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Dormio: A targeted dream incubation device

Adam Haar Horowitz[a,*], Tony J. Cunningham[b,c,d], Pattie Maes[a], Robert Stickgold[b,c]

[a] MIT Media Lab, Massachusetts Institute of Technology, Cambridge, MA, United States
[b] Center for Sleep and Cognition and Department of Psychiatry, Beth Israel Deaconess Medical Center, Boston, MA, United States
[c] Department of Psychiatry, Harvard Medical School, Boston, MA, United States
[d] Department of Psychology, Boston College, Boston, MA, United States

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ABSTRACT

Information processing during sleep is active, ongoing and accessible to engineering. Protocols such as targeted memory reactivation use sensory stimuli during sleep to reactivate memories and demonstrate subsequent, specific enhancement of their consolidation. These protocols rely on physiological, as opposed to phenomenological, evidence of their reactivation. While dream content can predict post-sleep memory enhancement, dreaming itself remains a black box. Here, we present a novel protocol using a new wearable electronic device, Dormio, to automatically generate serial auditory dream incubations at sleep onset, wherein targeted information is repeatedly presented during the hypnagogic period, enabling direct incorporation of this information into dream content, a process we call targeted dream incubation (TDI). Along with validation data, we discuss how Dormio and TDI protocols can serve as tools for controlled experimentation on dream content, shedding light on the role of dreams in the overnight transformation of experiences into memories.

1. Introduction

Dreaming is a phenomenon experienced by virtually all humans (Pagel, 2003), and possibly by other animals as well. It is generally thought of as delusional hallucinated experiences during sleep, although research differs dramatically on exactly which of these nightly experiences should be labeled dreams (Pagel et al., 2001). The relationship of dream content to waking life experiences is unresolved, although since the time of Freud (Freud, 1910), it has been thought to relate to events from the prior day ("day residue") as well as older, often related, memories. The mechanism of construction and function of dreams remain essentially unknown.

1.1. Sleep "Hacking"

Studies using auditory, somatosensory, vestibular and olfactory input during sleep demonstrate that sensory processing continues during sleep. This can be seen through the impact of such stimulation on brain event related potentials (Weitzman & Kremen, 1965), the formation of new memories (Arzi et al., 2012), enhancement of prior learning (Rasch, Buchel, Gais, & Born, 2007) and dream content (Leslie & Ogilvie, 1996). This opens up an avenue for simple sensory modulation of brain activity during sleep. Interventions can work at the sensory level via entrainment of cortical oscillations or at the symbolic level via reactivation of memories. Targeted Memory Reactivation (TMR; Oudiette & Paller, 2013) is the best researched sensory-level intervention to "hack" sleep mechanisms at

* Corresponding author at: 75 Amherst St, Cambridge, MA 02139, United States.
E-mail address: adamjhh@mit.edu (A. Haar Horowitz).

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the cognitive level. In TMR, a cue that was previously linked to a learning task during wake is re-presented during sleep to drive specific memory reactivation (Vargas, Schechtman, & Paller, 2019). Using this technique, reactivation of specific memories during sleep can enhance post-sleep memory performance. For instance, presenting humans with auditory cues during non-rapid eye movement (NREM) sleep that were previously presented during the learning of the location of specific objects enhanced post-sleep recall of the targeted locations (Rudoy, Voss, Westerberg, & Paller, 2009).

TMR is believed to target specific memories during sleep, augmenting their sleep-dependent reactivation and consolidation, and has been shown to improve subsequent performance on tests of declarative memory, skill learning, and spatial navigation (Oudiette, Antony, Creery, & Paller, 2013; Shimizu et al., 2018). It may also have an effect on fear networks, as re-presenting an auditory or odor cue during sleep can create stimulus-specific enhancement of fear extinction in mice and humans (Hauner, Howard, Zelano, & Gottfried, 2013; Wixted, 2013). Arzi et al. (2014) suggested that sensory presentation during sleep can lead to the formation of new associations as opposed to simply reactivating existing ones. They showed significant reduction in cigarette smoking when participants were presented with paired odors of cigarette smoke and rotten eggs during sleep, apparently forming a new association between the two. Importantly, this effect was shown following olfactory aversive conditioning during both Stage 2 NREM sleep and rapid eye movement (REM) sleep, but not during wakefulness (Arzi et al., 2014).

But what remains unknown is the experience of the sleeper during this sensory modulated reactivation. As we will discuss, one potential marker of successful memory reactivation is incorporation of the memory or associated imagery into dreaming. This raises questions of whether TMR participants dream about the presented stimuli, and the possible impact of such dream incorporation on the efficacy of TMR. There is, indeed, evidence that sensory stimulation during sleep can impact dream content (St. Denis 1867; Schredl, Hoffmann, Sommer, & Struck, 2014).

1.2. Dreams of daytime learning

A seminal study in the dream incubation literature provides a sense of the phenomenology that accompanies dream incorporation of waking learning tasks, and suggests that such incorporation might be related to sleep-dependent memory consolidation. Stickgold, Malia, Maguire, Roddenberry, and O'Connor (2000) had 27 participants play the computer game Tetris for 5–7 h over 2–3 days and collected sleep onset dream reports from participants over the first hour of sleep each night. Awakenings were performed by the Nightcap sleep monitoring system (Ajilore, Stickgold, Rittenhouse, & Allan Hobson, 1995), and reports were collected as participants were attempting to fall asleep as well as after intervals of 15–180 s of Nightcap-defined sleep (Stickgold et al., 2000). Out of the 27 participants, including 5 amnesiac patients, 17 (63%) reported at least one Tetris-related dream. Out of 526 reports, 64 (12%) contained task-related thoughts or images, demonstrating that specific themes can be induced in sleep onset (hypnagogic) dreams. A follow-up study using the arcade game Alpine Racer showed similar results, with reports of task-related imagery during hypnagogia in 24% of post-training dream reports (Wamsley, Perry, et al., 2010). The Tetris and Alpine Racer studies of hypnagogic replay inspired development of Dormio, a novel device that focuses on dream incubation during hypnagogia, but with exposure to "training" stimuli within the actual hypnagogic period, as opposed to hours earlier.

1.3. Dreams and sleep-dependent memory

Studies that do collect dream reports after task presentation suggest that dream experiences can directly reflect ongoing sleep-dependent memory processing, and 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, hippocampus-dependent memory sources (Baylor & Cavallero, 2001). In contrast, emotional memory is preferentially enhanced by REM sleep, and dream experiences from REM have uniquely intense emotions (Smith, Nixon, & Nader, 2004; Wamsley & Stickgold, 2011). These studies suggest dream reports can provide a valuable window into cognitive processing ongoing in the sleeping brain.

Several studies have found that dream content correlates with post-sleep task performance. Novel learning experiences are incorporated into the content of NREM dreams, which is thought to reflect the processing of newly learned material (Wamsley, 2014; Antrobus & Wamsley, 2017). There is also evidence that dream content drives memory consolidation for recently learned facts and for language learning, with faster incorporation of a newly learned language into dream content positively predicting language learning (De Koninck, Christ, Hébert, & Rinfret, 1990). Morning recall of short stories encoded the night before is correlated with story-related words in dream reports collected during the intervening night (Stickgold & Wamsley, 2011; Wamsley & Stickgold, 2011). The extent to which participants show improved coordination on a tennis video game task is correlated with how richly novel gameplay experiences are incorporated into hypnagogic dreams, but only for early hypnagogic dreams (the first four dream reports), not for late hypnagogic dreams (the last four dream reports) or for daydream incorporation (Fogel, Ray, Sergeeva, De Koninck, & Owen, 2018).

A particularly noteworthy instance of the association between dream content and sleep-dependent memory enhancement is a study associating dream content with spatial memory consolidation (Wamsley & Stickgold, 2019; Wamsley, Tucker, et al. 2010). Participants were trained on a 3D virtual maze task prior to a 1.5-hour nap opportunity or equivalent period of wakefulness. All participants were prompted three times during the 90 min to verbally report "*everything that was going through your mind.*" In the Sleep group, participants who referred to the maze task in their subjective dream reports improved ten-fold at retest compared to Sleep participants who gave no task-related reports. Yet thinking of the maze while awake was not associated with any significant 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 dramatically enhanced memory performance. Unfortunately, the participants who dreamed about the task also performed significantly worse in the pre-nap test, making conclusions about the causal relationship between the dreams and improvement impossible. The difficulty of making such causal claims provided impetus for the development of Dormio.

Importantly, the dreams in this experiment did not veridically "replay" waking experiences of the maze task, but were fragmented and mixed with older memories. Again, this suggests that the experience matches the mnemonic function of the sleep state: The fragmented, mixed experience may reflect that the memory consolidation process is more complex than simply strengthening memories in their original form. Instead new information is integrated into established cortical memory networks, allowing for the extracting meaning, novel associations, and more. Wamsley and Stickgold (2019) recently replicated this study, reproducing results of a significant relationship between task inclusion in dream reports and enhanced performance post-sleep (but see failure to find such effects in Klepel and Schredl 2019; for review see Schredl, 2017).

1.4. Targeted dream incubation (TDI)

Similar to TDI, targeted dream incubation is a protocol for reactivating memories during sleep in a manner that leads to incorporation of the targeted memory, or related memories, into dream content. Previous research, discussed above, indicates that such incorporation is most frequently accomplished during the hypnagogic sleep onset period, and the TDI protocol using the Dormio device described here aims at such hypnagogic incorporation.

Entering hypnagogia from sleep rather than from an extended period of wake also affects the ability to induce such targeted incorporation. The global shifts in brain function that occur during sleep do not reverse immediately upon awakening. The properties of the preceding sleep stage linger, leaving participants in a hypnopompic wake state that maintains some of the preceding sleep state's physiology. Upon awakening, blood flow is rapidly re-established in the brainstem, thalamus, and anterior cingulate cortex, but it can take up to 20 min to be fully re-established in dorsolateral prefrontal cortex, which may contribute to heightened suggestibility (Nir & Tononi, 2010). Experimenters have used this brief window of altered brain function to probe the properties of each preceding sleep states (Carr & Nielsen, 2015; Noreika, Valli, Lahtela, & Revonsuo, 2009; Stickgold, Scott, Rittenhouse, & Hobson, 1999; Tassi & Muzet, 2000). The aim of the current study is to assess the ability of Dormio to identify the sleep onset period and successfully manipulate the content of hypnagogic dream report through pre-sleep verbal prompts. We hypothesize that Dormio will be found to be an effective dream incubation device, with > 50% of awakenings yielding dream reports that incorporate the auditory prime, 'Tree', automatically captured by Dormio's audio recording system. Such a tool would provide substantial control over hypnagogic dream content, enabling more controlled experimentation on the relationship between dream mentation and post-sleep cognition.

2. Material and methods

2.1. The Dormio targeted dream incubation (TDI) protocol

For this initial study of TDI, we have used the Dormio system, which consists of a hand-worn sleep tracker and an associated app, used to communicate with users and record dream reports via bluetooth to a laptop or cellphone. The user interaction with the Dormio system occurs across multiple stages of consciousness including wake, sleep onset, sleep, and hypnopompic wake.

Dormio takes advantage of the window of altered hypnopompic brain function by suggesting a dream theme during each of a series of hypnopompic awakenings, creating a serial dream incubation paradigm. This dream-report system is an adaptive, automated version of the serial awakenings paradigm described earlier that has been used to collect hypnagogic dream reports with repeated awakenings during sleep onset, using either polysomnography (PSG) or the Nightcap (Wamsley, Perry, et al. 2010; Noreika et al., 2009).

Dormio's user interaction is detailed below (see Fig. 1). In its most autonomous mode, 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 reflect on or an emotional issue they

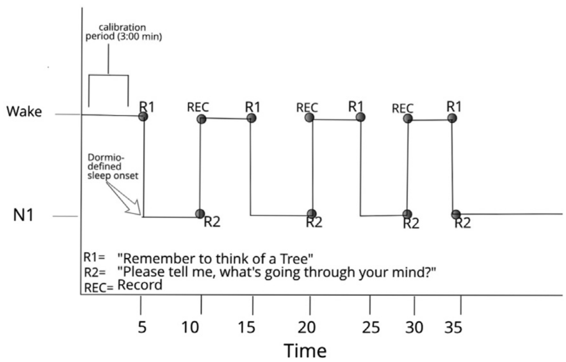

Fig. 1. Schematic of typical use of Dormio to elicit sleep onset hypnagogia and dreaming.

Fig. 2. The Dormio system, in use. Image by ***Oscar Rosello***.

want to develop a new perspective on. The user launches the Dormio app and records a personalized dream prompt message (R1) using their voice, such as 'Remember to think of a tree'. The dream prompt is then played as the user prepares for sleep onset. After falling asleep—an event detected by Dormio— and being allowed to sleep for a predetermined time, Dormio wakes the user and plays the recording to guide their thoughts during subsequent hypnagogia. After receiving the prompt, the user returns to sleep and then, again after a predetermined period of Dormio-defined sleep, is awakened and prompted for a dream report message (R2; 'Please tell me what was just going through your mind'). Their response is recorded, the dream prompt repeated, and they return to sleep. This cycle of sleep, reporting and re-prompting is repeated a predetermined number of times, set by the user (see Fig. 2).

From the moment the user lies down wearing the hand sensor, they are asked to close their hand as they descend into sleep and Dormio begins tracking heart rate, finger flexion and electrodermal activity. As the user begins to drift off to sleep, finger flexion begins to decrease as they forget or fail at this passive behavioral task. 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 sleep onset stages (Hori, Hayashi, & Morikawa, 1994; Tanaka, Hayashi, & Hori, 1999). Passive behavioral measures have been shown to be unobtrusive sleep onset trackers that offer information that can supplement physiological measures (Ogilvie, 2001; Mavromatis and University of Brunel 1983; Casagrande, De Gennaro, Violani, Braibanti, & Bertini, 1997; Prerau et al., 2014). Each of these signals are normalized over a calibration period each time a user starts a Dormio session and are used to identify subsequent Dormio-defined sleep onsets. While the use of serial awakenings may sound strenuous, participants have reported such serial awakenings at sleep onset as positive and relaxing (Hayashi, Motoyoshi, & Hori, 2005; Horowitz, Grover, Reynolds-Cuéllar, Breazeal, & Maes, 2018).

2.2. Dormio sleep-onset detection algorithm

One of the main challenges and contributions of the Dormio system is enabling interaction with hypnagogia without the need for polysomnographic (PSG) sensors. Hori and colleagues have defined nine substages of sleep onset (Hori et al., 1994) based on electroencephalographic (EEG) changes, leaving the line between wake and sleep blurry. The current version of Dormio aims simply to detect the sleep onset period (SOP), without making claims of identifying specific Hori stages or the exact moment of sleep onset.

The Dormio system aggregates data from three measures to predict sleep onset. First, after users gently close their hand when they lie down to sleep, a flex nnnnsensor monitors the slow opening of the hand, with its parallel loss of muscle tone. This passive behavioral measure of flexor digitorum profundus activity has been used in the past for reliable SOP detection (Kelly, Strecker, & Bianchi, 2012; Prerau et al., 2014) and is temporally tied to the onset of hypnagogic imagery (Ogilvie, 2001; Noreika et al., 2015; Prerau et al., 2014). Drops in heart rate and shifts in electrodermal activity (EDA) coincide with this loss of muscle tone and provide further indications of descent into hypnagogic sleep (Penzel, 2003; Penzel & Kesper, 2006; Herlan, Ottenbacher, Schneider, Riemann, & Feige, 2019; Ogilvie, 2001; Carskadon & Dement, 2011). Each of the three Dormio sensors is sampled at 100 Hz. 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 middle 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 (Murphy and Gitman, 2011; Symbol (2014); Boucsein et al., 2012). These three measures are averaged over the first 120 s when the subject initially lies down, and predefined deviations from these mean values are interpreted as Dormio-defined sleep onset. Threshold deviations for each metric, which were taken to indicate sleep onset, were based on pilot data from 5 participants with repeated descent into sleep followed by awakenings and subjective reports of the sleep state (asleep, half-awake or awake) they achieved (Rowley, Stickgold, & Hobson, 1998; Ogilvie, 2001). Based on this pilot data, Heart Rate (BPM) deltas of $>$ 5 BPM, Electrodermal Activity sensor deltas $>$ 4 μSemen or flexor muscle sensor deltas $>$ 8 KΩ were taken as indications of sleep onset. Awakenings were performed whenever one of these thresholds was passed.

2.3. Procedures

We enrolled 50 participants (mean age = 26.71 ± S.D. 7.86 yrs, females = 24) to participate in a daytime napping study. Half of the participants were assigned to each of two groups, the Sleep group and the Awake group. Participants arrived at the laboratory in the afternoon between the hours of 12:00 pm and 4:00 pm. Participants 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 in the wake condition failed to obey experimenter instructions and was eliminated from analysis, leaving a total n = 49.

Participants were told the experiment investigated the relationship between rest and cognitive flexibility, that they would engage in active rest or a sleep, and were offered a sleep mask as compensation for participation in the study. After consenting, participants completed questionnaires on creative self-efficacy, demographic information, and sleep quality. All participants wore the Dormio system, regardless of condition. Experimenters remained in the room with participants, out of sight as participants had eyes closed in awake conditions and wore an eye mask in sleeping conditions.

Participants in the Sleep group were given a 45-min sleep opportunity. Mentation reports were collected throughout this period, after each qualifying sleep onset and instrumental awakening. Participants in the Wake group were asked for 4–5 mentation reports, depending on timing of sensor setup and length of mentation reports taking up experimental time.

2.4. Instructions

The wording of instructions given to participants in administering sleep and dream studies is crucial, especially given that participants are in periods of semi-wake when executive control is transient, metacognitive ability is declining, and dream amnesia after waking is common. 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 (Dement and Kleitman, 1957). But by 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 between 23% and 74% (Rechtschaffen, 1994). Because of the importance of word choice here, each condition is described in detail below and the exact instructions read to participants can be found in *Appendix A*. Experimental instructions were delivered by an experimenter, while audio prompts from the Dormio were delivered via pre-recorded human voice:

Condition 1: Sleep + Tree. A prompted awakening from hypnagogic sleep, using Dormio 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 Dormio, a variable timer was triggered. This timer instigated wakeups from 1:00 to 5:00 min after Dormio-detected sleep onset, to allow participants to experience different depths of sleep. At the end of this time, the computer alerted participants, "*You're falling asleep,*" and asked them to verbally report, "*Please tell me, what's going through your mind*", and recorded their verbal response. Once participants finished speaking, Dormio asked about their sleep state ("*And were you asleep?*"), to which participants could respond 'Awake', 'Halfway' or 'Asleep'. Dormio then instructed them, "*Remember to think of a tree"* and "*You can fall back asleep now*". This loop of events was repeated for 45 min, enabling the collection of multiple hypnagogic reports. At the end of the last loop, the experimenter instructed the participant to wake up fully.

Condition 2: Sleep-Tree. Unprompted hypnagogic sleeps. Dormio functioned as it did in Condition 1, except *"Remember to think of a Tree"* was replaced with *"Remember to observe your thoughts"*.

Condition 3: Wake + Tree. Prompted periods of time-matched wake. Participants 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 min had passed, approximating sleep onset time, a variable timer was triggered from 1 to 5 min later. At the end of this time, Dormio alerted participants and asked them to *"Please tell me what's going through your mind"* and recorded their responses. Once participants finish speaking, Dormio instructed them, *("Remember to think of a tree")*, and repeated the process.

Condition 4: Wake-Tree. Involved an unprompted period of time-matched wake. Participants sat upright with eyes closed. Dormio functioned as it did in Condition 3, except replaced *"Remember to think of a Tree"* with *"Remember to observe your thoughts"*.

2.5. Data analysis

2.5.1. Kruskal Wallis H test

The Kruskal Wallis H rank-order was used to test for differences between groups, followed by *post-hoc* Mann-Whitney *U* Test without Bonferroni corrections (Conover 1971; Hsu 1996; 2004; Daniel 1990). For comparisons of frequency of "Tree" incorporation into reports, the percent of reports with "Tree" references were calculated for each subject, and the calculated values compared across conditions. 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 to minimize Type Two error (Hsu, 1996).

Table 1
Incorporation of tree references into mentation reports.

Condition	Reports	Rpts w/ content	% with content	Num. w/ tree ref	% w/ tree ref	Tree refs	Direct refs	Indirect refs
Sleep + Tree	67	66	99%	45	67%	91	77	14
Sleep-Tree	69	64	93%	2	3%	2	1	1
Wake + Tree	56	55	98%	29	52%	71	51	19
Wake-Tree	48	46	96%	0	0%	0	0	0

3. Results

3.1. Dream incubation rates

We performed serial awakenings of 25 sleep participants, collecting 136 dream reports, 67 from the Sleep + Tree condition and 69 from the Sleep, No Incubation condition. All sleeping participants (25/25) were able to recall at least 1 hypnagogic dream. One subject reported difficulty speaking while in hypnagogia, but uttered short phrases and elaborated on each after their final awakening. We collected a total of 104 wake reports from awake participants, 56 from the Wake + Tree condition and 48 from the Wake-Tree. All awake participants (24/24) gave at least 3 mentation reports from 4 to 5 requests (Table 1).

All dream reports were collected via audio, transcribed into typed text, and were not edited prior to scoring. For the purpose of assessing rates of dream incubation, a direct reference to 'Tree' is defined as an instance of use of the word "tree" or the parts of a tree in a dream mentation report, including "branch", "leaf", or "root". An indirect reference to 'Tree' is defined as use of words indicating themes related to but not directly referencing the object of a literal tree, including "paper", "plant", or "wood". One condition-blind rater counted instances of these specific words used in dream reports. Methods adapted from the Wamsley (2010) Alpine Racer study, which assessed "direct" and "indirect" incorporation of the theme of skiing into dreams.

Condition 1—Sleep + Tree: Out of 67 total verbal dream reports, 45 (67%) contained a total of 91 references to 'Tree' (2.0 per report with tree reference), including 77 direct references and 14 indirect references (Table 1 and Fig. 3).

Condition 2—Sleep-Tree: Out of 69 total verbal dream reports, 2 (3%) contained one reference each, one a direct reference to 'Tree' the other an indirect reference.

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

Condition 4—Wake, No Incubation: Out of 48 total verbal waking reports, there were no direct or indirect references to 'Tree'.

The percent of direct "tree" references varied significantly by group (Kruskal Wallis H test; $H = 29.69$, $p < .001$). A Mann-Whitney U test indicated that the inclusion of direct references to 'Tree' in reports was significantly greater in the + Tree vs. -Tree conditions (+Tree = 62 ± 35%, -Tree = 1 ± 3%, $U = 527.0$, $p < .001$). Additionally, direct references to 'Tree' in reports was

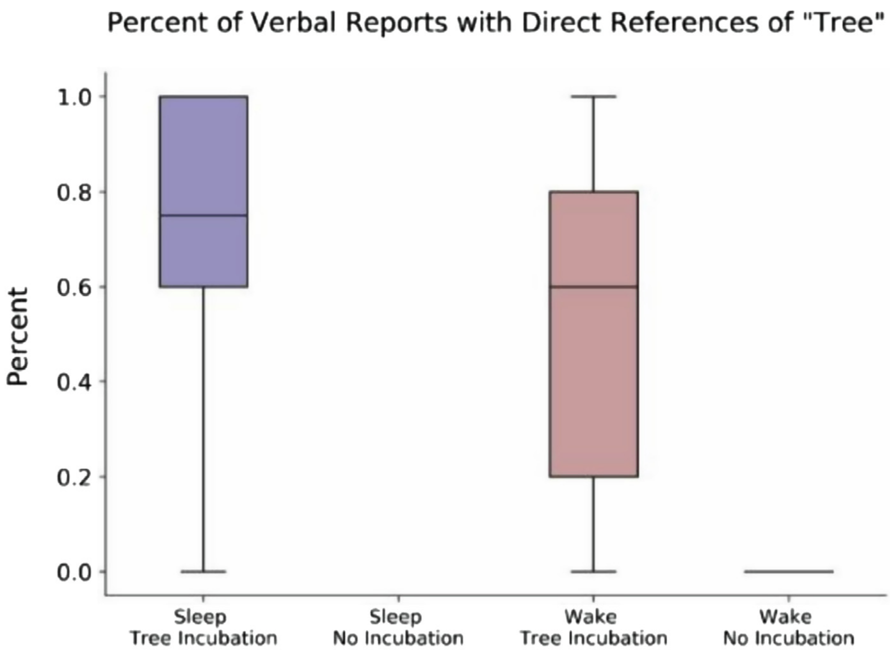

Fig. 3. The percent of direct references to 'Tree' in verbal reports, averaged across participants.

Table 2
Sleep Tree Incubation dream report examples.

	Time of Dream Report	Dream Content
Subject 11	Verbal report given after 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 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	Post-study debriefing	*"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	Post-study debriefing	*"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	Verbal report given after awakening	*"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."*

significantly greater in the Sleep + Tree condition than the Sleep-Tree condition (Sleep + Tree = 67 ± 35%, Sleep-Tree = 1 ± 5%; U = 131.0, p = 0.001) and in the Wake + Tree condition than the Wake-Tree condition (Wake + Tree = 52 ± 36%, Wake-Tree = 0 ± 0%; U = 132.0, $p < .001$). References to 'Tree' did not differ between the Sleep + Tree and Wake + Tree conditions (Sleep + Tree = 67 ± 35%, Wake + Tree = 52 ± 36%; U = 57.0, p = 0.129).

3.2. Dream phenomenology

3.2.1. Sleep + Tree reports

Hypnagogic mentation in the Sleep + Tree group revealed inclusion of the 'Tree' theme into 67% of dream reports that included episodic memories, current concerns, and dream narratives (Table 2). Dream reports increased in bizarreness and immersion with each awakening, but consensual rating of bizarreness was not performed. An example is given below:

Awakening 1: Trees, many different kinds, pines, oaks
Awakening 2: Who I'm going to have over for dinner on Saturday, and occasionally trees, and how I'm not falling asleep
Awakening 3: A tree from my childhood, from my backyard. It never asked for anything.
Awakening 4: Trees splitting into infinite pieces
Awakening 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…"

3.2.2. Sleep-tree reports

Hypnagogic mentation in the absence of priming revealed a range from flashing imagery to fully immersive narrative scenes. Reports often reflected low cognitive control, disinhibition, labile personal agency, acceptance of implausibility, as well as temporal, spatial and proprioceptive distortion (Table 3). An example of a series of reports from one subject is given below:

Awakening 1: The desert
Awakening 2: I was thinking about how someone else would have to fall
asleep here
Awakening 3: the sea, sharks, lots of movement
Awakening 4: clouds and movement
Awakening 5: the mothering feeling…in the middle…safe
Awakening 6: I lost it! I wasn't thinking of anything.

3.2.3. Wake reports

Reports from the Wake + Tree group revealed a range of imagery with low immersion. Reports often pulled from episodic memories or involved prospective planning, and revolved around current concerns or cultural references where trees played a central

Table 3
Sleep No Incubation dream report examples.

	Time of Dream Report	Dream Content
Subject 37	Post-study debriefing	*"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	Post-study debriefing	*"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	Post-study debriefing	*"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 min. I felt it was more likely around 10–15 min. 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	Post-study debriefing	*"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	Verbal report given after awakening	*"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 pig's 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"*

role.

Awakening 1: I'm thinking about an X Files episode where a creature ties people to trees
Awakening 2: I'm thinking about climbing a tree and reading at the top of it
Awakening 3: I'm thinking about walking through orange and almond groves
Awakening 4: the adventure I'm going to have this weekend
Awakening 5: I'm thinking about the tree that the peach grew on in "James and the Giant Peach"

Reports from the Wake-Tree group revealed low imagery, low immersion, high cognitive control, high reference to current concerns and future planning, and numerous references to the ongoing study and lab environment (see Table 4). A series from one subject is given below:

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

3.3. Sleep physiology

One goal of this study was to optimize the physiological thresholds for Dormio-defined sleep onset. Biosignals collected from participants have been used previously to characterize sleep onset (Ogilvie, 2001). The measures of interest were the changes in HR,

Table 4
Wake Tree Incubation and Wake No Incubation report examples.

	Wake Condition	Dream Content
Subject 23	Wake Tree Incubation, Post-study debriefing	*"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 17	Wake Tree Incubation, Post-study debriefing	*"I did get quite bored during the experiment but forced myself to think about things instead of going completely blank, which would cause me to fall asleep. At first I tried to think about the tree right when the voice directed me to. Each time I would think about the trees along the street of my childhood home and how the leaves would change colors in autumn. However, soon after I thought about that my mind would get distracted and I would think about what was really going on in my mind such as, what I had eaten for lunch, who I saw, what music I was listening too. I would also think about my day so far, and my plans for the rest of the day. I felt less inhibited when my mind wandered from thinking about the tree. I would say I only thought about the tree for 30 seconds or less after the voice would direct me to think about it. "*
Subject 42	Wake No Incubation, Post-study debriefing	*"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 40	Wake No Incubation, Post-study debriefing	*"It was very relaxing and allowed me to calm down after a long day of work. I was able to let my mind relax and think more calmly. My thoughts were based on things I was doing or had to do. None of these included a tree. I just kind of let my mind wander without any logic".*

EDA and Flexion from the onset of the experimental session (the moment the a participant lay down, when physiological data collection began) and the first subjective report of 'Sleep' or "Halfway sleep" obtained after each Dormio-iniated arousal, following the participant's mentation report. These changes are compared to the changes seen between the onset of the experiment and the first subjective report of 'Wake' following a Dormio-initiated arousal. Across all participants, sleep onset averaged 10.3 ± 6.4 (S.D.) minutes. Changes in HR, EDA and Flexion were more positive (HR, EDA) or less negative (flexion) for reported 'Wake' than for reported 'Sleep' and in the direction of greater arousal for all three (Fig. 4). To identify potential sleep onset threshold values for each parameter, we calculated the 80th percentile of 'Sleep' values, above which subjects would be likely to report being awake, and the 20th percentile for 'Awake' values, below which subjects would likely report being asleep.

The mean change in HR between experiment onset and first verbal report of 'Sleep': -+2.9 ± 22.9 bpm vs 'Wake': +10.0 ± 18.7. Eighty percent of 'Sleep' reports occurred with changes in HR < 6 bpm, while 80% of 'Wake' reports had ΔHR > -2 bpm. Mean muscle flexion change between experiment onset and first report of 'Sleep': was −6.7 ± 9.0 KΩ vs + 3.4 ± 6.3 KΩ for 'Wake'. Eighty percent of 'Sleep' reports were obtained with changes < -4 KΩ, 80% and 80% of 'Wake' reports were > -6.0 KΩ. Finally the mean change in EDA was −4.0 ± 13.4 µSemen for 'Sleep' reports and + 3.4 ± 8.6% for 'Wake'reports. Eighty percent of 'Sleep' reports showed changes in EDA < 5 µSemen, while 80% of 'Wake' reports were > -1 µSemen.

Physiological Measure	Provisional sleep onset threshold	80th percentile Sleep	20th percentile Wake
ΔHeart rate	> 5 BPM	6 BPM	−2 BPM
ΔFlexion	> 8 KΩ	−4 KΩ	−6 KΩ
ΔElcetrodermal activity	> 5 µSemen	5 µSemen	−1 µSemen

Future studies will look at the predictive power of system thresholds combining these presumptive values.

4. Discussion

4.1. Dormio: The dream incubation device

The Targeted Dream Incubation (TDI) protocol is designed for controlled generation of specific dream content at sleep onset, enabling experiments which probe the causal role of dream content in post-sleep performance. This protocol is available to anyone with an array of sensors that can track sleep onset, as well as deliver and record audio. Dormio is designed to enact this protocol automatically, making the TDI protocol mobile and cheap in comparison to techniques that require PSG. Though the choosing not to use PSG for TDI will likely lead to less specificity in staging sleep onset, given the extensive evidence that sleep onset imagery occurs from early drowsiness into the early minutes of stage 2 NREM sleep (Rowley et al., 1998; Nielsen, 2017), Dormio has a large margin of error for which sleep onset detection can be tolerated without sacrificing the hypnagogic dream incubation goal. This paper presents results suggesting that the Dormio device can track sleep onset with enough specificity and collect dream reports with sufficient reliability to enact TDI, incubating and capturing experimenter-chosen themes in hypnagogic dreams. Results suggest Dormio is an effective dream incubation device, with 67% of Sleep + Tree awakenings yielding dream reports that incorporate the auditory prime, 'Tree', automatically captured by Dormio's audio recording system.

There are significant limitations to keep in mind when interpreting this experiment. The age range of participants is limited, and

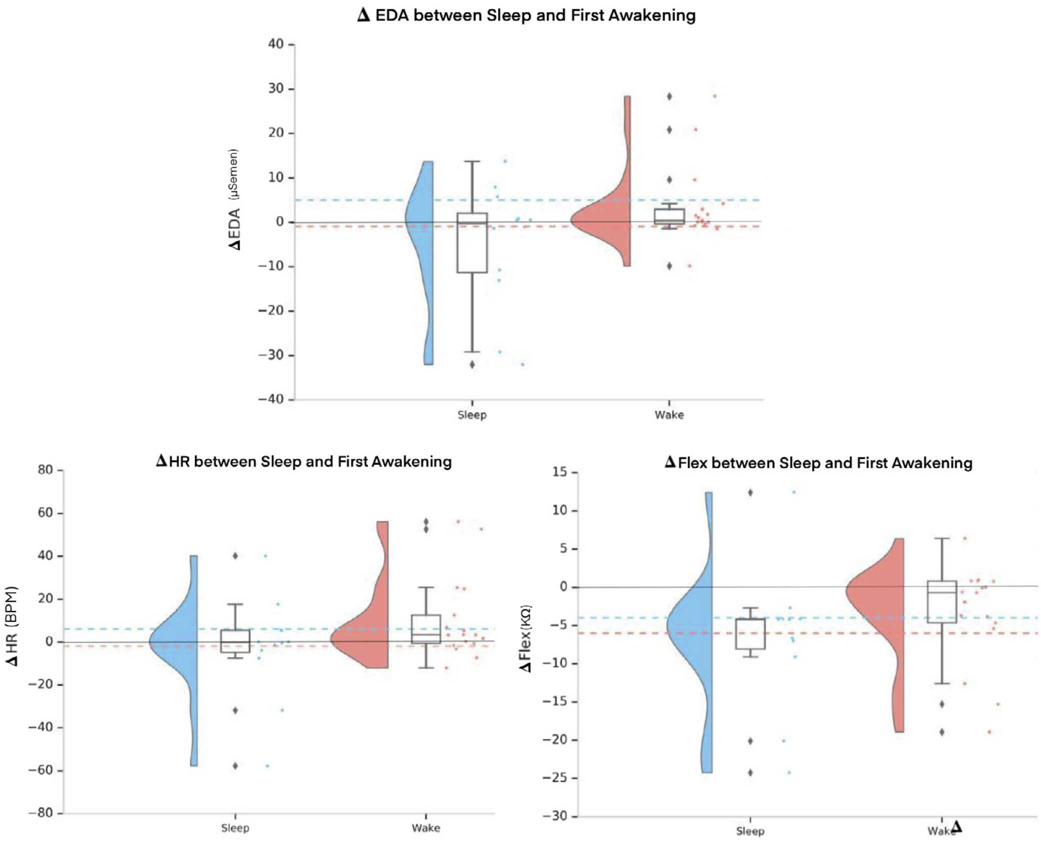

Fig. 4. Distributions in absolute change in HR, Flex and EDA. Measurements are from prior to beginning to try to sleep and first automated "awaken" with a subjective report of having in fact been asleep (left, blue) and the first with a report of actually having been awake (right, red). Blue dotted lines denote the 80th percentile of 'Sleep' awakenings, and hence above which 'Awake' is a likely report. Red dotted lines denote the 20th percentile of 'Sleep' awakenings, above which participants are likely to report having been 'Asleep'. (a) Change in heart rate between Dormio-defined sleep onset and first awakening. 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. (b) Delta in FDP muscle flexion between Dormio-defined sleep onset and first awakening. 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. (c). Delta in electrodermal activity between Dormio-defined sleep onset and first awakening. 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.

all are university-affiliated, yielding a somewhat homogenous population. This study, designed to investigate efficacy of TDI using only Dormio, did not have PSG measurements. This leaves us with little information as to where participants were awoken within the range of the sleep-onset process, and means experimenters must trust verbal reports with regards to sleep onset, which can be unreliable. Further, there is a methodological issue with trusting dream reports, as dreams can be forgotten or fabricated due to demand characteristics. We are aware of these issues in the TDI protocol, and look forward to future techniques which allow for direct capture of dream reports via neurophysiology as opposed to subjective report. Future studies on TDI should use multiple incubation themes, as opposed to our single theme 'Tree', as semantic or syntactic characteristic of auditory primes may influence incubation rates. Regardless of these limitations we think the Dormio device and TDI protocol warrant future study, and enable researchers to ask new questions about dream-related cognitive enhancement.

The potential utility for a device like Dormio to specifically enhance performance on a task pre-determined by the user is tantalizing. Significant correlations between dream content and sleep-dependent memory processing have been reported in several studies, which used a variety of learning tasks, including learning a story (Barrett, 1993; Nielsen & Stenstrom, 2005), a foreign language (De Koninck et al., 1990), word-picture associations (Schoch, Cordi, Schredl, & Rasch, 2019), a visual maze (Wamsley & Tucker, 2010; Wamsley & Stickgold, 2019), and explicit visuospatial memories (Plailly, Villalba, Vallat, Nicolas, & Ruby, 2019), although others have failed to find significant correlations (see Plailly et al., 2019 for summary). Taken as a whole, these studies provide substantial support for the existence of such correlations, although not necessarily for all forms of memory encoding. While correlations have been found, no studies have attempted to show a causal relationship between dream incorporation, and memory consolidation.

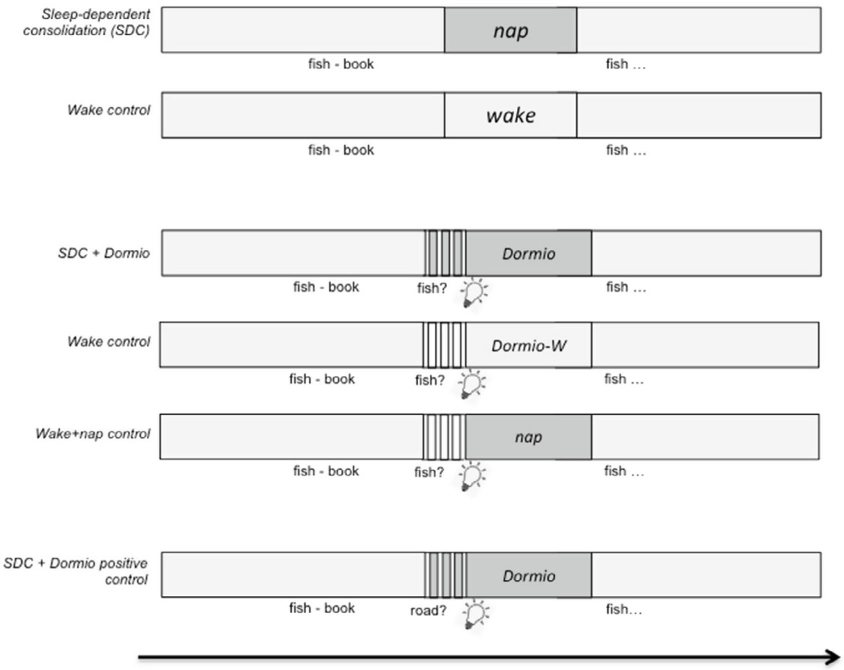

Fig. 5. Experimental design of future study of TDI and sleep-dependent memory consolidation (SDC).

4.2. Uses of targeted dream incubation (TDI)

Establishing a causal link between dream incorporation and sleep-dependent memory processing requires the experimental manipulation of dream content through targeted dream incubation. The design of one such experiment is shown in Fig. 5. This design tests the hypothesis that inducing dreams about the cue in a word pair enhances recall of the associated target word. Comparisons between the dream incubation condition and control conditions could confirm the specific contribution of dreaming about the cue word to subsequent, post-sleep memory enhancement. A similar design could test the hypothesis that inducing dreams about a topic increases creative thinking about the topic: where tests of creative uses of a target item (e.g. “bricks”) are conducted in the post-sleep period.

Considerable anecdotal evidence supports the effectiveness of creativity augmentation using sleep onset dream incubation. Reports by both Thomas Edison and Salvador Dali document its consistently successful applications to the design of inventions and works of art, respectively (Stickgold, 2019). In both of these cases, sleep onset dreams contained explicit images or thoughts that contributed to the creative resolution of complex problems. Similar to the experiences of Edison and Dali, the Dormio device could take advantage of the sleep onset period to incubate specific problems and generate specific solutions. Dream reports collected within seconds to minutes of sleep onset could deliver creative benefits immediately on awakening.

But TDI may also contribute to sleep-dependent memory processing by identifying and tagging memories for further processing later in the sleep period. Evidence for such tagging is found in TMR studies, where memory reactivation during deep NREM sleep (N3) led to enhanced integration of new memories into existing memory networks that was correlated with subsequent time spent in REM sleep, suggesting that TMR during N3 tagged the reactivated memories for subsequent processing during REM sleep (Tamminen, Lambon, & Lewis, 2017). TDI has not yet been explored for the enhancement of declarative memory or other purposes, but TDI at sleep onset might well tag the dream content for processing during subsequent N3 or REM sleep.

4.3. Researching Dreams: “The hard problem”

Correlational studies linking dream incorporation and memory consolidation leave two important questions unanswered. The first of these is whether there is a causal link between the two. For example, Wamsley et al’s study demonstrating a correlation between dream incorporation and improvement on a maze-learning task also reported that those who reported task-related dreams were among the most poorly performing participants at training (Wamsley, Tucker, Payne, Benavides, & Stickgold, 2010). Although the correlation between dream incorporation and task improvement remained significant even after initial performance was added as a covariate, this finding raises the possibility that the correlation is driven largely by factors that separately caused increases in dream incorporation and in task performance. TDI could resolve this issue by demonstrating that the experimental induction of task-related dreaming at the moment of sleep onset enhances sleep-dependent memory consolidation.

The second unanswered question, however, cannot be so easily resolved. In their 2010 paper, Wamsley and colleagues concluded, “it is not our contention that dream experiences cause memory consolidation during sleep. Instead, … dreaming may be a reflection of the brain processes supporting sleep-dependent memory processing" (Wamsley et al., 2010). While TDI may resolve the tightness of this link, it cannot help us know whether dreaming per se, that is the experiential phenomenon of dreaming as a mental event, is critical to this memory processing or simply a functionless epiphenomenon. But despite this remaining ambiguity, the Dormio data described here demonstrates that this device can be used to test whether TDI—targeted dream incubation—can significantly enhance creativity, learning, and memory performance, opening a door to a new era of dream research.

CRediT authorship contribution statement

Adam Haar Horowitz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Tony J. Cunningham:** Writing - original draft, Writing - review & editing. **Pattie Maes:** Conceptualization, Funding acquisition, Resources, Supervision. **Robert Stickgold:** Conceptualization, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors report no conflicts of interest

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Appendix A:

Below are the specific instructions given to the users in each condition. As the instructions are critical to correctly initiate dream incubation and hypnagogic imagery, attempts at replication should closely mirror the instructions below:

Instructions for Condition 1 (Sleep Tree Incubation): *"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 (Sleep No Incubation): *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 (Wake Tree Incubation): *"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 (Wake No Incubation): *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."*

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2020.102938.

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