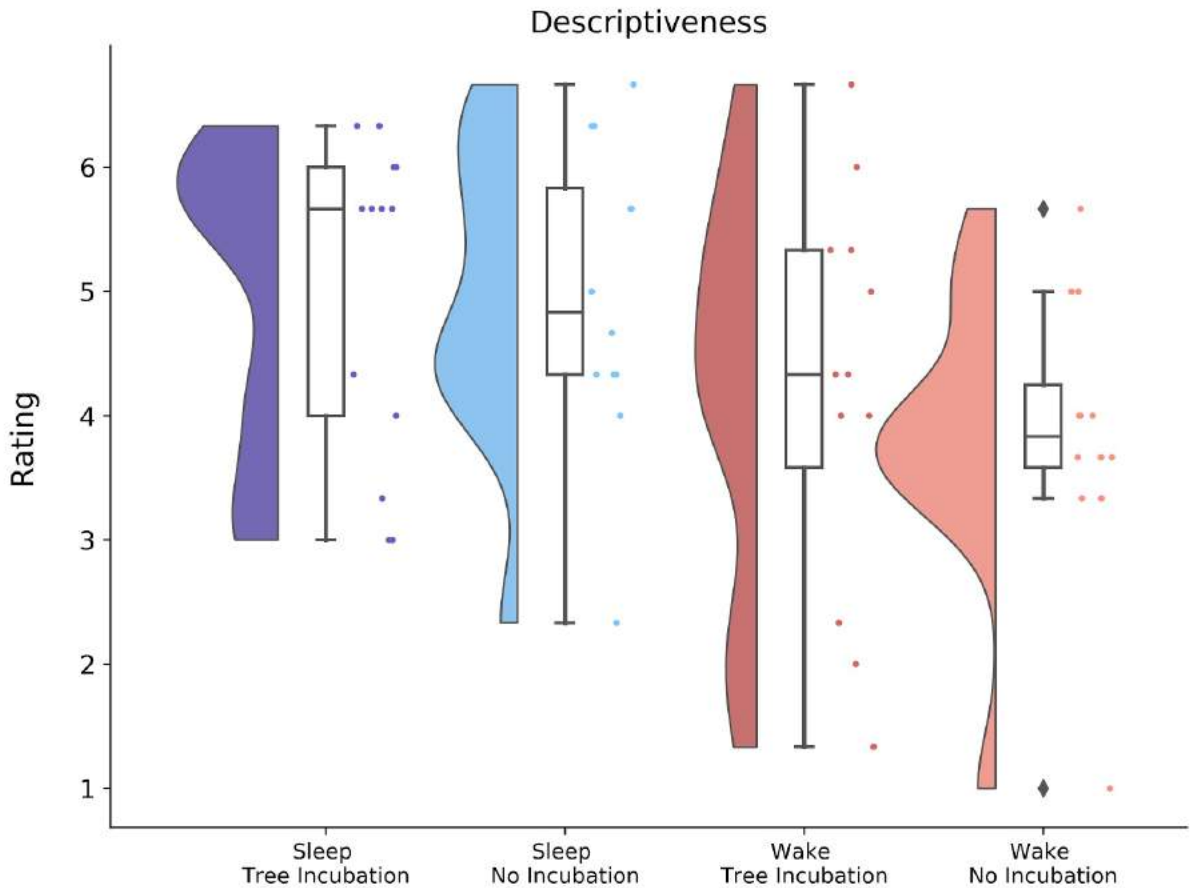

Figure 38.

Descriptiveness varied insignificantly by group (Kruskal Wallis H test; H=7.18, p=0.07). A Mann-Whitney indicated that the Descriptiveness ratings were significantly greater in the Sleep vs. Wake conditions (Sleep=4.93 ± 1.2, Wake=4.04 ± 1.36; *U*=422.0, p=0.007). Furthermore, Descriptiveness ratings were significantly greater in the Sleep Tree-Incubation group vs. Wake No-Incubation group (Sleep Tree-Incubation =5.0 ± 1.23, Wake No-Incubation=3.86 ± 1.11; *U*=114.0, p=.024), and the Sleep No-Incubation group vs. Wake No-Incubation group (Sleep No-Incubation = 4.85 ± 1.16; *U*=114.0, p=0.0086).

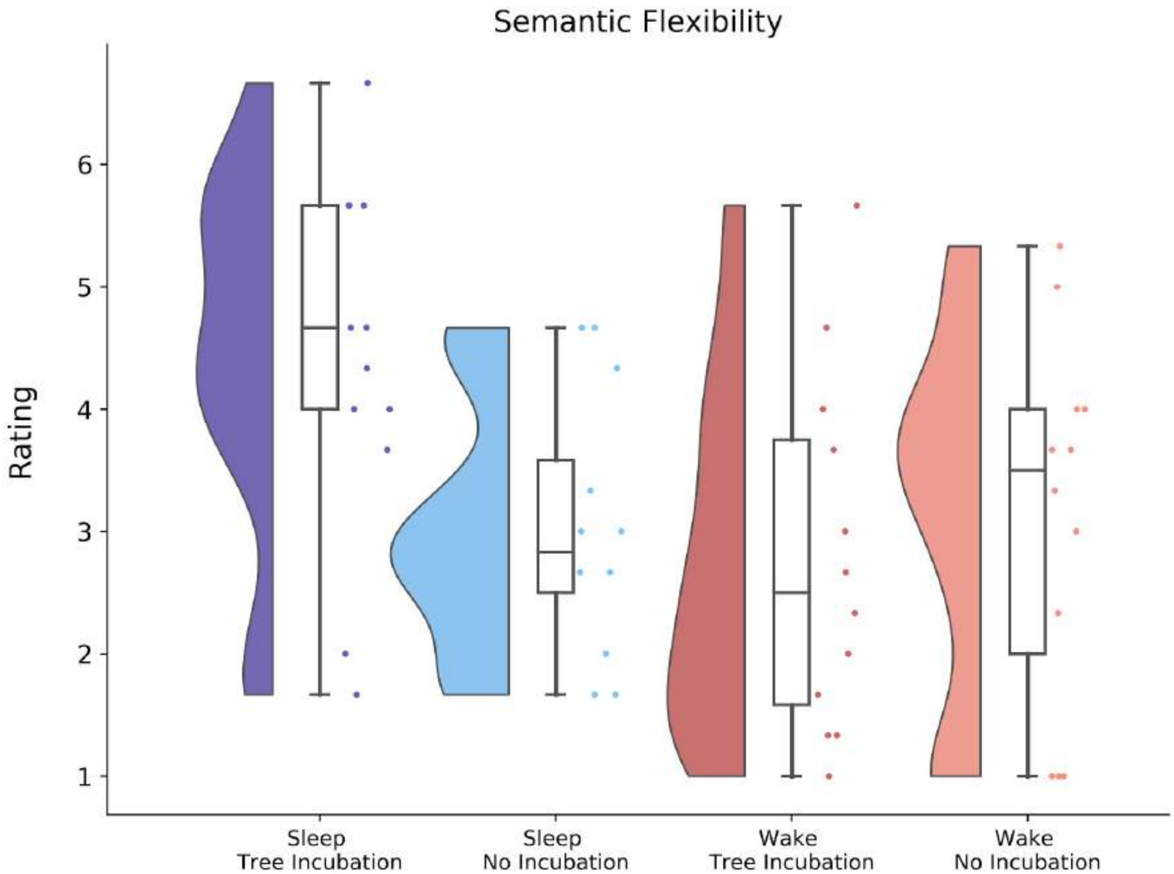

Figure 39.

Semantic Flexibility varied significantly by group (Kruskal Wallis H test; H=9.55, p=0.023). A Mann-Whitney indicated that Semantic Flexibility ratings were significantly greater in the Sleep vs. Wake conditions (Sleep=3.82 ± 1.45, Wake=2.94 ± 1.43; *U*=396.0, p=0.028), and were insignificantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation =3.67 ± 1.64, No-Incubation=3.07 ± 1.27; *U*=366.0, p=0.096). Furthermore, Semantic Flexibility ratings were significantly greater in the Sleep Tree-Incubation group as compared to the Sleep No-Incubation group (Sleep Tree-Incubation =4.49 ± 1.42, Sleep No-Incubation=3.03 ± 1.06; *U*=122.0, p=.0086), Wake Tree-Incubation group (Wake Tree-Incubation =2.78 ± 1.4; *U*=124.0, p=0.0059) and the Wake No-Incubation group (Wake No-Incubation=3.11 ± 1.44; *U*=121.0, p=0.01).

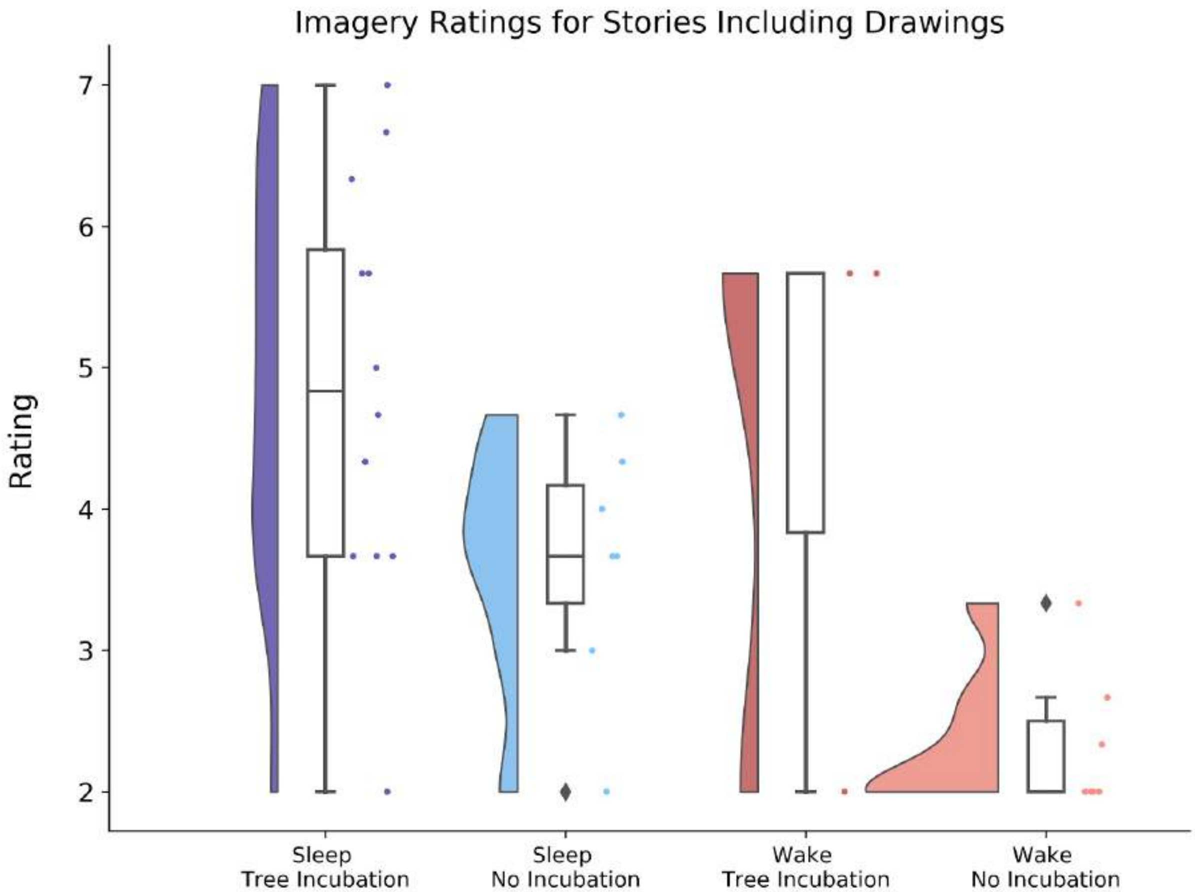

Figure 40.

Imagery ratings varied significantly by group (Kruskal Wallis H test H=12.12, p=0.01). A Mann-Whitney indicated that the creative Imagery ratings, excluding ratings of 1 assigned for 'no image used', were significantly greater in the Sleep vs. Wake conditions (Sleep=4.4 ± 1.37, Wake=2.97 ± 1.41; *U*=148.0, p=.007), and were significantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation =4.78 ± 1.49, No-Incubation = 2.98 ± 0.93; *U*=173.0, p=.001). Furthermore, Imagery ratings were significantly greater in the Sleep Tree-Incubation group as compared to the Sleep No-Incubation group (Sleep Tree-Incubation = 4.86 ± 1.42, Sleep No-Incubation=3.62 ± 0.82; *U*=64.0, p=0.036) and Wake No-Incubation group (Wake No-Incubation=2.33 ± 0.47, *U*=79.0, p=0.0009).

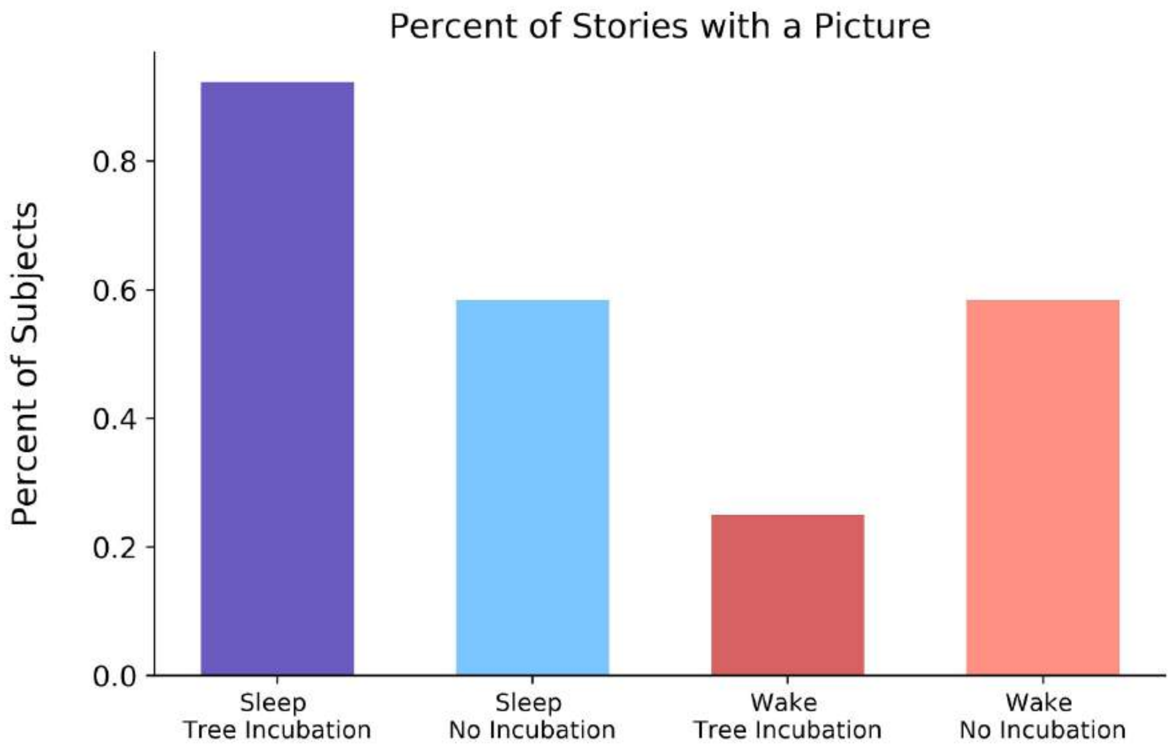

Figure 41.

A greater proportion of Sleep Tree-Incubation subjects included a picture with their creative story. To investigate which factor most affected whether or not a subject chose to include a picture with their creative story, we did an additional comparison in which subjects who included a drawing received a "1" and subjects who did not include a drawing received a "0". A Mann-Whitney *U* Test on this dataset showed Sleep conditions included significantly more pictures proportionally than Wake conditions (U=403.0, p = 0.008). Thus, if we redo the Imagery analysis while including ratings of 1 for no image used, all other groups have lowered values in comparison with Sleep Tree-Incubation *These results are included only for reference, not included in the results summary or discussion, as we do not take the omission of an image in a story as an indication of low imagery related creativity.*

Writing Time

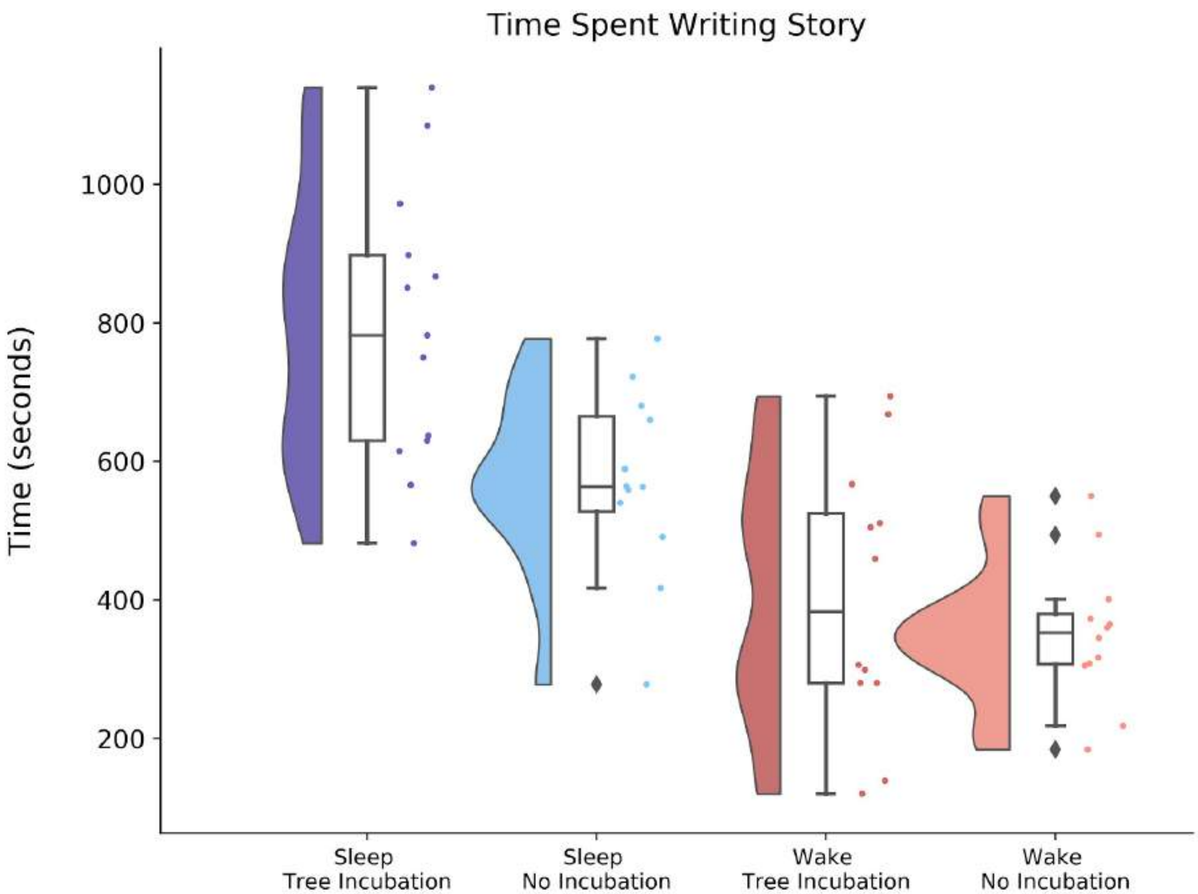

Figure 42.

Time Spent Writing varied significantly by group (Kruskal Wallis H test H=25.59, p=1.16e-05). A Mann-Whitney indicated that the time spent writing the creative story was significantly greater in the Sleep conditions than the Wake conditions (Sleep=684.6 ± 199.59, Wake=377 ± 149.54; *U*=531.0, p=2.012e-06), and were significantly greater in the Tree-Incubation conditions than the No-Incubation conditions (Tree-Incubation=604.12 ± 271.09, No-Incubation=460.83 ± 158.46; *U*=397.0, p=.0268). Furthermore, writing time was significantly greater in the Sleep Tree-Incubation group as compared to the Sleep No-Incubation group (Sleep Tree-Incubation =790.38 ± 194.2, Sleep No-Incubation = 570 ± 129.91; *U*=128.0, p=0.003), Wake Tree-Incubation group (Wake Tree-Incubation = 402.33 ± 184.23; *U*=142.0, p=0.0002), and Wake No-Incubation group (Wake No-Incubation = 351.67 ± 97.49;*U*=154.0, p=2.007e-05).

Objective Ratings

To complement subjective story ratings done with the Consensual Assessment Technique, linguistic properties of the short stories were analyzed with Coh-Metrix, a computational linguistic analysis tool which indexes aspects of text cohesion and readability. Coh-Metrix has been shown in a recent paper to predict human ratings of creativity to a significant degree.[301] We performed an exploratory analysis on 5 features used in the paper from Zedelius et al. (2019):

> (1) Narrativity reflects how well the text aligns with the narrative genre by conveying a story. Texts higher in narrativity are more conversational and more "story-like".
>
> (2) Deep cohesion is computed on the basis of the degree to which different ideas in the text are cohesively tied together with connective words signifying causality or intentionality.
>
> (3) Referential cohesion reflects how well content words and ideas are connected to each other across the entire text. Texts higher in referential cohesion have greater overlap between sentences throughout the story with regard to explicit content words and noun phrases.
>
> (4) Syntactic simplicity is computed on the basis of the simplicity of the syntactic structures in the text. Simple syntax uses fewer words and simpler sentence structures with fewer embedded sentences that require the reader to hold information in working memory.
>
> (5) Word concreteness is computed on the basis of the degree to which words in the text evoke concrete mental images that are easier to process than abstract words. We found significant results for Narrativity and Referential Cohesion.

We found significant results between our experimental groups across two of these features: Narrativity and Referential Cohesion.

[301] (Zedelius, Mills, and Schooler 2019)

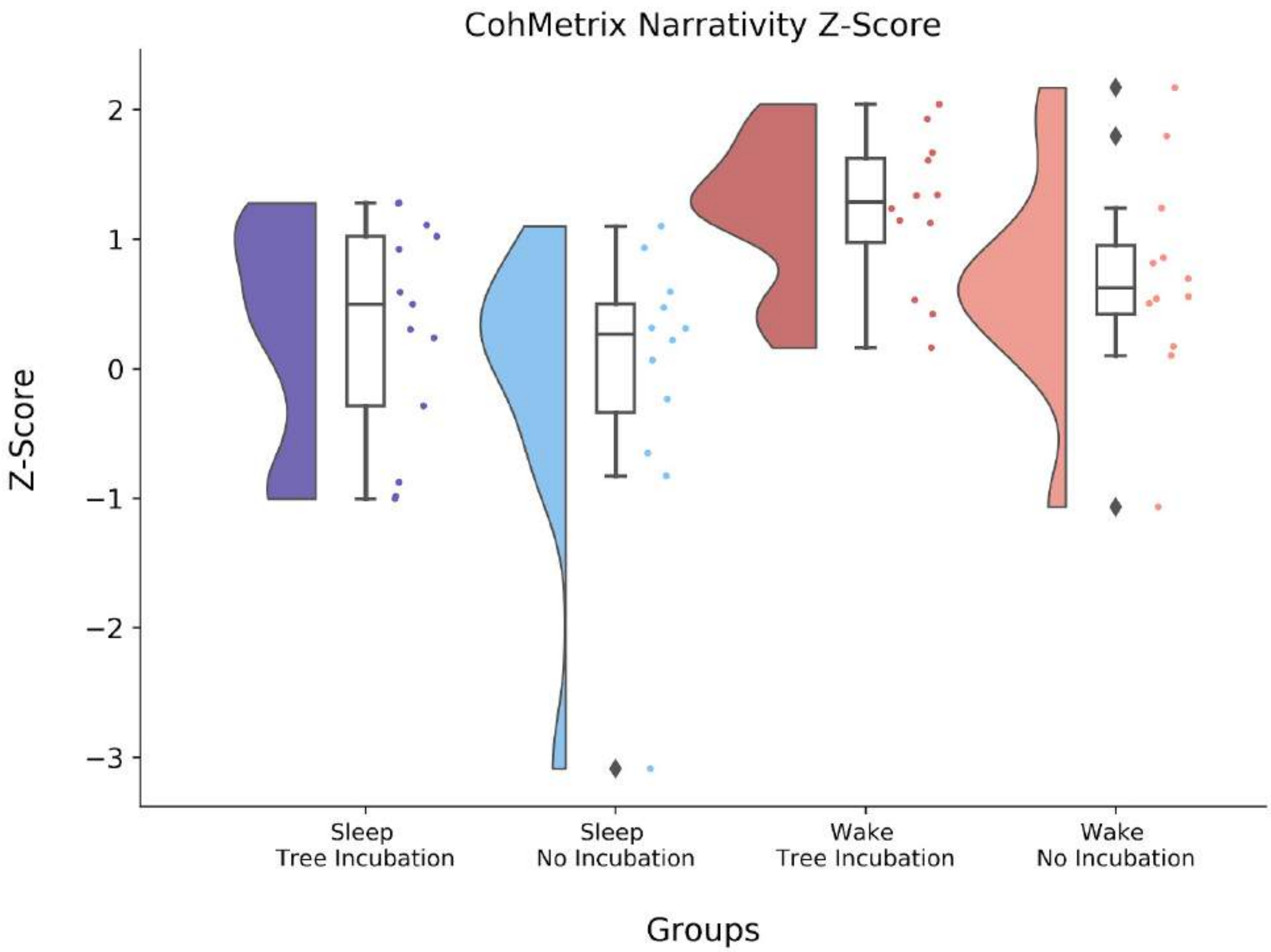

Figure 43.

A Mann-Whitney indicated that the Coh-Metrix Narrativity ratings were significantly lower in the Sleep vs. Wake condition (Sleep=0.13 ± 0.96, Wake=0.96 ±0.73; U=148.0, p=0.001), and were significantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation=0.75 ± 0.84, No-Incubation=0.32 ± 1.01; U=387.0, p=0.041). Furthermore, Narrativity ratings were significantly lower in the Sleep Tree-Incubation vs. Wake Tree-Incubation group (Sleep Tree-Incubation =0.32 ± 0.82, Wake Tree-Incubation = 1.21 ± 0.56; U=28.0, p=0.003) and significantly lower in the Sleep No-Incubation vs. Wake Tree-Incubation conditions (Sleep No-Incubation =-0.07 ± 1.06; U=121.0, p=0.0004).

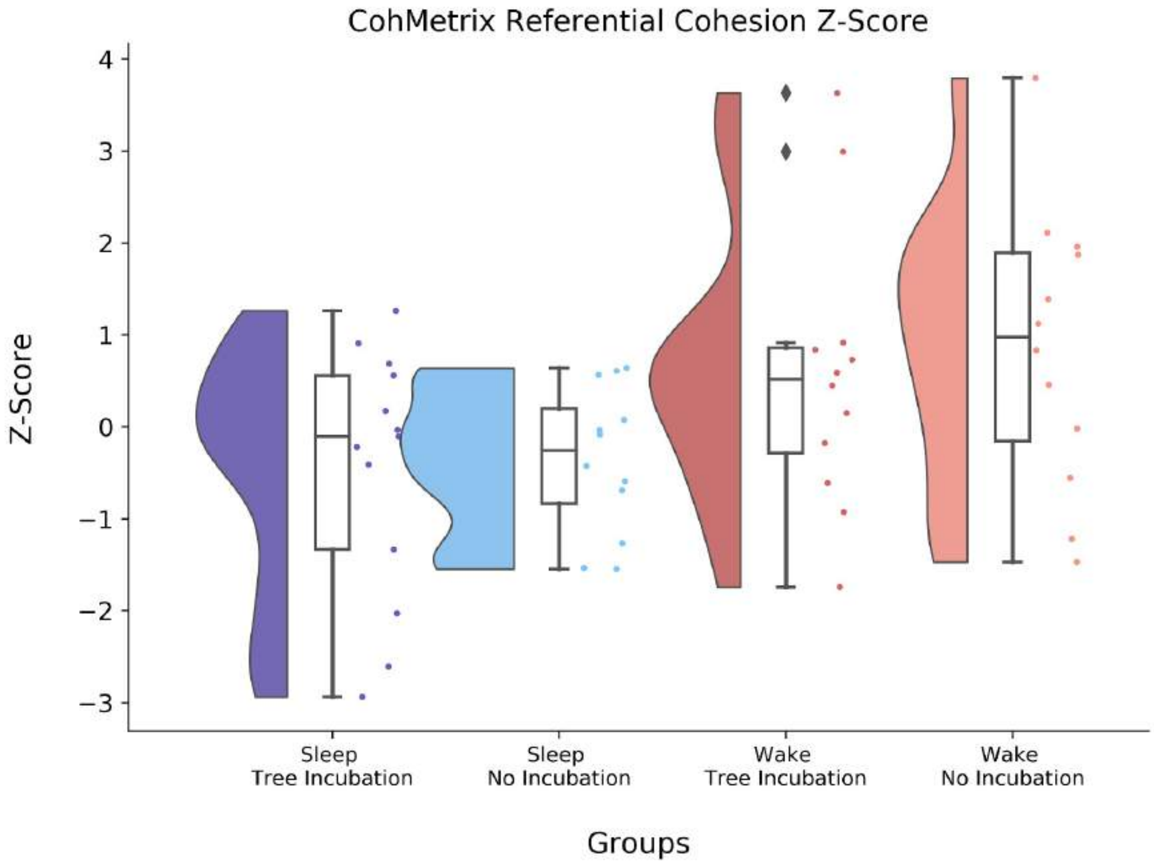

Figure 44.

A Mann-Whitney *U* Test indicated that the Coh-Metrix Referential Cohesion ratings were significantly lower in the Sleep vs. Wake conditions (Sleep=-0.41 ± 1.08, Wake=0.71 ± 1.47; *U*=168.0, p=0.004). In the original Coh-Metrix paper, lower levels of referential cohesion were the most significant predictor of higher scores of Creativity.

Creative Storytelling Task Results Summary

The Creative Storytelling Task was the first task subjects performed after awakening. There was a pronounced main effect of Sleep vs. Wake, a main effect of Tree-Incubation vs No-Incubation, and an interaction between State (Sleep vs Wake) and Incubation (Tree vs No).

We found that the creative stories' (*i*) overall creativity, (*ii*) plot continuity, (*iii*) fantasy, (*iv*) descriptiveness, (*v*) semantic flexibility, (*vi*) imagery ratings and (*vii*) time spent writing were significantly greater in the Sleep conditions than in the Wake conditions. We further found that the (*viii*) Coh-Metrix narrativity and (*ix*) referential cohesion ratings were significantly lower in the Sleep conditions than in the Wake conditions. In the original Coh-Metrix creativity paper, lower levels of referential cohesion were the most significant predictor of higher subjective scores of creativity.

We found that the creative stories' (*i*) imagery ratings and (*ii*) time spent writing were significantly greater in the Tree-Incubation conditions than the No-Incubation conditions. We found that the (*iii*) Coh-Metrix narrativity ratings were significantly lower in the Tree-Incubation conditions than the No-Incubation conditions.

Comparing between conditions, we found that ratings of (*i*) overall creativity, (*ii*) semantic flexibility, imagery, and (*iii*) time spent writing were significantly greater in the Sleep Tree-Incubation condition than in the Sleep No-Incubation Condition.

The Sleep Tree-Incubation condition also had significantly higher ratings than the Wake Tree-Incubation for (*i*) overall creativity, (*ii*) fantasy, (*iii*) semantic flexibility, (*iv*) time spent writing and (*v*) Coh-Metrix Narrativity. The Sleep Tree-Incubation condition had significantly higher ratings than the Wake No-Incubation condition for (*i*) overall creativity, (*ii*) fantasy, (*iii*) descriptiveness, (*iv*) semantic flexibility, imagery, and (*v*) time spent writing.

The Sleep No-Incubation condition had significantly greater ratings than the Wake No-Incubation condition for (*i*) descriptiveness, and significantly lower (*ii*) Coh-Metrix Narrativity ratings than the Wake Tree-Incubation condition.

Exploratory Measure

We also performed an exploratory correlation matrix analysis to see which of the 100+ indices that Coh-Metrix provides correlate with the subjective ratings from all raters[302] of stories in our study, in order to provide a more robust understanding of the relationship between computational features revealed by Coh-Metrix and human subjective creativity ratings. We adapted this analysis from an exploration of the Coh-Metrix/Creativity relationship by Zedelius et al. (2019), although their subjective creativity ratings were for Image, Voice, and Originality.[303]

We used Spearman's rank correlation coefficient to measure correlations between the Coh-Metrix indices and our subjective ratings, implemented with a SciPy function (scipy.stats.spearmanr). We found that most of the Coh-Metrix indices had a significant correlation with at least one of our subjective creativity ratings. We chose 11 of these indices to explore more closely. A full description of these indices and others can be found in the Coh-Metrix Documentation.

1. "Text Easability PC Referential Cohesion, percentile" measured how words and ideas overlapped across sentences and the entire text; a higher referential cohesion score has threads that connect the text for the reader.

2. "Argument overlap, adjacent sentences, binary, mean" measured the overlap of nouns and pronouns between adjacent sentences.

3. "Lexical diversity, VOCD, all words" uses the voc-D method of measuring lexical diversity, which refers to the range of different words used in a text.

4. "Sentence syntax similarity, adjacent sentences, mean" measured the proportion of intersection tree nodes between adjacent sentences.

5. "Noun phrase density, incidence" measured the incidence score (the number of classified units per 1000 words) of noun phrases.

6. "Verb phrase density, incidence" measured the incidence score (the number of classified units per 1000 words) of verb phrases.

7. "Preposition phrase density, incidence" measured the incidence score (the number of classified units per 1000 words) of preposition phrases.
8. "Adjective incidence" measured the incidence score (the number of classified units per 1000 words) of adjectives.

9. "Third person plural pronoun incidence" measured the incidence score (the number of classified units per 1000 words) of pronouns, third person, plural form.

---

[302] Note that these are not mean ratings, but all ratings. These adjustments are not done because this bivariate correlation analysis, looking at the strength of association between variables in two groups, does not assume independence of points given within each group. Future analyses will explore differences in significance with mean ratings and percentage of reports.
[303] In this Zedelius paper the creativity of stories was explained as a combination of Originality (what degree the story idea or plotline is unlike other stories), Voice (the degree to which the author has succeeded in creating their own unique, recognizable voice, or writing style) and Image (degree to which the writing evokes vivid mental images in the reader (Zedelius, Mills, and Schooler 2019)

10. "**Familiarity for content words, mean**" measured a rating of how familiar a word seems to an adult.

11. "**Hypernymy for nouns, mean**" measures hypernymy (a measure of word specificity) of nouns using WordNet.

	Overall Creativity	Plot Continuity	Fantasy	Descriptiveness	Semantic Flexibility	Emotiveness
Text Easability PC Referential cohesion, percentile	r = -0.247 p = 0.003	r = -0.056 p = 0.497	r = -0.27 p = 9.53E-04	r = -0.232 p = 0.005	r = -0.017 p = 0.834	r = -0.117 p = 0.159
Argument overlap, adjacent sentences, binary, mean	r = -0.209 p = 0.011	r = 0.026 p = 0.753	r = -0.255 p = 0.002	r = -0.031 p = 0.709	r = -0.206 p = 0.012	r = 0.008 p = 0.923
Lexical diversity, VOCD, all words	r = 0.301 p = 2.09E-04	r = 0.521 p = 0.0	r = 0.253 p = 0.002	r = 0.56 p = 0.0	r = 0.002 p = 0.98	r = 0.293 p = 3.12E-04
Sentence syntax similarity, adjacent sentences, mean	r = 0.135 p = 0.104	r = 0.237 p = 0.004	r = 0.222 p = 0.007	r = 0.157 p = 0.058	r = 0.18 p = 0.029	r = 0.27 p = 9.33E-04
Noun phrase density, incidence	r = -0.093 p = 0.262	r = -0.367 p = 4.72E-06	r = -0.217 p = 0.008	r = -0.083 p = 0.318	r = -0.087 p = 0.296	r = -0.172 p = 0.038
Verb phrase density, incidence	r = 0.19 p = 0.021	r = 0.349 p = 1.45E-05	r = 0.281 p = 5.73E-04	r = 0.21 p = 0.011	r = 0.265 p = 0.001	r = 0.182 p = 0.027
Preposition phrase density, incidence	r = -0.182 p = 0.027	r = -0.256 p = 0.002	r = -0.245 p = 0.003	r = -0.227 p = 0.006	r = -0.164 p = 0.047	r = -0.261 p = 0.001
Adjective incidence	r = -0.236 p = 0.004	r = 0.037 p = 0.653	r = -0.255 p = 0.002	r = -0.019 p = 0.822	r = -0.421 p = 1.10E-07	r = 0.169 p = 0.041
Third person plural pronoun incidence	r = 0.407 p = 3.20E-07	r = 0.355 p = 1.06E-05	r = 0.375 p = 2.81E-06	r = 0.4 p = 5.17E-07	r = 0.179 p = 0.03	r = 0.289 p = 3.82E-04
Familiarity for content words, mean	r = -0.405 p = 3.62E-07	r = 0.068 p = 0.416	r = -0.349 p = 1.47E-05	r = -0.161 p = 0.051	r = -0.104 p = 0.21	r = -0.015 p = 0.855
Hypernymy for nouns, mean	r = 0.253 p = 0.002	r = 0.19 p = 0.021	r = 0.262 p = 0.001	r = 0.156 p = 0.06	r = 0.006 p = 0.942	r = 0.158 p = 0.056

Table 3. Correlations between Coh-Metrix indices (left) and subjective ratings (top) using Spearman's rank correlation coefficient. Spearman's rho is reported as "r" within the table. Significant correlations ($p < 0.05$) are colored with blue indicating a positive correlation and red indicating a negative correlation. Insignificant correlations are grey.

Alternate Uses Task

AUT Subjective Ratings

Two types of subjective ratings were performed by three trained and condition-blind raters : (1) a "Snapshot" rating in which all of a subject's alternate uses were rated as a group and (2) an "Individual" rating in which a given alternative use was rated on its individual creativity. In the Snapshot rating, Originality, Flexibility (categorical changes) and Fluency (number of uses generated) were evaluated, resulting in raters assigning a value ranging between 1 (low creativity) to 5 (high creativity) to the subject's list of alternative uses. In the Individual rating, all responses were scrambled, and raters focused on Originality in assigning a value of 1 to 5 to each individual alternative use. After ratings were assigned, the Consensual Assessment Technique was used to address any discrepancy of $\geq$ 3 between any of the three raters to find a consensus (discrepancy of < 3).

Pairwise Comparisons

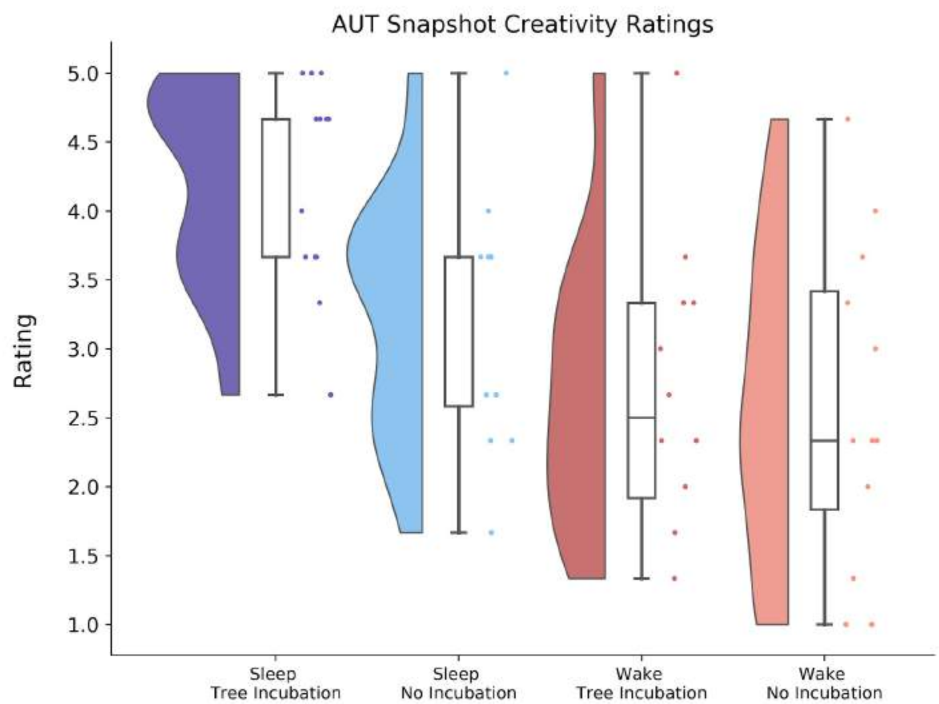

Figure 45.

AUT Snapshot Creativity ratings varied significantly by group (**Kruskal Wallis H test;** H=15.85, p=0.001). A Mann-Whitney *U* Test indicated that the AUT Snapshot Creativity ratings were significantly greater in the Sleep vs. Wake conditions (Sleep=3.75±0.93, Wake=2.64 ± 1.07; *U*=471.0, p=.0003), and were insignificantly greater but trending in the in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation=3.48±1.15, No-Incubation=2.92 ± 1.07; *U*=377.0, p=0.06). Additionally, they were significantly greater in the Sleep Tree-Incubation condition as compared to the Sleep No-Incubation condition (Sleep No-Incubation=3.25 ± 0.88; *U*=120.0, p= 0.0098), the Wake Tree-Incubation condition (Wake Tree-Incubation=2.69 ± 1; *U*=136.0, p=.0007) and the Wake No-Incubation condition (Wake No-Incubation=2.58 ± 1.13; *U*=136.0, p=.0007).

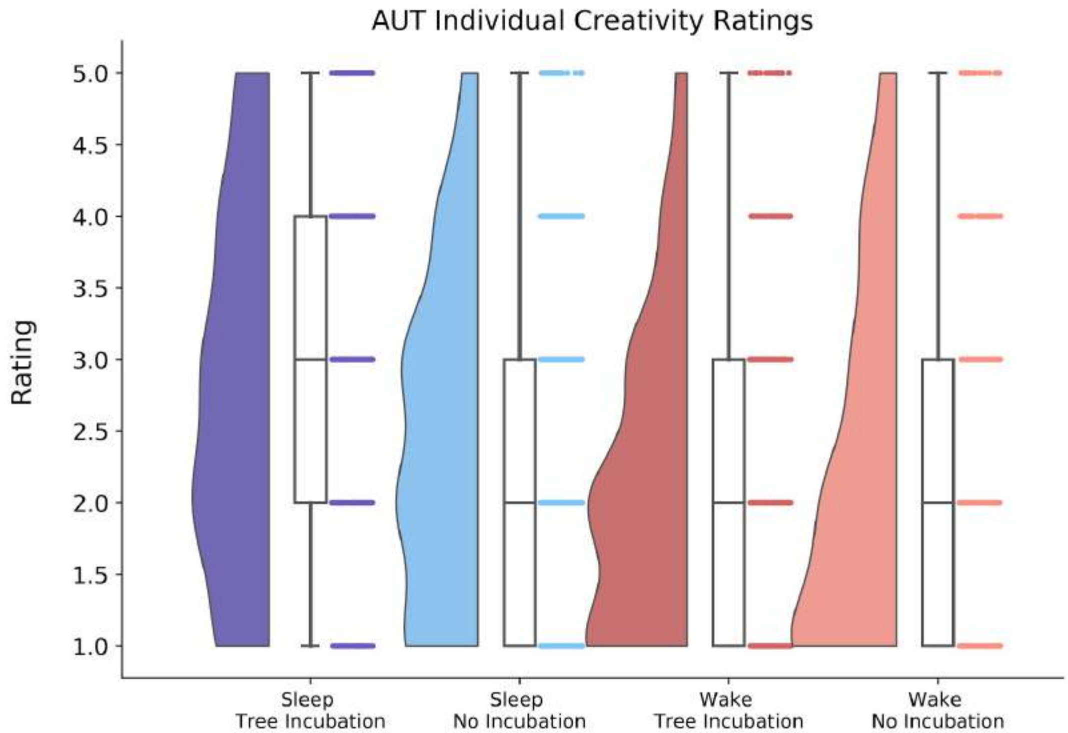

Figure 46.

AUT Individual Creativity ratings varied significantly by group (Kruskal Wallis H test; H=17.18, p=0.0007). A Mann-Whitney *U* Test indicated that the AUT Individual Subjective creativity ratings were significantly greater in the Sleep vs. Wake conditions (Sleep = 2.74 ± 1.13, Wake = 2.37 ± 1.11; *U* = 31516.0, p = .0002), and were insignificantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation= 2.66 ± 1.15, No-Incubation=2.53 ± 1.11; *U* = 29046.0, p = 0.12). Additionally, they were significantly greater in the Sleep Tree-Incubation condition as compared to the Sleep No-Incubation condition (Sleep Tree-Incubation=2.9 ± 1.16, Sleep No-Incubation=2.6±1.07; *U*=11142.0, p= 0.016), the Wake Tree-Incubation condition (Wake Tree-Incubation =2.35 ±1.05; *U*=9140.0, p=.0001) and the Wake No-Incubation condition (Wake No-Incubation=2.4±1.17; *U*=6748.0, p=.0009). Additionally, they were significantly greater in the Sleep No-Incubation condition as compared to the Wake Tree-Incubation condition (Sleep No-Incubation=2.6±1.07, Wake Tree-Incubation =2.35 ±1.05;*U*=8983.0, p=.03).

AUT Semantic Distance

AUT Semantic Distance was evaluated using GloVe as a measure of semantic distance between prompt word 'Tree' and use generated. The semantic distance of each alternative use was calculated by taking the mean of the cosine distances between each word in a given response and the word "tree".

We did comparison testing between the means taken per subject (calculated by taking the mean of the semantic distance values calculated for each of the alternative uses the subject produced) (see Figure 47). These comparisons mirror our Subjective "Individual" and "Snapshot" Creativity Ratings, respectively, by evaluating both the content produced (individual uses) as well as the performance of subjects (subject means) under the different conditions.

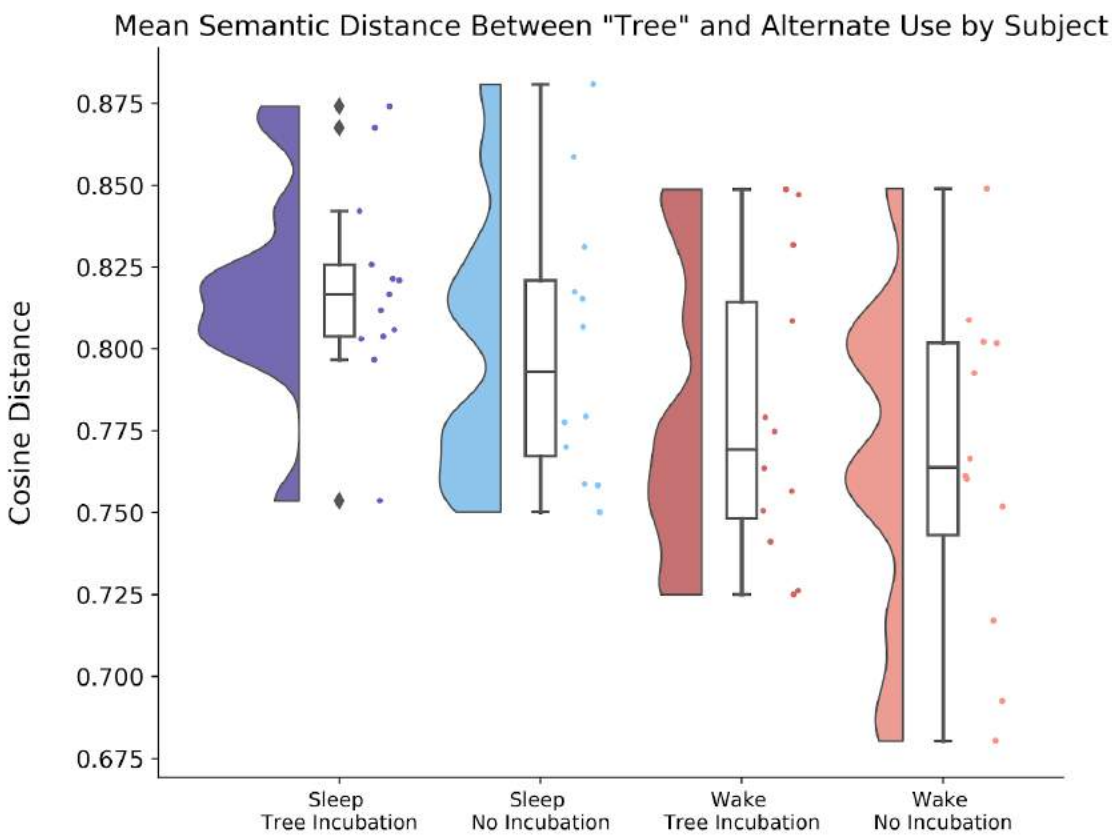

Figure 48.

AUT Mean Semantic Distance varied significantly by group (Kruskal Wallis H test; H=9.25, p=0.03). A Mann-Whitney *U* Test indicated that the mean semantic distances between "Tree" and all of a subject's alternative uses, as measured by GloVe, were significantly greater in the Sleep vs. Wake conditions (Sleep = 0.81 ± 0.04, Wake = 0.77 ± 0.05; *U*=439.0, p=.003), and were insignificantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation = 0.8 ± 0.04, No-Incubation = 0.78 ± 0.05; *U*=361.0, p=0.11). Additionally, they were significantly greater in the Sleep Tree-Incubation condition as compared to the Wake Tree-Incubation condition (Sleep Tree-Incubation = 0.82 ± 0.03, Wake Tree-Incubation = 0.78 ± 0.04; *U*=115.0, p=0.02) and Wake No-Incubation (Sleep Tree-Incubation = 0.82 ± 0.03, Wake No-Incubation = 0.77 ± 0.05; *U*=132.0, p=.002).

The significant differences seen in the subject mean semantic distance comparisons become insignificant when the words “tree” and “trees” are removed from alternative uses (for example, “painting the tree for your art” would have “tree” removed). This change is driven by the trend in how “tree” is referenced across groups, wherein we observe a higher frequency of direct “tree” references in Wake condition responses. We take this as an indication of bias towards stronger semantic links in wake as opposed to a bias towards weaker semantic links in sleep, as subjects in the wake groups clung more to the prompt word “Tree” while subjects in the Sleep conditions experienced greater spreading activation. These changes in cognitive flexibility across the sleep-wake cycle (indexed as preference towards weaker semantic links) mirror a similar effect seen in the AUT literature, the serial order effect. In waking performance of the AUT, subjects often begin their AUT with strong semantic links and explore weaker links as time goes on, which correlates tightly with increasing subjective creativity ratings.[304]

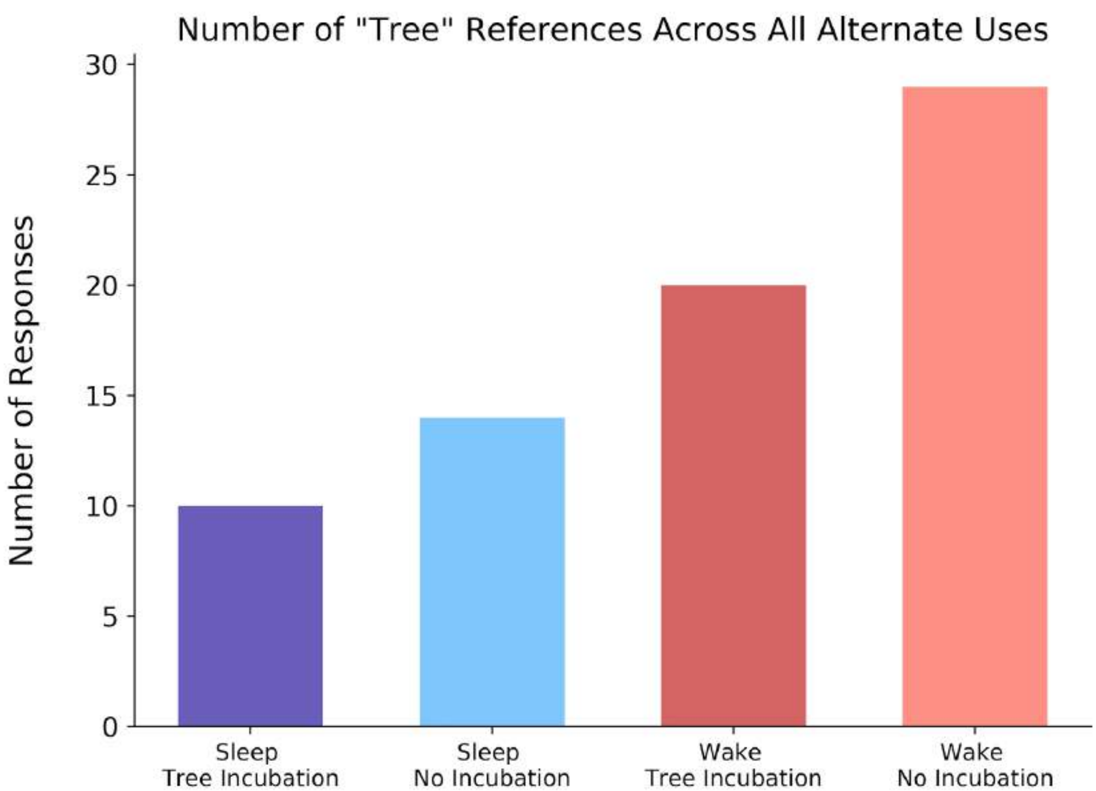

Figure 49.

The Wake conditions showed a greater number of total responses containing direct “tree” references in the AUT, i.e. uses which incorporated the word “Tree”.

[304] (M. P. Walker et al. 2002; R. Stickgold et al. 1999; Beaty and Silvia 2012)

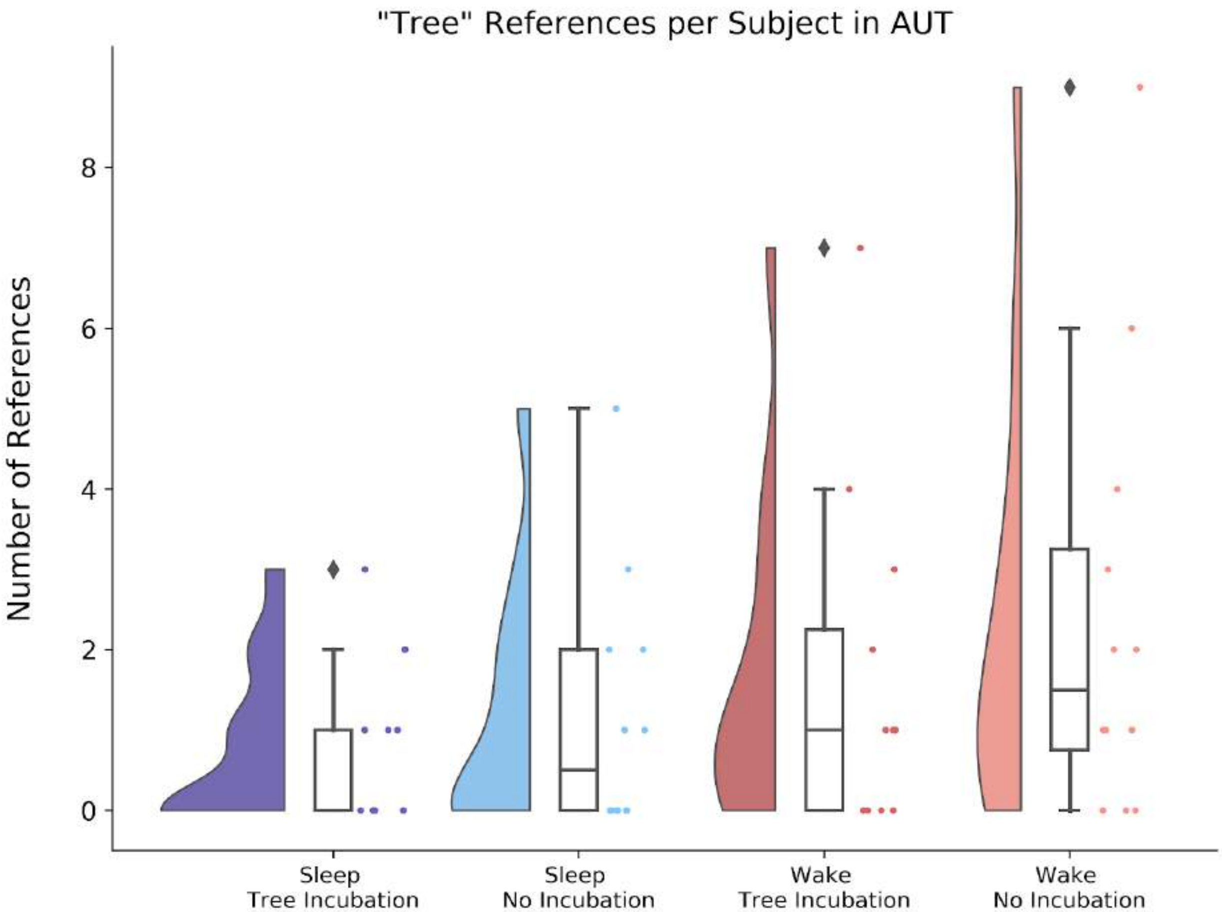

Figure 50.

Mean number of "Tree" References per Subject in AUT varied insignificantly by group (Kruskal Wallis H test; H=3.71, p=0.29). A Mann-Whitney *U* Test indicated that the number of "tree" references per subject were significantly less in the Sleep conditions than the Wake conditions (Sleep = 0.96 ± 1.28, Wake = 2.04 ± 2.37; *U*=217.0, p=.04).

AUT Elaboration

AUT Elaboration (Number of Uses) was evaluated by counting the number of uses for each subject.

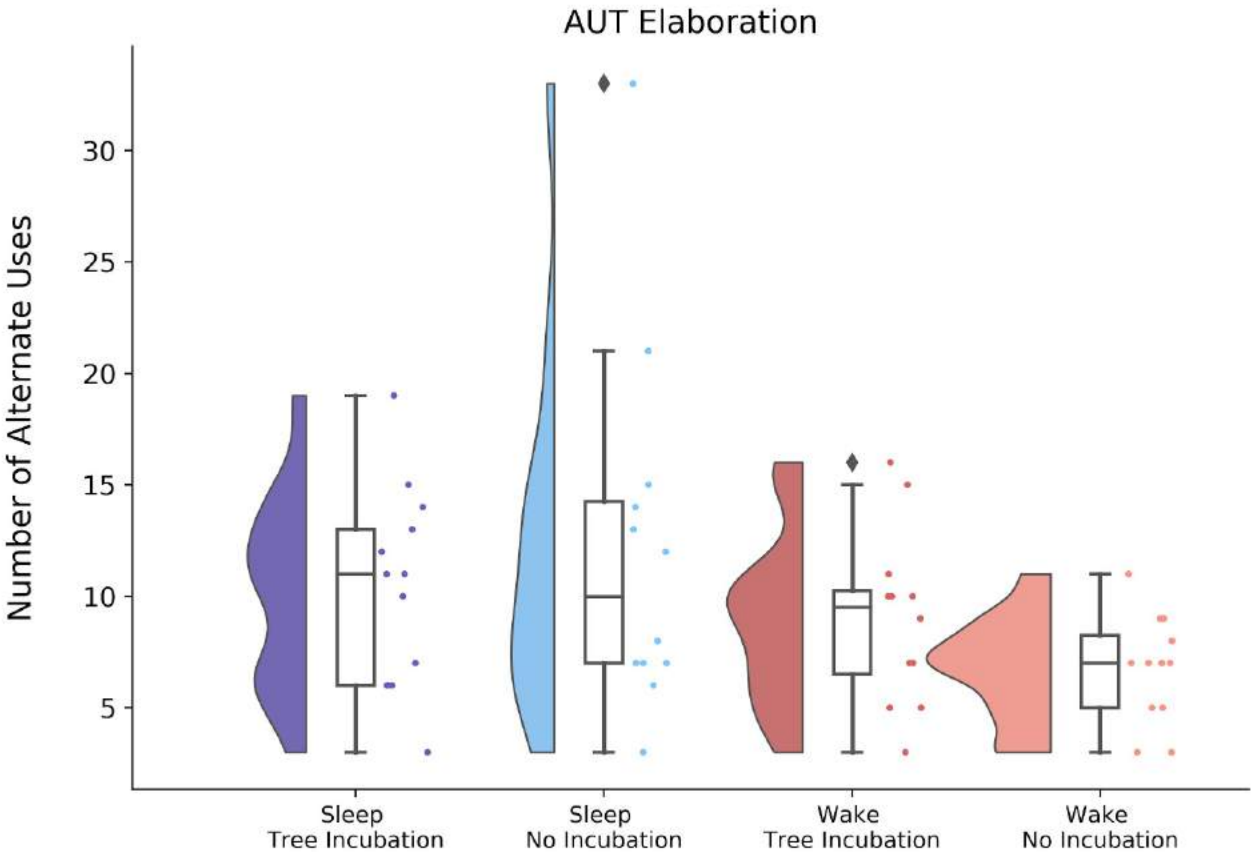

Figure 51.

AUT Elaboration ratings varied insignificantly by group (Kruskal Wallis H test; H=5.31, p=0.15). A Mann-Whitney *U* Test indicated that the AUT Elaboration instances were significantly greater in the Sleep vs. Wake conditions (Sleep = 11.16 ± 6.35, Wake=7.88 ± 3.31; *U*=394.0, p=0.03), but were insignificantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation = 9.64 ± 4.1, No-Incubation =9.46 ± 6.4; *U*=338.0, p=0.225).

AUT Results Summary

The AUT was the second task subjects performed after awakening. There was a main effect of Sleep vs. Wake and an interaction between State (Sleep vs Wake) and Incubation (Tree vs No).

We found that the (*i*) snapshot creativity ratings, (*ii*) individual use creativity ratings, (*iii*) elaboration (number of uses), (*iv*) and mean semantic distance between "Tree" and AUT individual uses generated were all significantly greater in the Sleep conditions than in the Wake conditions. We found that the mean number of direct uses of the word "tree" per subject in AUT were significantly less in the Sleep conditions than the Wake conditions. [305]

Comparing within conditions, we found that the (*i*) snapshot creativity ratings and (*ii*) individual use creativity ratings were significantly greater in the Sleep Tree-Incubation condition as compared to the Sleep No-Incubation Condition.

We found that the (*i*) snapshot creativity ratings, (*ii*) individual use creativity ratings (*iii*) and mean semantic distance between "Tree" and AUT individual uses generated were significantly greater in the Sleep Tree-Incubation condition as compared to each Wake condition.

We further found that the (*i*) individual use creativity ratings were significantly greater in the Sleep No-Incubation condition as compared to the Wake No-Incubation condition.

[305] We take this as a possible indication of increases in spreading activation in Sleep vs Wake conditions, leading to less direct semantic references, yet note that number of uses generated was not equal across conditions and is a confounding variable. More analysis is needed to make strong claims about spreading activation and AUT.

Verb Generation Task (VGT)

VGT Semantic Distance

Semantic distance in creative cued VGT has a demonstrated strong relationship to a creativity factor derived from verbal, nonverbal, and achievement-based creativity measures[306]. Before calculating the semantic distance between each noun prompt and the verb generated, verb responses were first processed to take the "-ing" form of the verb (for example, "run" was changed to "running"). Second, for instances where the prompt noun was repeated in the verb response (i.e. prompt noun "leaf" with a verb response of "eating a leaf") the repeated noun was removed from the response as they would introduce a confounding semantic distance value of 0. Finally, stop words (i.e. a, at, is, the, which, and on) were removed. The mean semantic distance between the noun prompt and the remaining words in the response was calculated. A mean for each subject was taken across the semantic distance values calculated for all of their noun prompt and verb responses. Methods adapted from Prabhakaran et al (2014).

Pairwise Comparisons

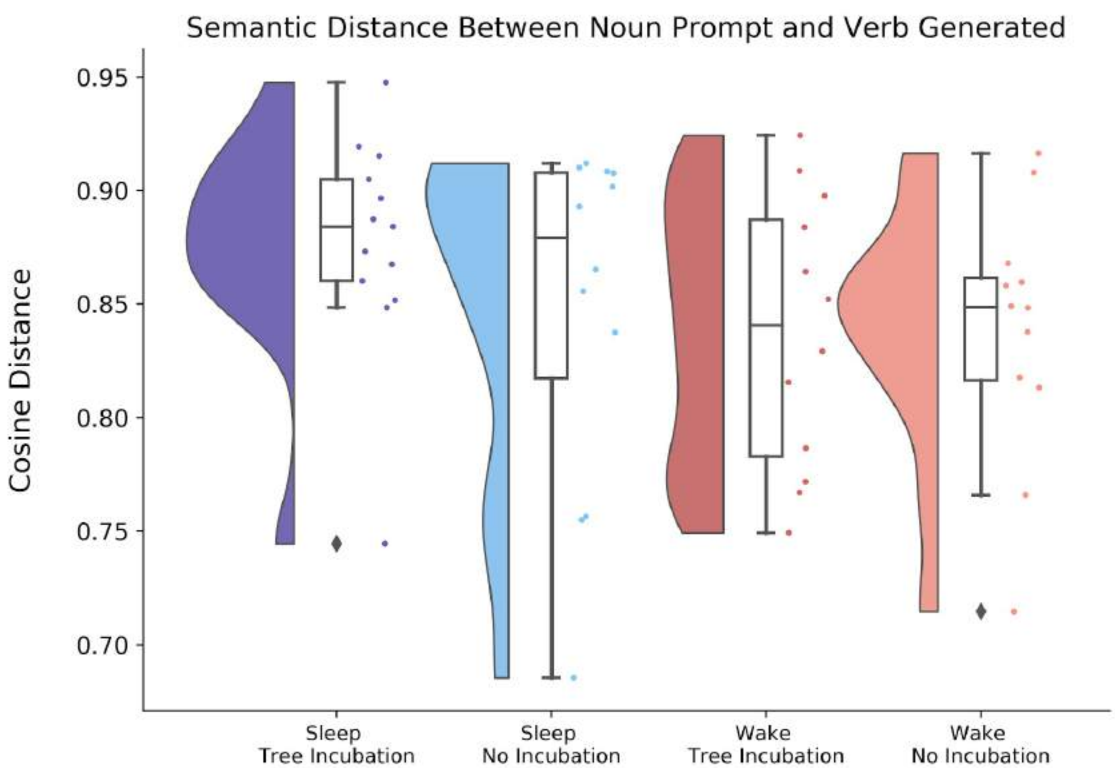

Figure 52.

VGT Semantic Distance varied insignificantly between groups (Kruskal Wallis H test; H=4.14, p=0.25). A Mann-Whitney test indicated that the GloVe semantic distance values across all noun-verb pairs were significantly greater in the Sleep conditions than the Wake conditions. (Sleep = 0.86 ± 0.06, Wake = 0.84 ± 0.06; *U*=392.0, p=.034).

[306] (Prabhakaran, Green, and Gray 2014)

VGT Word Count

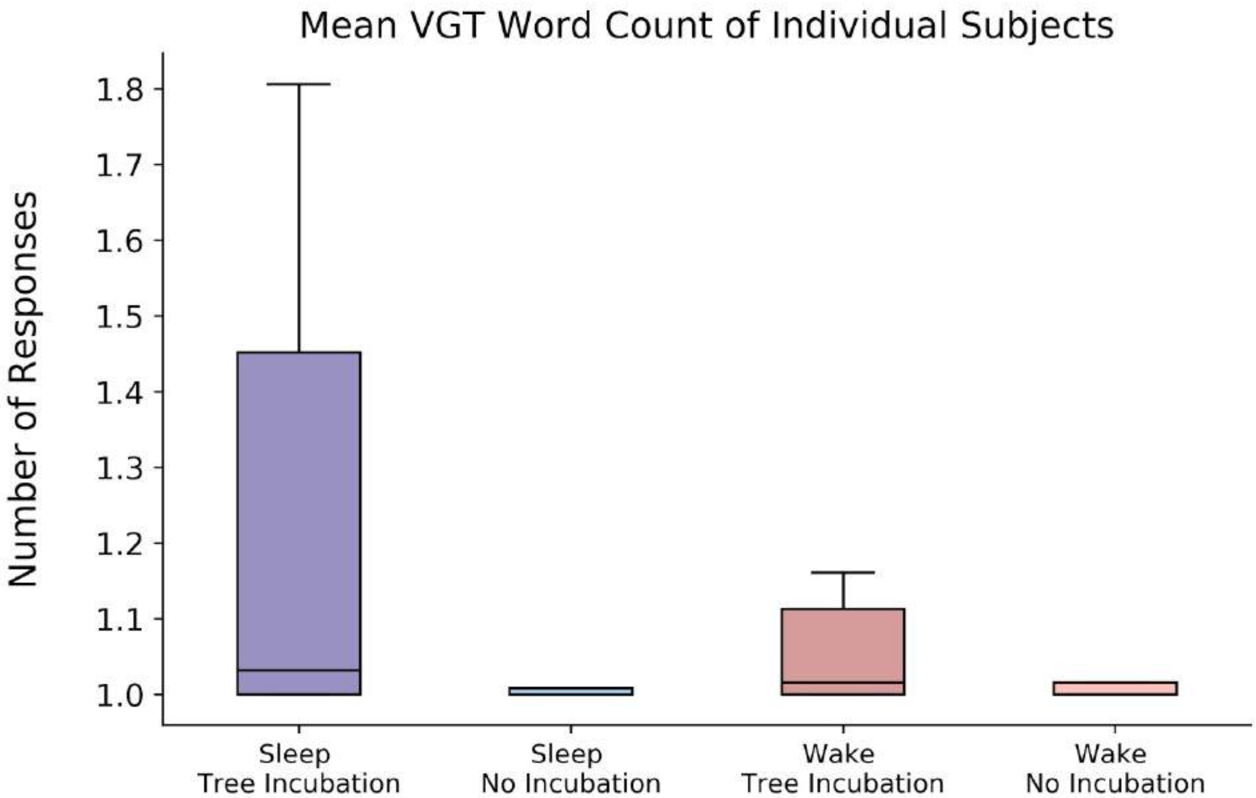

Figure 53.

VGT Word Count varied insignificantly between groups (Kruskal Wallis H test; H=5.89, p=0.12). Out of 1519 VGT responses, there were 132 multi-word responses (length of verb response > 1 word). Out of 49 subjects, 20 elaborated (verb response word count > 1). A Mann-Whitney *U* Test indicated that the mean VGT word count per subject was not significantly greater in the Sleep vs. Wake conditions (Sleep = 1.2 ± 0.44, Wake = 1.12 ± 0.33; *U*=313.5, p=0.39), but was significantly greater in the Tree-Incubation vs. No-Incubation conditions (Tree-Incubation = 1.24 ± 0.44, No-Incubation = 1.08 ± 0.32; *U*=390.0, p=0.02). Instances of elaboration were significantly greater in the Sleep Tree-Incubation vs. Sleep No-Incubation condition (Sleep Tree-Incubation = 1.37 ± 0.56, Sleep No-Incubation = 1.01 ± 0.02; *U*=112.0, p=0.02).

VGT Results Summary

The VGT was the third task subjects performed after awakening. There was a main effect of Sleep vs. Wake, a main effect of Tree-Incubation vs No-Incubation, and an interaction between State (Sleep vs Wake) and Incubation (Tree vs No).

We found that the (*i*) semantic distance between noun prompts and verb responses was significantly greater in the Sleep conditions than in the Wake conditions.

We also found that the (*i*) mean word count on the VGT was significantly greater in the Tree-Incubation conditions than the No-Incubation conditions.

Comparing within conditions, we found that the (*i*) mean word count on the VGT was significantly greater in the Sleep Tree-Incubation condition as compared to the Sleep-No Incubation condition.

Correlations Between Number of Tree Reports and Performance on Creative Tasks

An analysis of correlations between degree of incubation (raw count of number of direct references to tree in reports) and post-condition creative performance (all ratings from all raters): [307]

- Combined Sleeping Conditions: Correlational analyses show that the number of direct references to "Tree" in dream reports is **significantly positively correlated** with creative performance.
    - This correlation analysis offers a view of the effects of dreams on creativity regardless of incubation condition, while the above pairwise comparisons show effects of incubation condition regardless of dream content. This is a subtle but significant distinction. This analysis is called for considering that one Sleep Tree-Incubation subjects did not report tree related dreams (n=1/13), that one Sleep No-Incubation group did report tree related dreams (n=1/12), and that those who did report tree related dreams (n=13/25) reported them to varying degrees.
    - This analysis does not control for influences of auditory dream prompt stimulus, which may or may not manifest as conscious dream content, and varies across Sleeping conditions. This analysis looks at the effects of changing *contents* of consciousness (dreams) while holding *level* of consciousness (sleep) constant.

- Sleep Tree-Incubation Condition: Correlational analyses show that within the Sleep Tree-Incubation condition, number of reports including direct references to "Tree" is **significantly positively correlated** with creative performance.
    - This analysis offers a specific view of the effects of incubated dreams during Sleep on creativity.
    - This analysis controls for influences of auditory stimulus dream prompt, and looks at the effects of changing *contents* of consciousness (dreams) while holding *level* of consciousness constant (sleep).

- Wake Tree-Incubation Condition: Correlational analyses show that within the Wake Tree-Incubation condition, number of reports including direct references to "Tree" is **significantly negatively correlated** with creative performance.
    - This analysis is interesting in light of the fact that 3 of the 12 subjects in the Wake Tree-Incubation condition included no direct references to "Tree" in their verbal reports. This analysis offers a specific view of the effects of incubated thoughts during Wake on creativity.
    - This analysis controls for influences of auditory stimulus, and looks at the effects of changing *contents* of consciousness (thoughts) while holding *level* of consciousness constant (wake).

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[307] Note that these are **not mean ratings, but all ratings**. Note that number of tree references is r**aw number per subject, not percentage of reports** with tree references per subject. These adjustments are not done because this bivariate correlation analysis, looking at strength of association between variables in two groups, does not assume independence of points given within each group. Future analyses will explore differences in significance with mean ratings and percentage of reports.

Correlation between Number of Dream "Tree" References and Creative Performance

	Sleep Conditions	Sleep Tree Incubation	Wake Tree Incubation
Story Overall Creativity	r = 0.5 p = 5.04E-06	r = 0.382 p = 0.016	r = -0.238 p = 0.162
Story Narrative Cohesion	r = -0.079 p = 0.503	r = -0.194 p = 0.236	r = 0.144 p = 0.402
Story Fantasy	r = 0.34 p = 0.003	r = 0.251 p = 0.124	r = 0.044 p = 0.8
Story Descriptiveness	r = 0.172 p = 0.141	r = 0.197 p = 0.229	r = -0.167 p = 0.33
Story Semantic Flexibility	r = 0.542 p = 4.98E-07	r = 0.598 p = 5.85E-05	r = -0.276 p = 0.103
Story Emotiveness	r = -0.076 p = 0.515	r = 0.113 p = 0.493	r = -0.526 p = 9.77E-04
Story Imagery	r = 0.437 p = 8.81E-05	r = 0.045 p = 0.784	r = 0.236 p = 0.166
AUT Snapshot Rating	r = 0.481 p = 1.28E-05	r = 0.349 p = 0.029	r = -0.497 p = 0.002
AUT Individual Rating	r = 0.063 p = 0.051	r = 0.017 p = 0.716	r = -0.185 p = 8.25E-05
AUT Semantic Distance	r = -0.021 p = 0.811	r = -0.302 p = 0.027	r = 0.171 p = 0.209
VGT Semantic Distance	r = -0.037 p = 0.859	r = -0.411 p = 0.163	r = -0.285 p = 0.37
Delta in Self-Assessment	r = -0.096 p = 0.647	r = 0.096 p = 0.754	r = -0.065 p = 0.859

Table 4. Correlations between degree of incubation (raw count of number of direct references to tree in reports) and post-condition creative performance (all ratings from all raters, not means). The three columns (top) separate correlations for different groups and combinations of groups with degree of incubation. Significant positive correlations (p < 0.5) marked in blue, significant negative correlations marked in red. Insignificant correlations in grey.

Creative Self-Efficacy

Subjective questionnaires given both before and after the experiment (including the 45 minute period of nap or wake and the three creativity tasks) reveal a differential effect of condition on self-assessment of creative thinking. Before each experimental condition, subjects were asked "Do you consider yourself a creative thinker?" and "Do you consider yourself a flexible thinker?". After subjects completed the creativity tasks, these questions were repeated. Pre-experiment, pairwise comparisons indicate no significant differences between groups. However, post-experiment, there was significantly higher self-assessment of creativity following sleep compared to wake. Furthermore, pairwise comparisons indicate a significant increase in pre-post delta of self-assessment as a flexible thinker in sleeping as compared to waking conditions.

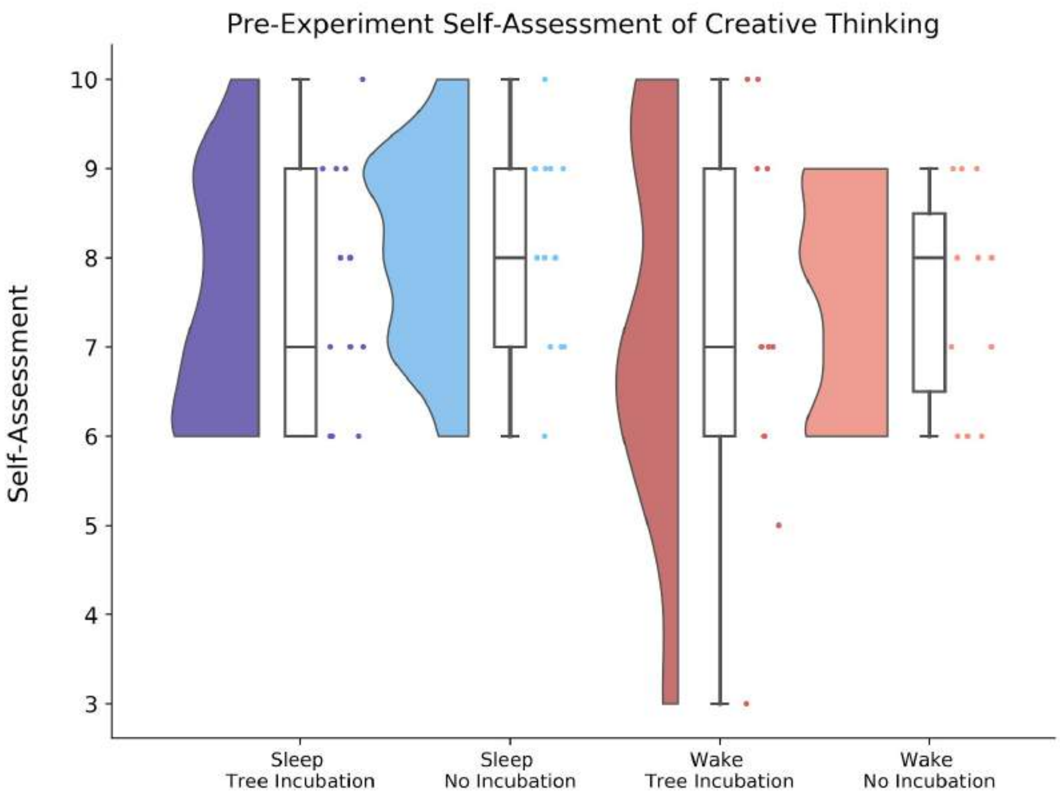

Figure 54.

Pre-experiment self-assessment of creative thinking varied insignificantly between groups (Kruskal Wallis H test; H=1.72, p=0.63). A Mann-Whitney *U* Test indicated no significant difference between groups in self-assessment of creative thinking before Sleep vs. Wake conditions (Sleep = 7.8 ± 1.29, Wake = 7.31 ± 1.7; *U*=312.0, p=0.411), and Tree-Incubation vs. No-Incubation Conditions (Tree-Incubation = 7.3 ± 1.77, No-Incubation = 7.83 ± 1.19; *U*=258.0, p=.807).

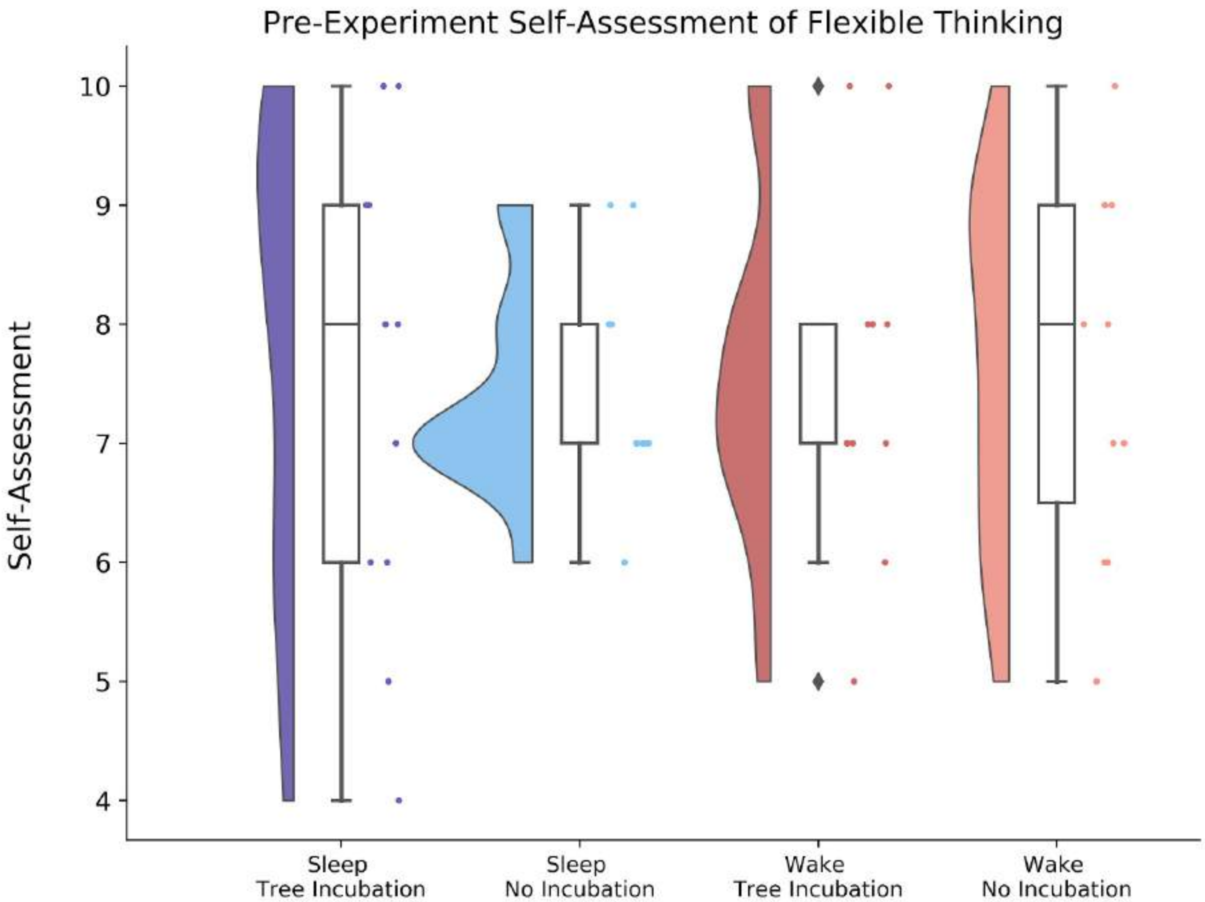

Figure 55.

Pre-experiment self-assessment of flexible thinking varied insignificantly between groups (Kruskal Wallis H test; H=.67, p=0.88). A Mann-Whitney *U* Test indicated no significant difference between groups in self-assessment of creative thinking before conditions. Sleep vs. Wake conditions (Sleep = 7.6 ± 1.55, Wake = 7.45 ± 1.4; *U*=278.0, p=0.673), Tree-Incubation vs No-Incubation Conditions (Tree-Incubation = 7.56 ± 1.73, No-Incubation = 7.52 ± 1.24; *U*=320.0, p=.345).

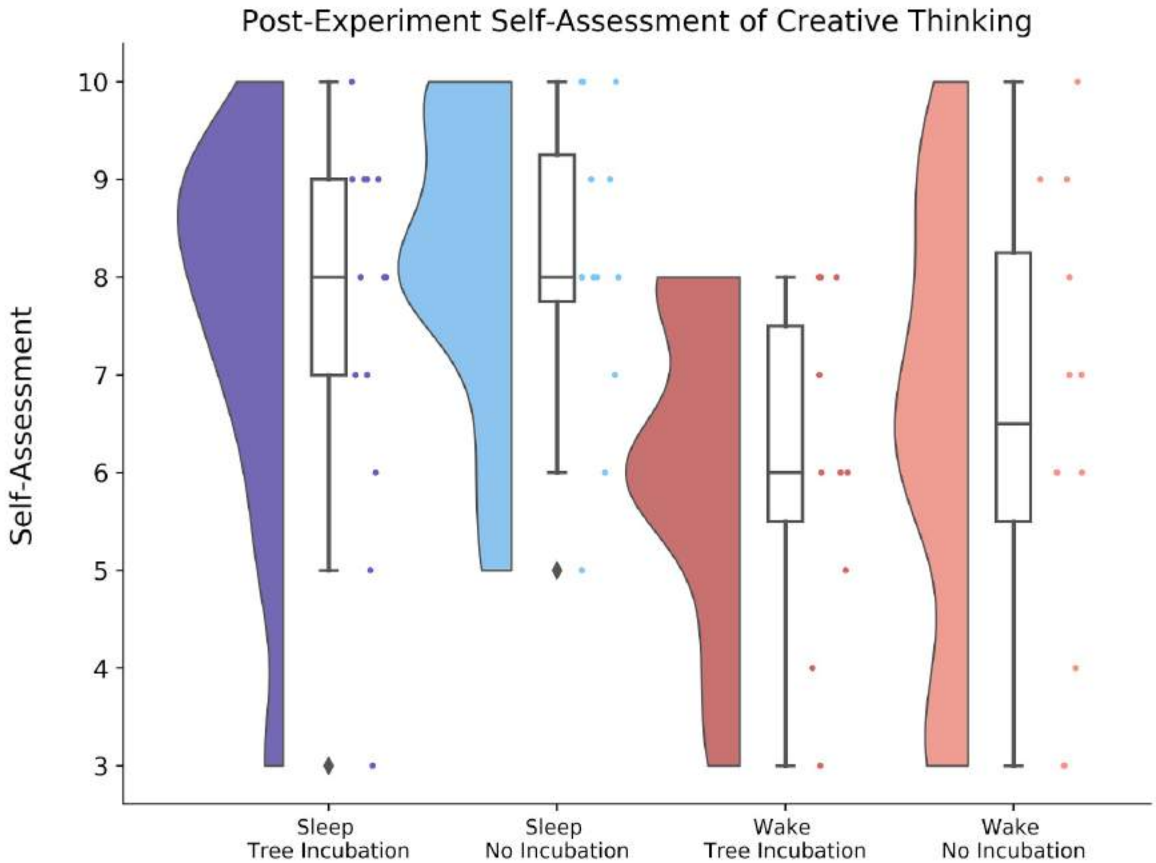

Figure 56.

Post-experiment self-assessment of creative thinking varied significantly between groups (Kruskal Wallis H test; H=8.37, p=0.04). A Mann-Whitney *U* Test indicated that post-experiment self-assessment of creative thinking was significantly greater in the Sleep as compared to the Wake conditions (Sleep = 7.84 ± 1.77, Wake = 6.64 ± 1.84; *U*=417.0, p=0.009). Additionally, it was significantly greater in the Sleep No-Incubation condition as compared to the Wake No-Incubation condition (Sleep No-Incubation = 8.17 ± 1.59, Wake No-Incubation = 6.82 ± 2.14; *U*=103.0, p=.037) and Wake Tree-Incubation condition (Sleep No-Incubation = 8.17 ± 1.59, Wake Tree-Incubation = 6.3 ± 1.57; *U*=108.0, p=.018).

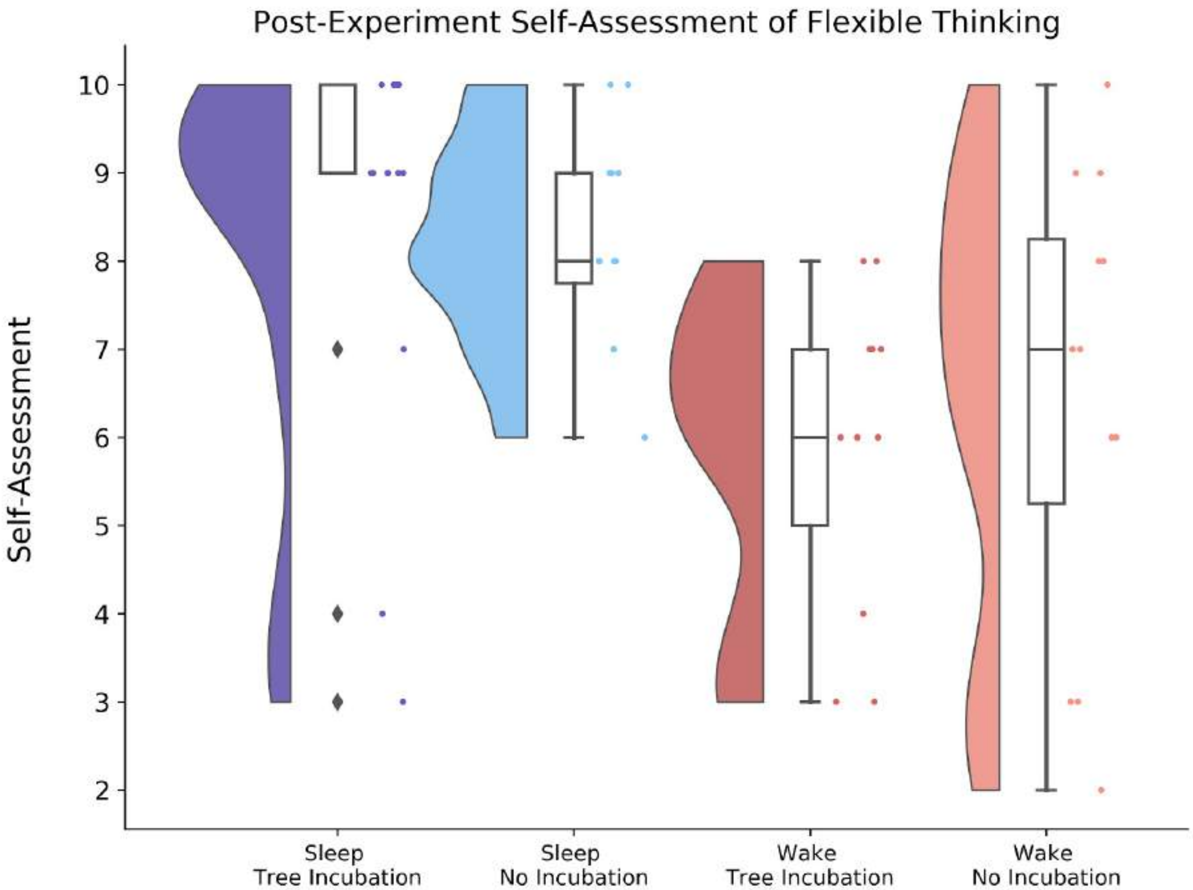

Figure 57.

Post-experiment self-assessment of flexible thinking varied significantly between groups (Kruskal Wallis H=13.35, p=0.004). A Mann-Whitney *U* Test indicated that post-experiment self-assessment of flexible thinking was significantly greater in the Sleep as compared to the Wake conditions (Sleep = 8.28 ± 1.81, Wake = 6.14 ± 2.2; *U*=454.0, p=0.001). Additionally, it was significantly greater in the Sleep Tree-Incubation condition as compared to the Wake No-Incubation condition (Sleep Tree-Incubation = 7.77 ± 2, Wake No-Incubation = 6.82 ± 2.48; *U*=117.0, p=.016) and Wake Tree-Incubation condition (Sleep Tree-Incubation = 7.77 ± 2, Wake Tree-Incubation = 5.8 ± 1.87; *U*=117.0, p=.016*U*=121.0, p=.0096).

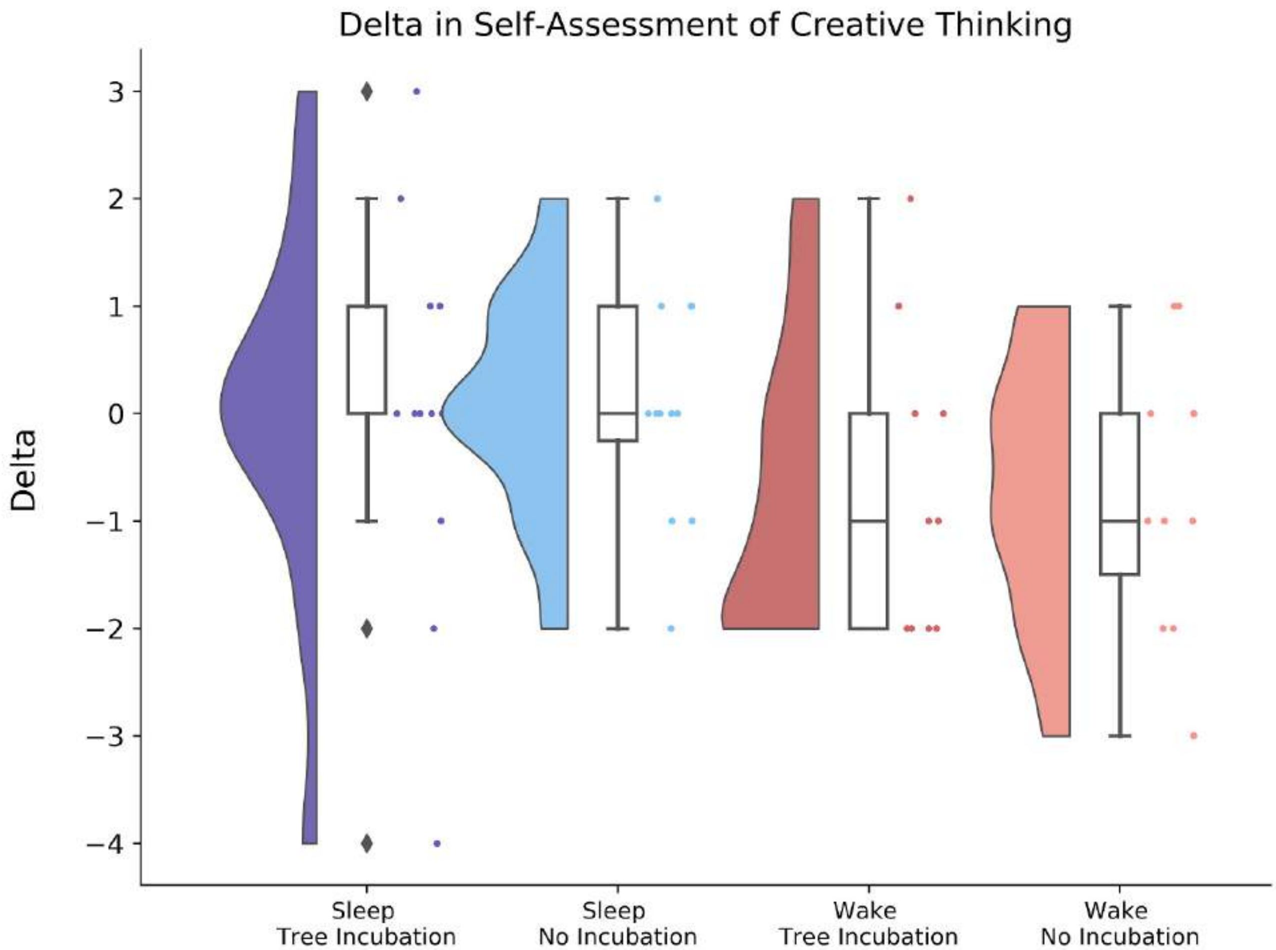

Figure 58.

Delta in self-assessment of creative thinking varied insignificantly between groups (Kruskal Wallis H test; H=4.01, p=0.26). A Mann-Whitney *U* Test indicated no significant difference in delta in self-assessment of creative thinking between groups. Sleep vs. Wake conditions (Sleep = 0.04 ± 1.43, Wake = -0.68 ± 1.29; *U*=350.0, p=0.15).

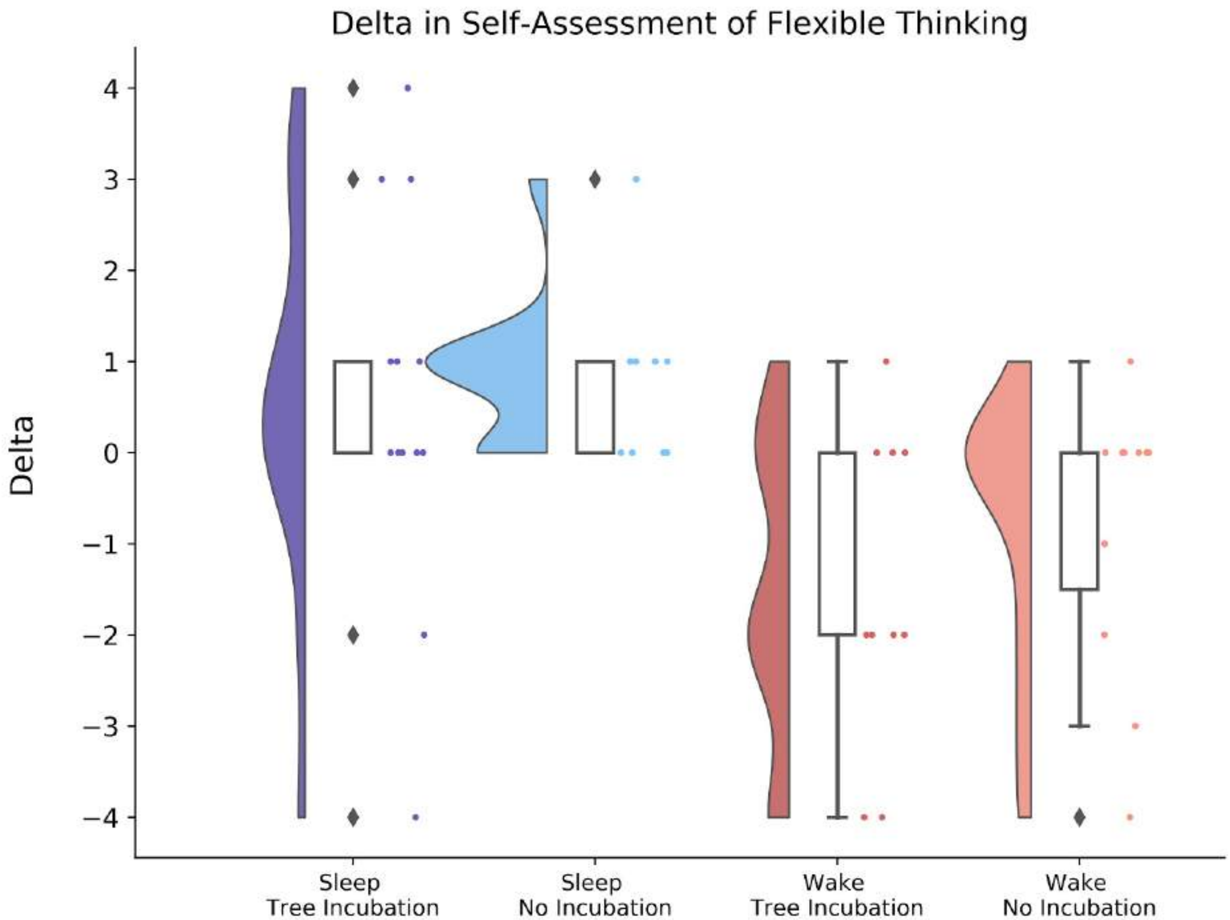

Figure 59.

Delta in self-assessment of flexible thinking varied significantly between groups (Kruskal Wallis H test; H=14.64, p=0.002). A Mann-Whitney *U* Test indicated that the delta in self-assessment of flexible thinking was significantly greater in the Sleep as compared to the Wake conditions (Sleep = 0.68 ± 1.6, Wake = -1.05 ± 1.65; *U*=422.0, p=0.006). Additionally, it was significantly greater in the Sleep No-Incubation condition as compared to the Wake No-Incubation condition (Sleep No-Incubation = 0.83 ± 0.83, Wake No-Incubation = -0.81 ± 1.54; *U*=112.0, p=.007) and Wake Tree-Incubation condition (Sleep No-Incubation = 0.83 ± 0.83, Wake Tree-Incubation = -1.5 ± 1.72; *U*=106.0, p=.02).

Creative Self-Efficacy Results Summary

Subjects rated their self-efficacy before the experimental condition, and then again after completing the creativity tasks. There was a main effect of Sleep vs. Wake and an interaction between State (Sleep vs Wake) and Incubation (Tree vs No).

We found that the (*i*) post-condition self-assessment as a creative thinker and (*ii*) as a flexible thinker, as well as (*iii*) pre/post delta in self-assessment as a flexible thinker was significantly greater in the Sleep conditions than in the Wake conditions.

Comparing within conditions, we found that the (*i*) post-condition self-assessment as a creative thinker and (*ii*) as a flexible thinker, as well as (*iii*) pre/post delta in self-assessment as a flexible thinker, was significantly greater in the Sleep Tree-Incubation condition as compared to each of the Wake Tree-Incubation condition and Wake-No Incubation conditions.

Dream Content Outlier Subjects

Within the Sleep conditions, we had two dream content outlier subjects. Subject 8 in the Sleep Tree-Incubation condition **did not report any dreams** involving a Tree, though they received audio stimuli including the word "Tree" and confirmed hearing said stimulus. Subject 14 in the Sleep No-Incubation **did report dreams** involving a Tree, though they received no audio stimulus including the word "Tree" and confirmed they were unaware of the "Tree" dream incubation condition.

These subjects provide an opportunity to observe trending relationships between dream content and post-sleep performance regardless of incubation. This offers insight into two important questions:

1) if a subject is prompted with the word "Tree" but reports no related dream content (i.e. Subject 8), will unconscious underlying processing in the absence of conscious phenomenology positively influence post-sleep performance? And:

2) if a subject in an unprompted group reports "Tree" related dream content (i.e. Subject 14), will that conscious phenomenology exert a positive influence on task performance in the absence of the effect of whatever unconscious processing accompanies the delivery of each audio prompt? And is an unincubated organic dream going to influence creative performance in the same direction as an incubated dream?

To understand the directionality of effects of dream content within these subjects, we report any instances where either subject is > 1 standard deviation from their respective group means. We observe a trend in the direction of the standard deviation for each subject along multiple creativity tests.

Distance of >2 Standard Deviations From Group Mean

	Subject 8 (Sleep Tree-Incubation w/o Tree report) *Compared to Sleep Tree-Incubation*	Subject 14 (Sleep No-Incubation w/ Tree report) *Compared to Sleep No-Incubation*
Storytelling Overall Creativity	-2.185	+1.61
Storytelling Time	-2.017	-1.575
AUT Elaboration	-0.98	+2.65
Tree Dream Reports	-1.762	+3.317

Table 5 *Dark red denotes > 2 negative SD from group mean, dark blue denotes > 2 positive SD from group means*

Distance of >1 Standard Deviations From Group Mean

	Subject 8 *Compared to Sleep Tree-Incubation*	Subject 14 *Compared to Sleep No-Incubation*
Storytelling Overall Creativity	-2.185	+1.61
Storytelling Fantasy	-1.95	+1.39
Storytelling Descriptiveness	-1.38	+1.26
Storytelling Time	-2.017	-1.575
Semantic Flexibility	-1.51	-1.12
AUT Snapshot	-1.06	+0.43
AUT Subject Mean Semantic Dist	+1.64	+0.37
AUT Elaboration	-0.98	+2.65
Tree Dream Reports	-1.762	+3.317

Table 6 *Light red denotes > 1 negative SD from group mean, light blue denotes > 1 positive SD from group means. Dark red denotes > 2 negative SD from group mean, while dark blue denotes > 2 positive SD from group means*

Figure 60. *A painting of my own tree dream, incubated by Dormio. Collaboration with Ben Tritt.*

All Creativity Results Summary

All comparisons across groups described here were based on **specific, directional *pre-hoc* hypotheses**. Primary analyses employed a 2 (Sleep v Wake) × 2 (Incubation v No-Incubation) Mann Whitney *U* Test, followed by planned paired comparisons.

Sleep (Incubation and No-Incubation) offered a significant increase over **Wake (Incubation and No-Incubation)** for:

- Creative Storytelling Task Overall Creativity, Imagery Ratings, Plot Continuity, Fantasy, Descriptiveness, Semantic Flexibility, TIme Spent Writing
    - And a significant decrease in Coh-Metrix Narrativity and Coh-Metrix Referential Cohesion
- AUT Elaboration, Individual Use Ratings, Snapshot Subjective Ratings, Semantic Distance between "Tree" and AUT uses generated
    - And a significant decrease in direct use of the word "Tree" in AUT responses
- VGT Semantic Distance between noun prompt and verb generated
- Post-condition self-assessment as a creative thinker, post-condition self-assessment as a flexible thinker, Pre/Post delta in self-assessment as a flexible thinker

'Tree' Incubation (Sleep and Wake) offered a significant increase over **No-Incubation (Sleep and Wake)** for:

- Creative Storytelling Imagery Ratings, and Time Spent Writing, and Coh-Metrix Narrativity
- VGT Mean Word Count

'Tree' Incubation in Sleep offered a significant increase over **No-Incubation in Sleep** for:

- Creative Storytelling Task Overall Creativity, Imagery Ratings, Semantic Flexibility, and Time Spent Writing
- AUT Individual Use Ratings, Snapshot Subjective Ratings
- VGT Mean Word Count

'Tree' Incubation in Sleep offered a significant increase over **'Tree' Incubation in Wake** for:

- Creative Storytelling Task Overall Creativity, Imagery Ratings, Fantasy, Semantic Flexibility, Time Spent Writing
    - And a significant decrease in Coh-Metrix Narrativity ratings
- AUT Individual Use Ratings, AUT Snapshot Subjective Ratings, Semantic Distance between "Tree" and AUT uses generated
- Post-condition self-assessment as a creative thinker, post-condition self-assessment as a flexible thinker, Pre/Post delta in self-assessment as a flexible thinker

'Tree' Incubation in Sleep offered a significant increase over **No-Incubation in Wake** for:

- Creative Storytelling Task Overall Creativity, Imagery Ratings, Descriptiveness Fantasy, Semantic Flexibility, Time Spent Writing
- AUT Individual Use Ratings, AUT Snapshot Subjective Ratings, Semantic Distance between "Tree" and AUT uses generated
- Post-condition self-assessment as a creative thinker, post-condition self-assessment as a flexible thinker, Pre/Post delta in self-assessment as a flexible thinker

Sleep No-Incubation offered:

- A significant increase in Descriptiveness as compared to the Wake No-Incubation condition.
    - A significant decrease in the Coh-Metrix Narrativity ratings as compared to the Wake Tree-Incubation condition.
- Higher AUT Individual Use Ratings as compared to Wake Tree-Incubation

'Tree' Incubation in Wake offered a significant increase over **No-Incubation in Wake** for:

- Creative Story Imagery Ratings

Further, two subjects reported dream content which did not align with the rest of the subjects in their condition. Subject 8 did not report tree related dreams, though they were in the Sleep Tree-Incubation condition. Subject 14 did report tree related dreams, though they were in the Sleep No-Incubation condition. With an analysis of creative performance of these subjects we see each is an outlier in creative performance as well, such that dream content drives performance regardless of incubation condition:

- Subject 8 is > 2 standard deviations below condition mean on Storytelling Overall Creativity and Storytelling Time
- Subject 14 is < 2 standard deviations above condition mean on AUT elaboration

Lastly, a correlational analysis reveals the relationship between the degree of incubation (number of direct references to 'Tree' in reports) and creative performance. We see that:

- In combined Sleep Groups (Sleep Tree-Incubation and Sleep No-Incubation), **degree of incubation is positively correlated** with performance on Story Overall Creativity, Fantasy, Semantic Flexibility, Imagery, and AUT Snapshot ratings.
- In the Sleep Tree-Incubation condition specifically, **degree of incubation is positively correlated** with performance on Story Overall Creativity, Semantic Flexibility, and AUT Snapshot ratings, but **negatively correlated** with AUT Semantic Distance.
- In the Wake Tree-Incubation condition, **degree of incubation is negatively correlated** with performance on Story Emotiveness, AUT Snapshot and AUT Individual uses ratings.

[redacted]

Figure 61. *A second painting of my own tree dream, incubated by Dormio. Collaboration with Ben Tritt.*

Discussion: Expounding, Exploring, Expanding

Our Results: Expounding

This study offers the first controlled experimental evidence supporting the positive effect of ***dreams per se*** on creative performance. The results suggest creative boosts are specifically related to dream content, as opposed to the sleeping brain state in which dreams occur. These benefits are apparent in both subjective and objective assessment, of both real-world relevant creative story tasks and extensively validated laboratory AUT and VGT tasks. These benefits go beyond divergent thinking, reflecting differences in the descriptiveness, degree of fantasy and semantic flexibility of creative products, and extend to post-sleep benefits in self-perception as a creative and flexible thinker.

That sleeping as compared to waking benefitted post-sleep performance suggests that sleep onset engenders a creative brain-state over and above waking mind-wandering brain-states. That sleeping incubation of the 'Tree' theme benefitted subsequent performance over and above sleeping without incubation indicates that task related mental content, and not only the brain-state of hypnagogia, offer a creative boost. That correlational analyses reveal a tight link between tree related dream reports and creative performance suggests that conscious, dreamt task related mental content specifically is a driver of creative benefits, not only the combined conscious and unconscious effect of audio incubation. The post sleep performance of dream content outliers (subjects 8 and 14) within each group, in turn, suggest that having a task-related dream regardless of incubation benefits creative performance. That waking incubation of the 'Tree' theme did not benefit subsequent performance, and that waking reports of tree related mentation in fact negatively correlated with creative performance, indicates that the beneficial effects of task-related mentation are in fact specific to the sleep state. This study thus zeroes in on beneficial effects of dreams, first showing effect of sleeping brain-state, then the effects of combined unconscious and conscious incubated mental contents, and then the effects of conscious mental content.

This study is markedly different from previous work in the dream literature, because it focuses on causal links between dreams and post-sleep performance. The Wamsley et al (2010, 2019) virtual maze study[308] described above, the most compelling evidence to date that dreams relate to post-sleep learning, is not in fact evidence that dreams affect learning.

> "*We observed that dreaming of a spatial learning task predicted enhanced post-nap memory performance. However, it is not our contention that dream experiences cause memory consolidation during sleep. Instead, we propose that task-related dream experience and the subsequent behavioral enhancement of memory performance both result from an underlying process of memory reactivation and consolidation in sleep. Thus, dreaming may be a reflection of the brain processes supporting sleep-dependent memory processing.*"
>
> Wamsley et. al, 2010

The authors describe the dream, in this 2010 experiment, as a window into the underlying processing in sleep, the smoke as opposed to the fire. The experience remains a spandrel, correlated with post-sleep improvements but not causal, simply a useful way for experimenters to gauge degrees of ongoing learning

[308] (Wamsley and Stickgold 2019)

and predict performance. The study is limited to conclusions about correlations between dreams and learning because it is a study of memory, and the task is presented pre-sleep — thus any dream could be the actual processing of a problem, or a mere reflection of underlying unconscious problem processing, or some combination, with no way of distinguishing.[309] Our study instead presents tasks post sleep, showing that task-related dreams drive performance improvements without any possibility for incubation. This in turn eliminates the possibility that task-related dreams are epiphenomenal reflections of unconscious processing. They must be the fire which drives the creative furnace. We prime core concepts related to a problem to create task-related dreams without presenting the actual task, showing that the conscious thinking in sleep is core as opposed to solely correlated with creative benefits.

The significantly higher self-perception as a creative and flexible thinker following sleep also suggests these hypnagogic thoughts not only are convincingly creative for third party raters and computational creativity metrics, but to the thinker themselves. This suggests the possibility of enhancing creative self-efficacy, convincing users that they have creative capacity beyond their own self-perception. This sense of personal creativity has been shown to have positive longitudinal effects on creative performance.[310] Everyone is an artist, as Joseph Beuys said, but not everyone believes it — perhaps watching their minds whirr in the altered state of hypnagogia rife with hyper-associative visions and encounters with the implausible, could help users see themselves as such.

The dream phenomenology reported by Dormio users offers experimental backing for the historical, anecdotal descriptions of experiences of hypnagogia. We see imagery laden dreams ranging from flashing scenes to fully immersive narratives, reductions in anxiety, alterations in sense of self, out of body experiences, switches in perspective, lapses in metacognition and executive control, the return of old episodic memories, sudden synesthesia and hyper-associativity. Each of these could be harnessed for a separable intervention in future work, be it reflecting on a personal problem of choice without anxiety or exploring novel associations in sleep onset.

The experiences reported, the high comfort ratings, the biosignals gathered and the dream-mediated benefits evidenced, suggest that the Dormio device is effective for accessing and affecting the sleep onset period. Yet any claims are specific to the Dormio-defined sleep onset period. This is not PSG sleep-staging, and has very different aims than PSG sleep-staging: so long as sleep science is built around a device which is immobile and prohibitively expensive, the investigations and applications enabled by PSG will always be stuck in a sleep-lab centric conversation and beneficial primarily to those with sleep-lab access. This aim of the Dormio device, to be abundantly clear, is introspection and experience in or out of lab, on the couch, during that boring opera or that unending bar mitzvah, wherever a nap may strike and muses might alight. The aim of the Dormio device is a broader conversation around thinking, day and night. Sleep is a doorway, the aim is interaction, and measurement is a means to an end.

It is somewhat unsurprising that different ways we consciously think about a concept in different brain-states provide differential benefits for subsequent performance, whether these brain-states are during sleep or wake. This poses a question to any experiment where sleep related benefits are studied

---

[309] The distinction between learning and the experience of learning becomes quite vague at times. When we teach a child addition on their fingers, how much of the 2+2 logic is experienced as a mathematical concept, how much is embodied, how much is embedded in the environment, and how much of each of these is conscious? These blurred lines are also present in sleep, wherein the distinction between underlying memory consolidation during sleep and the experience of memory consolidation during sleep seems extremely shaky. Yet regardless, experiments like the virtual maze do not offer conclusive evidence distinguishing unconscious sleep learning and dreamt experience of learning.
[310] (Tierney and Farmer 2011)

without concurrent collection of dream reports, which happens to be pretty much every sleep study ever: Could it be that Targeted Memory Reactivation benefits, for example, are driven by successful incubation of task-related dream mentation by audio cues? Perhaps control group outliers who benefit without cues are simply experiencing unprompted (and unreported) dreams related to the laboratory or pre-sleep task? Whether or not the thinking in sleep is causally related to TMR benefits, this thesis and the historical anecdotal and empirical evidence for the importance of dreams calls for a future sleep science which takes the experiencing self seriously. They call for a cognitive revolution in sleep.

Other Techniques: Exploring

Piloting Hypnagogic Conversations

There is an open question as to whether each serial incubation in Dormio is:

a) reinforcing, or reactivating, the original dream theme suggestion issued in wake. This would mean that, like TMR, participants process the audio cue 'Tree' primarily as a reminder of a waking experience. This would suggest participants have multiple tree dreams because each references the original cue, and that subsequent cues need not be words, but could be instead simple sounds which recall original cues.

or b) awakening participants enough with each report and incubation to reprocess each audio cue and begin a new dream with each wakeup. This would suggest participants have multiple tree dreams because the same cue is repeated, not because these dreams are reinforcing the original waking cue. This would suggest that multiple cues in hypnagogia could differ from wake, and a much more complicated, iterative serial incubation paradigm would be possible.

To understand whether giving iterative cues was possible, we conducted a pilot experiment (n=1) where each serial incubation differed from the last, eventually forming a narrative of 4 continuous cues. If feasible, this would allow more detailed dream guiding, even an ongoing conversation across levels of consciousness.

A single participant came into the laboratory at 1:00 pm for a 45 minute nap opportunity. They were outfitted with the Dormio glove and an eye mask. Data streamed to the Dormio Web App for sleep staging, and audio cues were delivered accordingly. Staging was done by the experimenter. Audio cues were delivered via the text-to-speech function in the Mac OS Terminal, as they were not pre-written but instead written in real-time according to each dream report given.

Transcript:
TTS Incubation 1: Remember to think of a Volcano
Wakeup Report 1: There is a mountain, sharp, I am climbing
TTS Incubation 2: Go inside the mountain
Wakeup Report 2: There is a house inside the mountain, sucking me in. There is fire but I cannot eat it.
TTS Incubation 3: Go inside the house
Wakeup Report 3: There are 2 people inside playing countryside music. They turn into fire, then me, but they are still playing music. I am floating.
TTS Incubation 4: Go out of the house
Wakeup Report 4: I am being fire. Now packing for a trip. People helping. I visited many places.

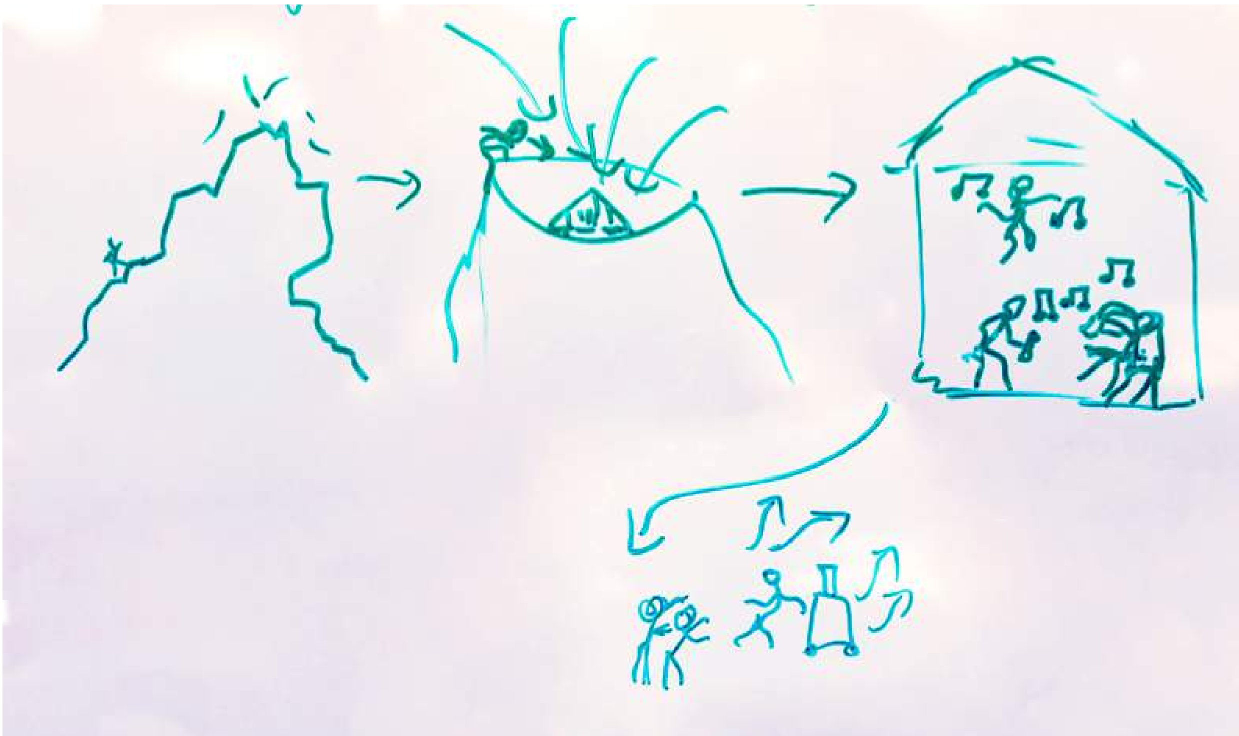

Figure 62. *Drawings done by the experimenter of the iterative storyline, made while the subject is in hypnagogia, Pilot Experiment Subject 1, Iterative Serial Incubation*

Figure 63. *After the subject is fully awakened from hypnagogia, they are asked to draw their dream. Drawings from Pilot Experiment Subject 1, Iterative Serial Incubation*

This pilot subject was able to communicate hypnagogic dreams after each wakeup, and integrate differing dream prompts into subsequent dreams. This allowed for co-creation between the experimenter and the subject of a multi-staged dream narrative. After wakeup, each prompt was recalled and the dream storyline was described as continuous, but staged, with the subject drawing 4 separate scenes after awakening, corresponding to each of 4 prompts given. These drawings correspond remarkably well with experimenter drawings of each suggested dream.

This pilot experiment suggests the possibility of a much more detailed, guided hypnagogic incubation than the single-repeated prompt incubation tested in this n=48 Thesis Experiment. This pilot experiment is included here in the hopes of inspiring future investigation into the tools and techniques for detailed, extensive dream incubations and real-time co-creation of dream experiences between experimenter and subject. A dream-guide chatbot, with language processing and text-to-speech functions, could also be an effective future tool for iterative serial incubation.

Pilot PSG Validation

We performed a pilot PSG validation of Dormio over the course of a 65 minute nap opportunity with awakenings delivered via the Dormio system, replicating awakening methods from the thesis experiment. Two expert scorers from the Center for Sleep and Cognition at the Beth Israel Deaconess Medical Center[311] scored the PSG record as a mix of wake and N1 sleep. Throughout the 65 minutes the subject drifted in and out of N1 as evidenced by fluctuations in the amount of alpha waves throughout the record. The sleep was classified as “light N1” because the subject never spent more than 5 minutes at a time in N1 before an awakening, and because the sleep achieved was characterized by a slightly higher amount of alpha than typical N1. The subject never reached N2, N3, or REM. These pilot data show the success of the Dormio system in facilitating multiple rounds of sleep onset, while ensuring subjects do not fall into N2 sleep.

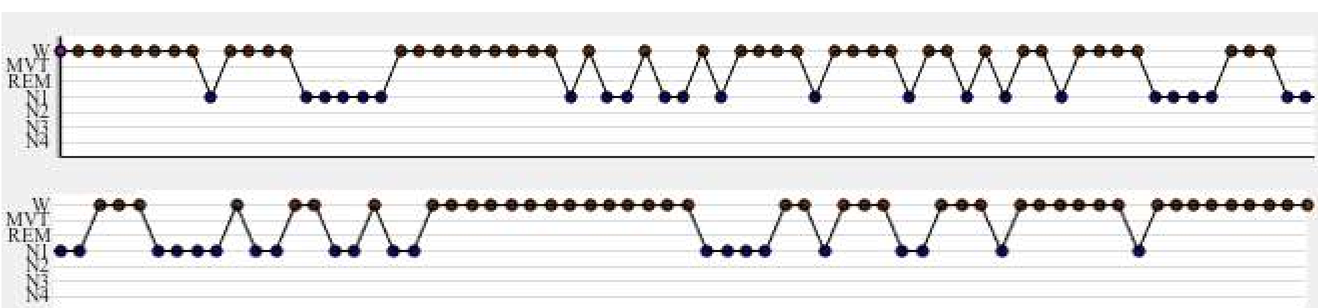

Figure 64. PSG scoring of a 65 minute nap session with Dormio. Timing reads left to right, top to bottom.

[311] Many thanks to Dr. Daniel Denis and Craig Poskanzer for their assistance with PSG setup and scoring.

Other Communities: Extending

One of the primary challenges in dream research is a cultural one. The number of laboratories and researchers devoted to dreaming is on a steady decline, and the principal figure associated with dream research, Sigmund Freud, has been largely dismissed by the scientific community for his unsupported psychoanalytic claims.[312] Google literally has used psychoanalysis as their example for what lacks credence in the public eye (see Figure 65) !

Figure 65.

While sleep is very much part of the public health discussion, dream research has been consistently underfunded and underemphasized. In part, this is because the work is difficult and interdisciplinary: To do dream science in depth, it is necessary to link concepts from psychoanalysis, psychobiology, neuroscience, engineering and the arts. It is necessary to build a community of active, interdisciplinary researchers who can produce work of high scientific caliber and credence, while they remain open to the subtle, subjective, creative and unavoidably personal character of dreams.

Into the Engineering and Brain Science Communities

With this community in mind, Dr. Michelle Carr reached out to me about the Dormio project and the larger Dream Engineering initiative ongoing in the Fluid Interfaces Group. She proposed that the momentum behind these dream technology projects could serve as a convener for the spread scientific community of dream researchers. To bridge and help build that community, we conceived the first *Dream Engineering Symposium*, held at the MIT Media Lab on January 28th, 2019. The workshop brought together about 50 top researchers studying sleep and dreams (including many cited in this thesis, Ken Paller and Björn Rasch and Dierdre Barrett and Francesca Siclari and Stephen LaBerge and many more) with engineers who develop novel technologies for studying, recording and influencing dreams. Researcher panels covered themes of nightmares, lucid dreaming, memory replay and sensory stimulation while technology talks, demos, and posters showed new devices and techniques for incubation of dream content and dream lucidity.

All this work, and the collective brainstorming sessions which occurred afterwards, centered on the theme of Dream Engineering - how technological innovation and scientific expertise can be applied to record or influence dreaming, further dream research, and translate scientific advancement into boosts in health and cognition outside of the laboratory. We hope to run this conference many times in the coming years, and create a regular gathering where the necessary interdisciplinary collaborations can be born. This conference was the first of its kind, and convened a powerful group of builders and brain scientists to further the field of dream and sleep science. Further, the journal *Consciousness and Cognition* has agreed to host a Special Issue on *Dream Engineering*, with submissions from the Dream Engineering Symposium and beyond to share these experiments and engineering opportunities.

[312] (Tore A. Nielsen and Germain 1998)

Figure 66. *Poster made for the Dream Engineering Symposium. Collab between Bruno Olmedo and Adam Haar Horowitz*

Dream Research Presenters

Ken Paller – Northwestern University – Investigating memory processing during sleep with Targeted Memory Reactivation

Björn Rasch – Department of Psychology, University of Fribourg, Switzerland – TMR: Chances and Limits.

Robert Stickgold – Harvard Medical School and Beth Israel Deaconess Medical Center – Sleep, memory and dreams: A neurocognitive approach

Stuart Fogel – School of Psychology, University of Ottawa – Memory reactivation, human intelligence and dreaming

Martin Dresler – Donders Institute, Sleep & Memory Lab – Virtual Reality for lucid dream induction

Benjamin Baird – University of Wisconsin - Madison — Lucid dreaming: An update on recent findings and a methodology for consciousness research

Stephen LaBerge – The Lucidity Institute – Lucid Dreaming Induction: What is the State-of-the-Art?

Karen Konkoly – Northwestern University – TMR to induce lucid dreams

Leslie Ellis – The International Focusing Institute – Working with nightmares to unlock the potential for transformation of emotional memories

Kendra Moore – Center for Mind and Culture – Virtual Reality for treatment of nightmares

George A. Mashour – Center for Consciousness Science, University of Michigan – Consciousness Studies and Anesthesiology

Peter Simor – Institute of Psychology, ELTE Eötvös Loránd University, Budapest, Hungary – Impaired sleep regulation, hyperarousal, and PTSD-like symptoms in Idiopathic Nightmare Disorder

Tore Nielsen – University of Montreal - tAC stimulation for inducing lucid dreams: a replication attempt

Elizaveta Solomonova – McGill University, departments of Psychiatry and Philosophy, Neurophilosophy Lab; Culture, Mind and Brain research group – Sensory incorporation in dreaming

Carlyle Smith – Trent University – 'Heads Up' health dreams

Francesca Siclari- Centre d'Investigation et de Recherche sur le Sommeil, Lausanne, Switzerland - Dream experiences during Non-REM parasomnia episodes: phenomenological and EEG characteristics

Figure 67. *Presenters during the 2018 Dream Engineering Symposium. Organized by Michelle Carr, Pattie Maes, Adam Haar Horowitz and Judith Amores.*

Poster and Demo Presenters

Daniel Erlacher –University of Bern, Switzerland – Utility of scent stimulation for lucid dream induction

Cherysse Ulsa & Katelyn Oliver – Boston University - Nightmares, hyperarousal and trauma

Javier Hernandez - MIT Media Lab - Global Vitals: Physiological parameter estimation from body vibrations

Perrine Ruby – Lyon Neuroscience Research Center - DYCOG team — Incorporation of a spatio-visuo-olfactory task into dreams and learning

Claudia Picard-Deland – University of Montreal – TMR of a VR flying game

Bryan Baxter – Harvard Medical School – Electrical/auditory stimulation for psychiatric interventions during sleep

Alejandro Ezquerro-- Universtiy of Cambridge, UK— Microdream neurophenomenology

Tony Cunningham – Harvard Medical School, Beth Israel Deaconess Medical Center, and Boston College – Sleep, emotional memory consolidation and regulation

Daniel Denis – Beth Israel Deaconess Medical Center & Harvard Medical School – Predicting sleep-dependent memory consolidation from EEG activity during initial encoding

Ryan Bottary – Department of Psychology, Boston College, Chestnut Hill, MA – The role of napping in in-vivo learning experiences

Enmanuelle Pardilla-Delgado – Harvard Medical School Department of Psychiatry – Dream reporting supports gist-based (false) memory processing

Remington Mallett and Ethan Oblak– University of Texas at Austin – Controlling a Brain-Computer Interface from within a lucid dream

Nathan Whitmore – Northwestern University – Using mobile and wearable devices for memory reactivation

Michelle Carr- Swansea University - Zmax - A portable PSG system for lucid dream experiments

Tara and Todd Youngblood--Kryo Inc. - Kryo ChiliPad - full-body temperature-regulation sleep system

Figure 68. *Demos during the 2018 Dream Engineering Symposium. Organized by Michelle Carr, Pattie Maes, Adam Haar Horowitz and Judith Amores.*

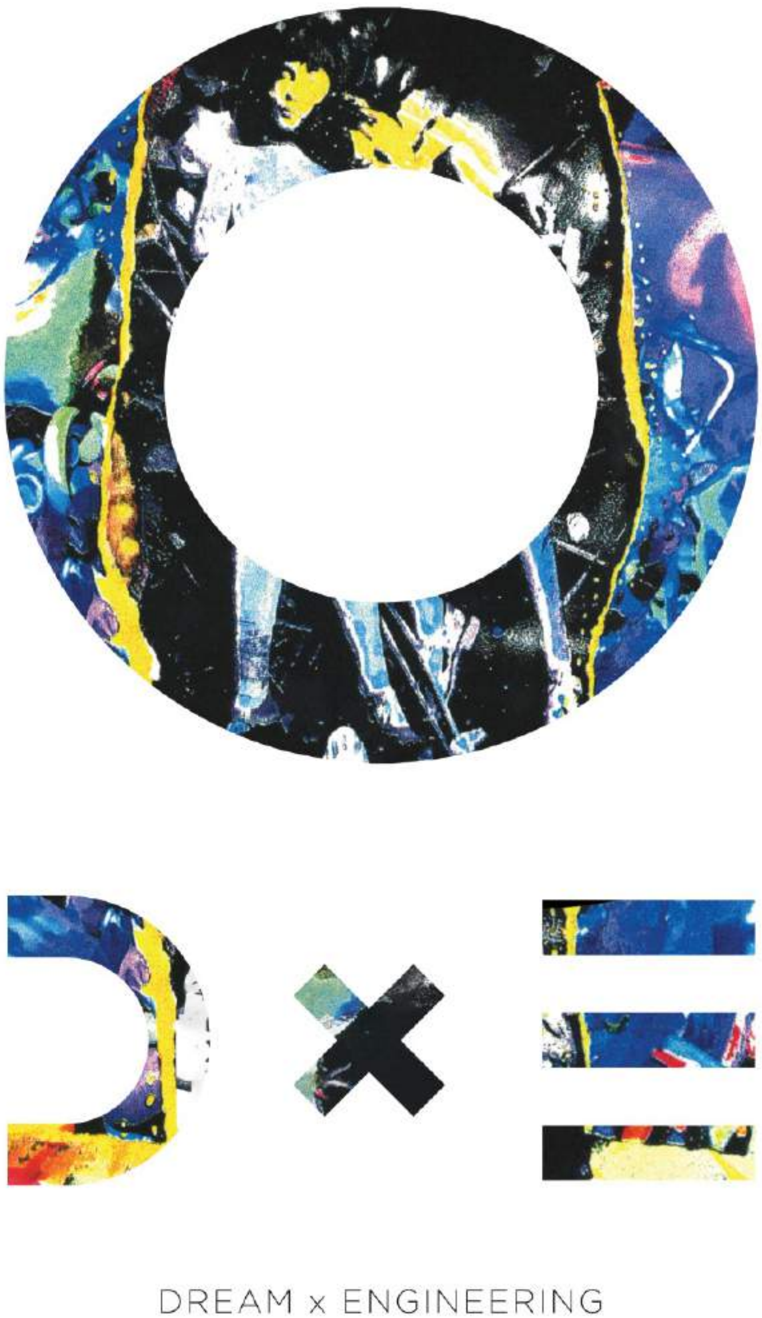

Figure 69. *Logo made for the Dream Engineering Symposium. Collab b/w Bruno Olmedo and Adam Haar Horowitz*

This symposium produced many valuable connections and future collaborations around Dream Engineering, including for the Dormio project. Researchers Dierdre Barrett, Paul Seli, Roger Beaty, Michelle Carr, Tony Cunningham and Pedro Lopes are now all planning experiments using the Dormio device after seeing symposium demos! These experiments range from testing efficacy of serial incubation for creativity in the wild, for influencing daytime contents of mind-wandering, for improving language learning, for inducing lucid dreams, and more. By expanding tests of serial incubation across multiple labs, contexts and application areas we can learn about sleep onset with greater ecological and experimental validity.

Into the Artistic Community

> *"I think of that pygmy legend of the little boy who finds the bird with the beautiful song in the forest and brings it home. He asks his father to bring food for the bird, and the father doesn't want to feed a mere bird, so he kills it. And the legend says the man killed the bird, and with the bird he killed the song, and with the song, himself. He dropped dead, completely dead, and was dead forever."*
>
> — Joseph Campbell, *The Power of Myth,* 1988

Yet 'ecological and experimental' are not the only kinds of validity, especially when we are wading in the waters of artistic expression and dreamt introspection. The aim of my work with dreams is facilitating the rediscovery of the imaginative impulse in others. My own time spent experimenting with my semi-lucidity and listening to the hypnagogic hallucinations of dozens of subjects, has been an inspiration. This experience is valid, and valuable, beyond p values. To study something so magical and to approach it only as material for practical purposes is to overlook something fundamental about dreams.

Dream science and sleep HCI are practices of participant-observation and intuition, a combined first + third person science for, about and by human experience-experiencers.[313] There is a subjective art to this objective science. We stand on a bridge between the current scientific trend of reduce/compute/control and the other aim: of recognizing the irreducibility and beauty and unending movement of complex adaptive human cognitive systems, of developing a sentiment for a dynamic thing in context, of studying at all Marr's levels of analysis.[314] While we break dreams down to definitional pieces to instrumentalize and generalize, we must also recognize that human experience is in a real sense emergent, unbreakable, wholly personal and untameable. Dreams in some sense can only ever be understood by the dreamer, and in another can only be understood by a neutral 3rd party observer. And if we keep these two ways of knowing alive simultaneously, we see so much more. I'm reminded of Jane Goodall, ridiculed for refusing to number her chimps and naming them instead, later praised for seeing their humanity when others couldn't.

> *"Take from all things their number, and all shall perish."*
>
> — Saint Isidore of Seville, *Etymologies,* c. 600-625

The arts are allowed to see these things unseen, to step into and speculate on the many futures that our choices today potentiate. As a Dream Engineering team, Judith Amores, Oscar Rosello and I conceived of a speculative art project called *Cocoon* for the Ars Electronica, to envision a future world where dreams are fully controllable. Our aim was to initiate a conversation around which of many possible future uses for these technologies the audience would choose, and how we could collectively aim our progress. *Cocoon* combined multiple ongoing research projects from the Dream Engineering work ongoing in our lab, making one collective dreaming environment called the Cocoon. In the electronic arts context, we showed a film where subjects stepped into a womb-like container and slept, infused with smell and shock and sound. We then performed live experiments with audience members as well, allowing them to nap in the gallery setting and experience our techniques and technologies firsthand.

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[313] Part of what Daniel Dennett calls heterophenomenology, mixing objective and subjective report.

[314] This is a reference to David Marr, a legendary MIT computer scientist and neuroscientist who advocated for research and explanation of complex phenomena like vision across many levels of complexity, i.e. from how (concrete implementation) to what (complex rules by which it's implemented) to why (the contextual problem it solves in the world).

Figure 70. *A dreamer has sounds, smells and small electric shocks administered overnight to guide their dreams. Image from the Cocoon video project, from the Dream Engineering team.*

Figure 71. *EEG channels are displayed in real time on the Cocoon surface, allowing scientists to survey changing sleep stages. Image from the Cocoon video project, from the Dream Engineering team.*

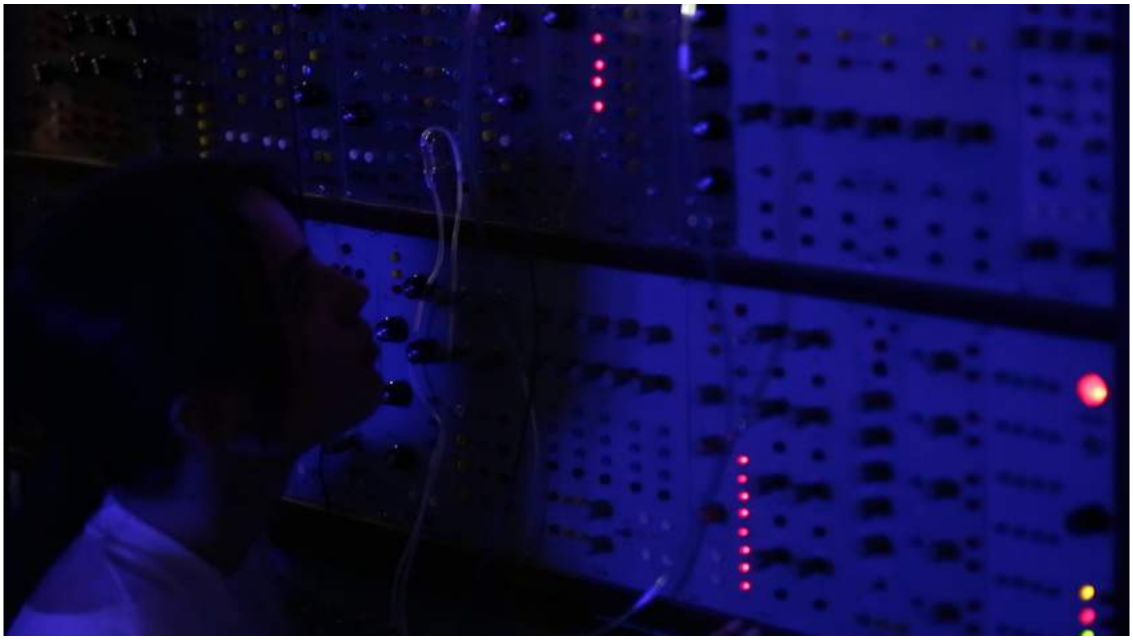


Figure 72. *Based on changes in sleep stages, a surveying sleep scientist changes sound, smell and shock inputs. Image from the Cocoon video project, from the Dream Engineering team.*

Figure 73. *Sleep scientists greet dreamers in the morning, releasing them from programming pods and reviewing dream content. Image from the Cocoon video project, from the Dream Engineering team.*

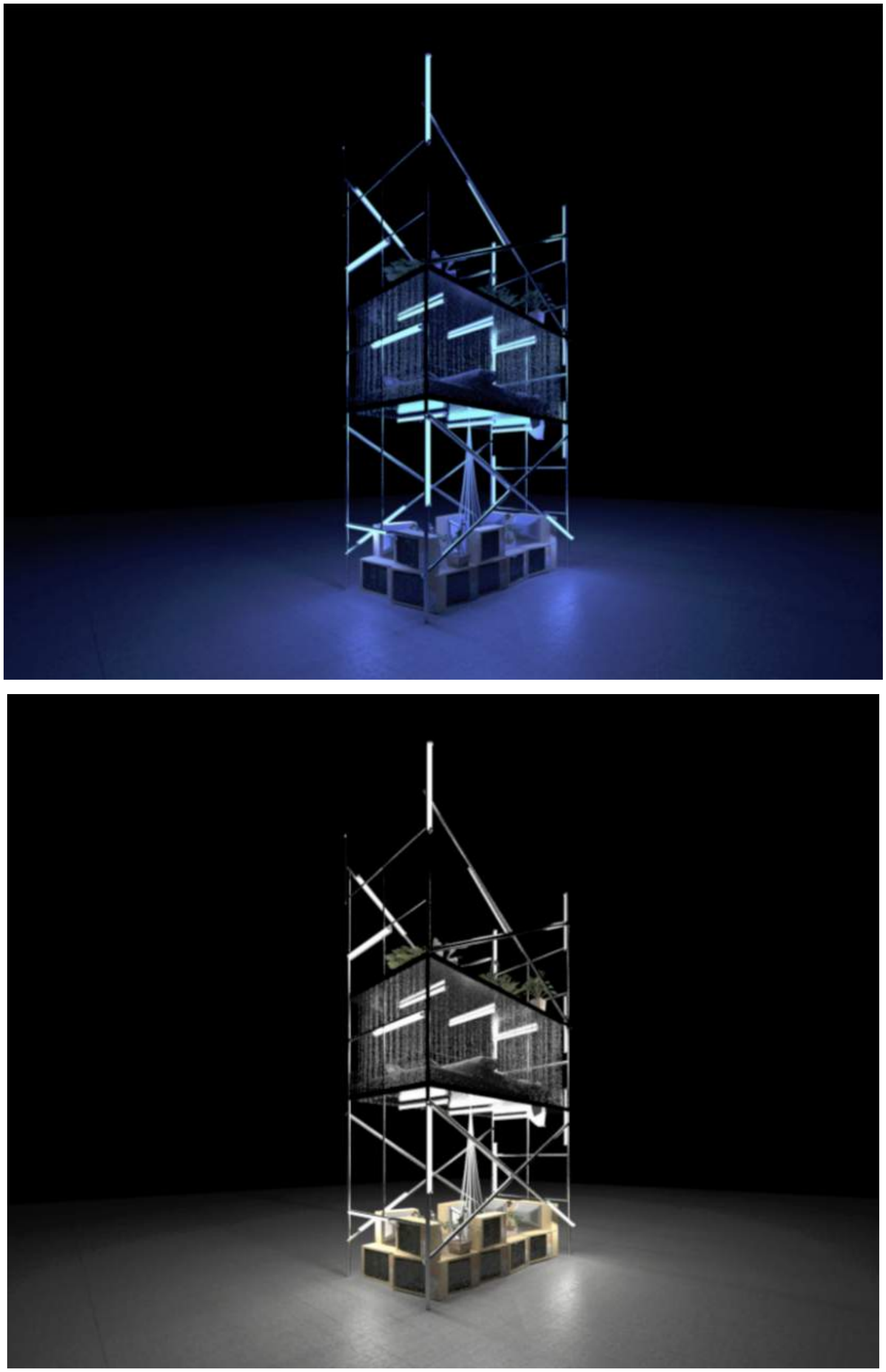


Figure 74. *Renderings of our proposed Live Dream Experimentation Station at Ars Electronica 2018. A bed in the middle platform, signals displayed on the ground floor. Project collaboration with Oscar Rosello, Judith Amores and Adam Haar Horowitz. Renderings done by Oscar Rosello.*

Figure 75. *We traveled to Austria as a Dream Engineering team to perform Cocoon live. From left to right, Oscar Rosello, myself, and Judith Amores.*

Figure 76. *Photos of the actual Live Dream Experimentation Station, with project display. Collaboration with Oscar Rosello and Judith Amores, photo credit Oscar Rosello.*

Figure 77*. Napping in the Live Dream Experimentation Station wearing Dream Engineering devices from the Fluid Interfaces Lab. Collaboration with Oscar Rosello and Judith Amores, photo credit Oscar Rosello.*

The intersection where dream science lies, between signals and stories, between concrete sound or smell inputs and the ingrained algorithms which abstract them in the mind, offer a unique meeting point for scientific regiment and experiential art. The nightly dissolution of our perceptually grounded experience into dreams, and the concrete signals associated with them, link science and the imaginary. *Cocoon* asks a question rather than posing an answer, a necessary kind of humility when building technological interfaces which engage with and alter human experience. The Cocoon video was played at the Beijing Media Arts Biennale 2018, the Ars Electronica Festival 2018, the MIT Museum Compton Gallery, the Harvard Arts@29 Gallery, and National Academy of Sciences 2018 Cybernetic Serendipity show. Each sparked a series of different, and difficult, questions. The integration of the arts into science not as aesthetics but as ontologies recognizes the primacy of intuition and experience, and frames progress as an ethical and contextual choice amongst many speculative options as opposed to a single direction forward.

Ethics

> *"A device is a device, but…it also has consequences: once invented it takes on a life, a reality of its own."*
>
> — Lorraine Hansberry, *What Use Are Flowers,* 1969

This set of experiments is a beginning, a budding idea. It offers evidence for a formula to slip an idea into semi-lucidity, to back away and watch that idea blossom, become. What would the world do with such a tool, if it sat in homes, spoke through Amazon Alexa and Google Home?

In Aldous Huxley's *Brave New World,* hypnopaedia is used to expose children to powerfully suggestive phrases in sleep and groom them for societal castes. In Philip K. Dick's *Do Androids Dream of Electric Sheep,* we see a future where mass media infiltrated our dreamscape. In my time working on Dormio I have been approached by multiple corporations interested in branded dreams and the creation of subconscious emotional ties to products. Any dream direction technology should take seriously the added vulnerability of users who are not fully conscious while engaging with sleep interfaces, and the opportunities this provides for political, personal and capitalist coercion.

In dreams we are suggestible, and often amnesiac to the attempts made to influence us. Creating technology which allows for external direction of thoughts in semi-conscious states brings up hard questions. Who will be in control of dream theme choices? How much will subjects be aware of incubation strategies? During the Dormio experiments, many subjects were surprised at how effective the theme incubation was, having lain down thinking their dreams were by definition uncontrollable. If users are not aware of the degree to which hypnagogic dreams can be directed, they are of course more vulnerable.

I take this concern seriously, and part of my work has been futurecasting, outlining possible futures these devices potentiate and purposefully building towards preferable ones. The Ars Electronica project outlined above is a speculative design project created in collaboration with Oscar Rosello and Judith Amores to envision and film a sci-fi future where clinics incubate dreams in groggy patients with smell, shock and sound, somewhere between an Aldous Huxley and David Cronenberg aesthetic. The video piece sparked conversation on the feelings that this future vision engendered, and viewers voiced concerns about nefarious outside influence on a private part of the psyche.

Hypnagogia, within this question of outside influence, is far less scary than incubation techniques designed for deeper states of sleep. Being semi-lucid in hypnagogia, subjects have transient executive control. Subjects are often aware of the experimental environment, and every auditory report prompt causes an increase in alertness evident in responsiveness to cues, and subjects report that these increases in wakefulness lead to increases in cognitive control. This makes subjects far less vulnerable to outside influence, because every serial awakening is an opportunity for them to refuse to sleep again if they so desire. And one of the key safeguards we have created, from the beginning of the project, is ensuring that Dormio can work without an experimenter involved. The iOS app and web app both prompt people to make their own incubation recordings, and function automatically without the need for a third party in the room. This system is designed for people to influence their own dreams, or for consensual prompting of dreams in an experimental setting. Because of the repeated awakenings, and the design for easy individual use, it seems unlikely this device could be used for political persuasion or Amazon Alexa incubating a pastoral Pepsi-Cola scene.

But Dormio brings up other questions even when used alone. In Christopher Nolan's *Inception*, dreams expose us to personal demons hidden in our subconscious, to painful memories, and can even become an addictive escape from reality. What do you see when you look inside? How can we prevent addiction to or escapism into the dreamscape? Is this really a responsible tool to use alone? These are questions that should be answered before considering scaling up this tool, and will require collaboration between engineers and those with clinical experience at the intersection of therapy, dreams and self-exploration.

> *"Every tool carries with it the spirit by which it has been created."*
>
> — Werner Heisenberg, *Physics and Philosophy: The Revolution in Modern Science,* 1958

Limitations

The Dormio device and the empirical investigations on serial incubation presented here have clear limitations to be remedied in future work. Firstly, the device has not been properly validated with polysomnography, thus while this thesis functions as an **investigation of Dormio-defined sleep onset**, it has not been compared to the gold standard. While classic PSG sleep scoring is inadequate for interfacing with hypnagogia in real time, it would be beneficial to see that the Dormio system at least is able to keep participants in classically defined N1 sleep, beyond our pilot validation.

The hypnagogic hallucinations which are the focus of this thesis, some would contend, are **not true dreams** since they occur in sleep onset and not in definite sleep. While there are no clear lines differentiating hallucinations and dreams, and while the REM=dream equation is no longer widely accepted, future investigation of serial incubation should try and delineate these blurry divisions. Specifically, we should investigate whether serial incubation in hypnagogia leads to inclusion of a dream theme in subsequent REM sleep later in the night. This would establish some continuity between the hypnagogic hallucinations and REM hallucinations, and would establish Dormio as a dream (as opposed to hallucination) incubation machine.

There is a clear question of **report bias and priming**. As the incidence of inclusion of dream themes in dream reports was remarkably high compared to past attempts at incubation, we are concerned that participants were over-reporting to please investigators. Thematic dreams reported here do include typical hypnagogic features, though, a literature which participants are unaware of and phenomenology they would have difficulty fabricating. As to the question of priming, it seems self-defeating to eliminate the effect of suggestion when studying a dream suggestion device. Yet it would be fruitful to compare the efficacy of a single dream suggestion pre-sleep to multiple with serial awakening to see the effect of simple suggestion, or to change the wording from 'Remember to dream of X' to simply 'X' and see if incubation is reduced by reducing the level of suggestibility.

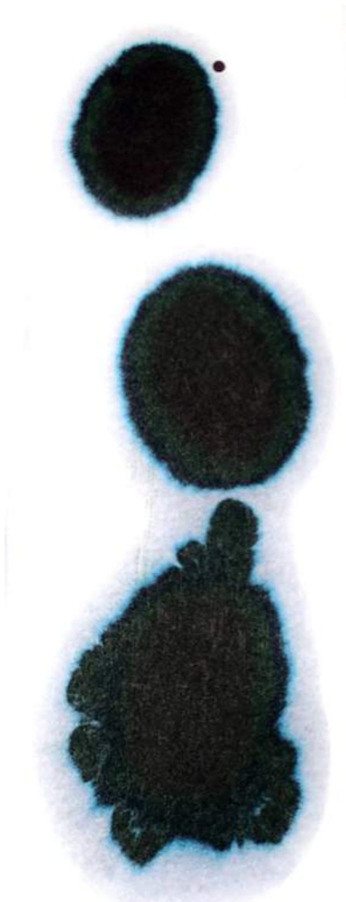
There is an issue of distinguishing what exactly we mean by causal relationships between dreams and creativity, be it **necessary or just useful additional** contributions to post-sleep performance. This current experimental design cannot distinguish between (*i*) Conscious phenomenology is necessary for post-sleep performance improvements and (*ii*) Conscious phenomenology is useful additional activation for post-sleep performance improvements.

During the experiment conducted here an experimenter was always in the room. This meant that audio cues, while triggered by the Dormio system, could always be stopped if the participant was clearly awake and relaxing. These first minutes of lying down often involve movement, hand clenching and initial relaxation, which can trick the Dormio system into an early false detection of sleep onset. For the purpose of this experiment this was safeguarded against by a human eye, which makes the system **not entirely autonomous**. With the data gathered here, we are hopeful that the system is ready for the real world.

While this experiment assessed thematic incubation of dreams, it **did not attempt to influence emotional character**, positive or negative valence, of that theme. Future work must go beyond audio, into scent and sensory stimulation which can alter emotional dream content concurrently.

Creativity assessments here are limited as there are **no measures of convergent thinking** used. As convergent creativity has been suggested to improve in the dream state, it is unfortunate that this set of experiments focuses on one facet of creativity only, and this should be remedied in the future. Further, this thesis does not empirically test relationships between dream content and transformations of emotion, memory, or learning that could be key for future work or contributing factors to the creativity results seen in this thesis.

Within a field which is progressing towards extended notions of the mind as embedded in the body and in the environment,[315] this thesis remains largely focused on thought, expressible with language, in our heads. There may be much more to see with a broader view of intelligence in the body or in situ, but this thesis is limited because it primarily aims to investigate between language spoken to sleepers, written reports of dreams, and language expressed post-sleep.



[315] (Noë 2018; Clark and Chalmers 2010)

Conclusion: It's Just A Dream

The 'Why' Tying Neuroscience and HCI

Since beginning my time at MIT, my focus has been **bridging the gap** between the design of experiential tools in HCI and the study of human experience in the brain sciences to augment introspection and well-being. This focus was borne out of my frustration seeing so few successful cognitive science experiments leave the lab as real world projects, and so few integrated with tech and design to make them accessible at scale. So many projects see significant effects in the laboratory, effects that could ease disorders and open up new avenues of understanding, and are stopped in their tracks by reliance on tools which are immobile, expensive and overly complex.

One of the features of Dormio that excites me most is that it's mobile, inexpensive and simple to use: Each are key features for good **translational neuroscience** tools. There is so much to be mined from neuroscience laboratories that produce validated techniques ripe for technologically mediated translation and application. With this in mind I have tried to speak about my work in broadly accessible terms, in varied spaces to diverse audiences: I reject the notion that expert language is necessarily enigmatic, and try to insist on tools which are as approachable as possible. Because the magic happens at intersections, in interstitial space, formal and informal, with quacks and quants in the hands of the instigators in-between. My interdisciplinary lab, my advisor's expertise across fields, the **hugely diverse and collaborative team behind Dormio** and my own background offer a unique opportunity for creation of new experimentally validated tools for sleep science in the wild. The Dormio device represents one step along the path to use device design to make sleep neuroscience inspired interventions available outside of the laboratory.

Linking HCI and neuroscience disciplines offers ample **opportunities for novel techniques** as well as translation of established protocols: Each tool which expands the possible contexts of a laboratory intervention also expands intervention and experimental possibilities. Wireless, wearable sleep interfaces could augment memory with targeted memory reactivation over months, boost creativity with incubated dreaming ideation at home, ameliorate PTSD with nightmare therapies at the clinic, or augment human health by targeting sleep latency and sleep quality. Sleep HCI presents new exciting challenges, from designing devices for comfort in bed, to tailoring audio intensity to half-wake participants, to designing for ethical implementation and easy use while taking unconsciousness into account. I hope the initial demonstration of feasibility of technologically mediated dream incubation presented here encourages HCI researchers to take on the challenges and inspires a **host of future Dream Interfaces.**

The Dormio system is built not just to bridge across disciplines, but **across time**. Dormio uses modern technology to build upon the 'Steel Ball technique', responding to queries posed by Aristotle and the Old Testament and before them.[316] Today so much of science and technology faces and races only forward, but the study of our subjective experience is nothing new. My past projects focusing on the neural mechanisms of mindfulness made this abundantly clear, where neuroscience has time and time again found the wisdom of spiritual practice and philosophy can precede scientific insight by centuries. Pressing for progress mustn't blind us to rich precedents, and the contemporary primacy of scientific objectivity mustn't blind us

[316] Setting it apart from the Steel Ball technique, Dormio allows for multiple entrances into hypnagogia for an extended interaction experience; has automated methods for dream direction for more user control; has automated prompts for capture of dream reports to enable future dream recall; and allows users to wake up at an adjustable range of levels of consciousness as opposed to solely with loss of muscle tone.

to **older, other ways** of knowing ourselves. I have spent many of my days here reading forgotten papers on forgotten topics — how else to come across a **fertile, fallow field** such as hypnagogia? Probing sleep onset allows us to understand the mechanisms that link daytime and nighttime thought. Investigating hypnagogic creativity allows us to understand cognitive flexibility across the sleep-wake cycle. These are age-old questions, and I hope this technology which builds so clearly from old artistic, spiritual and philosophical practices illustrates the fruitfulness of looking backwards and broadly for inspiration.

> *"There are things you know about, and things you don't… and in between are the doors..."*
>
> — Ray Manzarek, keyboard bassist and co-founder of the Doors, 1967

The questions are old because they are fundamental, archetypal. The study of the brain is a modern take on the age-old tradition of self examination, a science of participant-observers who see themselves in the microscope. And as this seeing is part and parcel with our definition of the self, in gazing down at atoms we risk being atomized in our souls. Much of our science of sleep today treats the sleeping brain as a collection of mechanisms with no self, a bundle of signals with no experience worth probing. Studies of even the most interactive sleep science paradigm, TMR, specifically **avoid interaction with the sleeping self**; they eliminate subjects who report awareness of cues delivered in dreams as outliers.[317]

> *"The lines of communication between the conscious zones and unconscious zones of the human psyche have all been cut, and we have split in two."*
>
> — Joseph Campbell,The Hero with a Thousand Faces, 1949

Yet the beeps and blinks of PSG are **signals for rich self-exploration,** and taking subjective reports from sleep seriously is the only way to tie effector, environment and experience for a full picture of the sleeping brain and mind. Studies linking sleep onset physiology, phenomenology, and post-sleep performance have demonstrated dreamt experience is a valuable window into the function of the asleep brain, but studies which triangulate in such a way are exceedingly rare.[318] These studies are a rejection of eliminative materialism; the idea that the mental vocabulary of psychology is fated to be replaced by the material lexicon of neuroscience. Yet such studies are generally not done because dreamt experience is regarded as the territory of woo-woo folk psychology, and mechanistic dream generators the niche of froufrou elite neurophysiology.[319] The brain sciences have seen the logic in looking past the phrenological focus on particular parts in the study of the brain, but often fall into the same rut regarding specialization in the architecture of research.[320] The braids that bind the experiencing mind and sleeping brain call for work which speaks the language of signals and self simultaneously. I hope that Dormio, creating dialogue across levels of consciousness while grounded in physiology, serves as a binding thread and a tool for cross-examination.

The best comparison I have heard to interpreting research on consciousness is to **training a horse.**[321] As a human, I simply have no solid philosophical grounds on which to prove, or even comfortably suppose, that

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[317] (Cairney et al. 2016)
[318] (Wamsley and Stickgold 2011; Wamsley 2013)
[319] A veritable Butter Battle of the sleep science variety!
[320] "For every parent discipline such as psychology...there is a more fundamental field, an anti-discipline — in this case, brain science – that challenges the precision of the methods and claims of the parent discipline...The parent discipline is larger in scope and deeper in content and therefore cannot be wholly reduced to the anti-discipline...This is what is happening in the merger of cognitive psychology, the science of mind and neural science, the science of the brain, to give rise to a new science of mind." — Eric Kandel, *The Age of Insight*
[321] Thank you to Bob Stickgold and Tony Cunningham for the discussion of this parallel! The ideas reference a New Yorker article from 1986, by Vicki Hearne, titled *Questions About Language I-Horses*

a horse is conscious. It does not speak to me, nor I to it, and if it did, I'd just write it in my dream journal. I thus have no grounds on which to suppose that horse consciousness matters for horse training. But in practice, I don't remotely restrict myself to philosophical solid ground — I speak to my animal as if he has a personality, a memory, preferences, even a moral compass. Equal treats for equal deeds! And if I don't move beyond Skinnerian behaviorism in my horse training and treat this animal as a thinking thing, I will be a worse horse trainer. And that's all I can say — that treating the animal as if it's experience mattered, matters. In the same sense, I have no solid ground on which to prove that another human is experiencing, let alone prove that their experience matters mechanistically. While someone sleeps I can see ERP and EEG and N350 signal changes and these feel solid and definite, serious and defensible. To then ask about their subjective experience which corresponds to such signals, I have to wade into much more empirically wavy waters. To further say that this experience contributes to performance, I must be so far afloat that I'll meet another shore. But I can say that interventions which target experience improve task performance, making claims of efficacy without making claims to understand experience in all it's irreducibility and inscrutability. I can say that treating another human as if their experience matters, matters.

Context is crucial in choosing your set of assumptions with which to see. With the right context, be you horse or head-doctor, the conclusions of this thesis are totally unsurprising:

1. Reminding someone to think about something makes them think about that thing. Reminding them while they're half-asleep, hypnagogic, and still hearing you, works too.
    a. It seems to work better if you remind them multiple times while they're half asleep, instead of reminding them during wake and giving no reminders in half-sleep, as people have tried in the past.

2. Thoughts in hypnagogia are known to be narrative, dreamy, bizarre, and highly associative. Thus, prompting people to think of something specific in half-sleep helps them access and utilize more creative, divergent thoughts about that specific thing.

The Much That Calls For More: Now and Next

"The uses of flowers are infinite."

— Lorraine Hansberry, *What Use Are Flowers,* 1969

Within the context of sleep science and HCI, this thesis makes a big claim: That the flowers, the smoke, the experiential epiphenomena of the fire of adaptive brain processes in sleep, the dreams must be addressed as more than a byproduct. This thesis posits a causal role for contents of consciousness in mediating sleep-dependent benefits for creativity tasks. Evidence that we can experimentally manipulate dream content and cause a significant difference in post-sleep performance suggests the role of dream mentation is more than correlational. Transforming this evidence into many modes of applied dream incubation, along with careful experimentation addressing as many of the listed limitations as possible, is the stuff of future work: new dream interfaces targeting other key sleep signals and other sleep-dependent benefits.

I hope this thesis woke you up a little, and brought you closer to your sleeping self, and woke you up again.

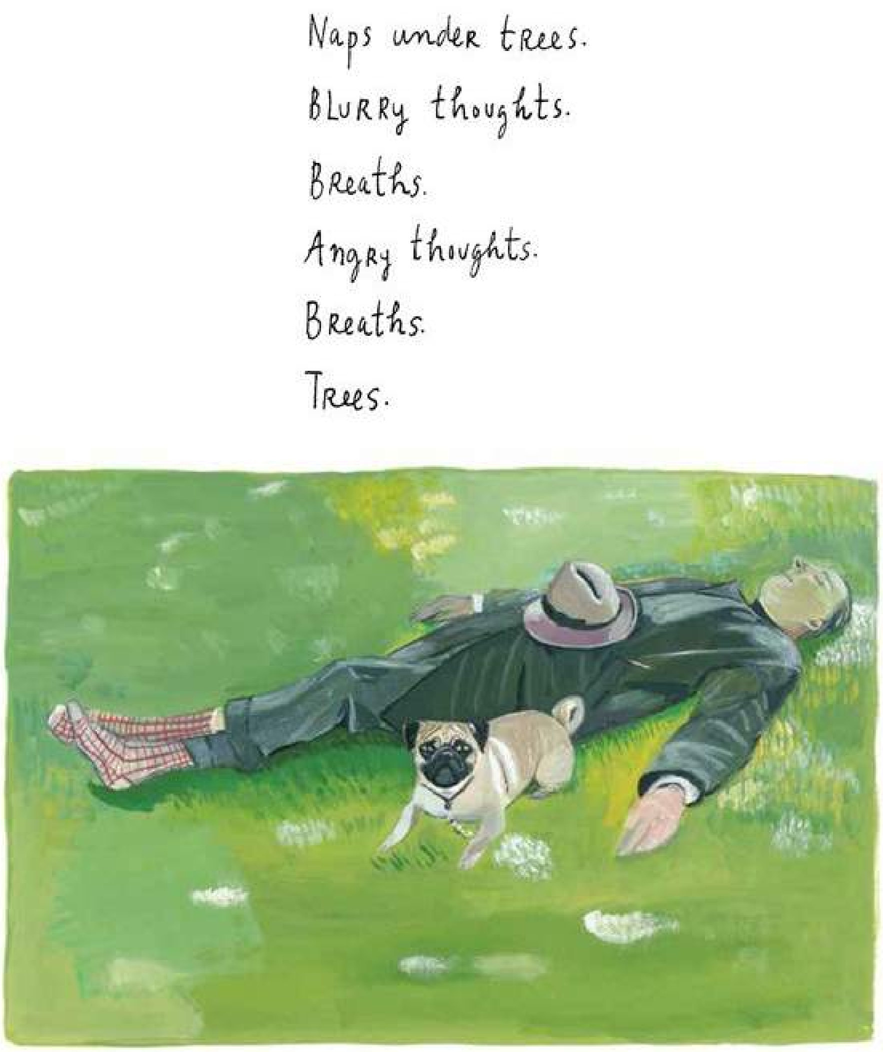

Figure 78. *Napping with trees, painted by Maira Kalman*

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