FOREWORD

Sleep is a complex biological phenomenon at the crossroads of all human body functions. Poor quality concerns 1/3 of the adult population in the United States and European countries (Léger 2005, Roth 2007). Poor sleep has been linked to most of the leading causes of death in the U.S., including cardiovascular diseases and diabetes and its annual cost in the US has been estimated at 411B$ (Rand, 2017). Existing solutions for sleep improvement range from sleep trackers, offering indirect and inaccurate measures of sleep, to addictive sleep drugs.

Rythm is a neurotechnology sleep solutions startup seeking to merge the greatest in neuroscience sleep research and advanced technologies into a consumer product.

We think there is room to develop accurate, efficient and individualized solutions to improve sleep quality. To reach this goal, we are conducting iterative research internally and validating our solutions in a clinical trial setting. We have developed a large portfolio of features to allow our users to find the best fit. Moreover, each feature is continuously optimized and personalized based on the daily sleep data and the measured impact. This process is key to overcoming one of the main problem with sleep: intra- and inter-individual variability.

Dreem is our first product dedicated to improving sleep quality. It integrates features at three key periods of the night: sleep onset, during deep sleep and at wake-up time.

The purposes of this whitepaper are to:
- Give an overview of the technical specifications of Dreem
- Describe the features and the scientific rationale behind each
- Explain the internal test results to assess the efficacy.
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1. TECHNICAL OVERVIEW

Over the past three years, we have developed two versions of an EEG-dry device to monitor and stimulate sleep in real-time. The Dreem First version (beta) WAS launched in September 2016 to 500 selected users, who offered feedback and improvement suggestions for the next version. We validated the performance of deep sleep detection and stimulation accuracy of this version in a clinical trial (Debellemaniere, 2017). After many iterations, we updated Dreem with new sensors and features designed to improve sleep quality.

1.1. Hardware

The Dreem headband is a wireless device which analyses sleep automatically and in real-time. The Dreem headband integrates the following features:

- Sleep induction techniques (SITs)
- Deep-sleep stimulation
- Smart Alarm

Dreem is composed of foam and fabric. An elastic band behind the head ensures that the fit is tight enough to be secure, but loose enough to maximize comfort. An audio system delivers sounds via two bone conduction transducers in the frontal band or through a standard headset jack plug.

Dreem records three types of physiological signals:

- brain activity via electroencephalography sensors (EEG)
- heart rate via a pulse oximeter
- movements and breathing frequency via a 3-D accelerometer

1.1.1 Sensors and audio system

The EEG signal is measured by three electrodes in the frontal band (prefrontal position) and two at the back of the head (occipital position). One additional EEG electrode is used as a bias to allow micro-amplifier to work better. These custom/proprietary electrodes, made in carbon-filled, high-consistency silicone, acquire signals through the user’s hair. A patented mechanical system distributes the...
pressure on the largest area in order to decrease pressure and maximize comfort. The sampling rate is set at 250 Hz.

The pulse oximeter measures the blood oxygen saturation and heart rate via the light reflected by tissue (i.e., reflectance oximetry). This technique relies on the absorption characteristics of hemoglobin. As the heart beats, the blood volume changes slightly and affects the amount of light transmitted through the tissue. The sampling rate is also set at 50 Hz. The 3D accelerometer is embedded in the top of the headband to ensure accurate measurements of the user’s head position and breathing frequency during the night. The sampling rate is set at 50 Hz.

Two bone conduction transducers are positioned in the frontal band on the right and left sides to maximize sound quality. The transducers are among the smallest on the market, and provide limited sound distortion.

1.1.2 Electronics

Dreem embeds miniaturized electronics in order to run calculations onboard while maintaining low-cost energy and ultra-low latency. This also allows Wi-Fi and Bluetooth to be deactivated during the night.

Schematically, the EEG, accelerometer and pulse oximeter are filtered analogically and converted for subsequent digital signal processing in the acquisition board and calculation board. A nonlinear combination of these signals is computed for optimal robustness yielding a reference “virtual signal”. Up to 1.6MB per second of sensors data signal can be analyzed. An ultra-efficient power management of only 275 mW (on average) allows the system to have a consequent autonomy of more than 10 hours.

Real-time algorithms are coded via low-level embedded software requiring very low latency in execution time. Learning algorithms for prediction and classification are trained and optimized offline on our servers before being incorporated and updated in the embedded code. Audio execution latency (25ms) is incorporated and compensated when running stimulations. Active features include sound modulation based on EEG and respiratory signals, phases and periods.
1.2. Software

1.2.1 Signal Analysis in Real Time

**ALGORITHM PIPELINE**

Signal analysis is processed in real time on the headband’s low-power processor (ARM CPU). The headband acquires signals from the following outputs:

- 4 simultaneous EEG channels, each sampled at 250hz
- 3 accelerometer channels, sampled at 50hz
- 2 pulse oximeter channels signals, sampled at 50hz

Each piece of data is cleaned, processed and analyzed to ensure correct usage for features.

Schematically, the data of every channel has been pre-filtered by the electronics part (see above). Then, each channel’s data are processed independently, then combined and used to predict sleep stages and execute active features. The signal-processing parts are based on Fourier and wavelet transform filtering as well as signal combinations and the analysis detects sleep stages or sleep patterns.

**EEG MODULE**

Two of the four EEG channels are acquired by measuring the difference of potential between occipital and prefrontal electrodes (Fpz-O1 and Fpz-O2). The other two EEG channels are acquired by measuring the difference of potential between the two prefrontal electrodes (Fpz-F7 and F8-F7). Different types of information can be extracted from these signals depending on electrode locations. The four EEG channels are filtered in real-time in the frequency band of sleep data. The quality is assessed, and noisy signals are removed from the analysis. Specific sleep patterns such as spindles, K-complex, alpha rhythms, slow oscillations and blinks are detected in real-time, and EEG features are extracted for sleep stages classification.

![Figure 4: Overview of the real-time digital processing pipeline applied to each data sample](image)

![Figure 5: Overview of real-time EEG analysis](image)
ACCELEROMETER PROCESSING
The specific position of our accelerometer (on top of the headband) provides more informative data than if it was located on the wrist. Movements and head positions are analyzed on three accelerometer axes. The data is filtered in the respiration data frequency range, then combined with an online Principal Component Analysis to detect respiratory oscillations and frequency.

PULSE OXIMETER MODULE
Pulse oxymetry is a noninvasive method for monitoring someone’s oxygen saturation. The infrared pulse oximeter signal is filtered, and heartbeats are detected in real-time. The heart rate is useful for night analysis because its variability during the night indicates transition between sleep stages. Heart rate also provides inputs on the sleep onset process.
1.2.2 Offline Analysis

Once records are uploaded to Dreem servers, a team of sleep experts manually label the signal on random recordings, assigning the right sleep stage to individual 30-second epochs of EEG recordings. Internally, we annotate two-second portions of the same signal that display adequate quality. This process is realized periodically to generate annotations for our algorithms.

Both annotations are used to form two datasets, one for quality purposes and another for sleep stages prediction and EEG patterns detection. Each dataset is cleaned and filtered in sleep-specific frequency bands to order to be input into in-house AI (machine learning and deep learning) algorithms. These combine expertly-crafted features and raw measurements to build predictive models for signal quality prediction, sleep stage classification and EEG patterns detection. Special attention ensures models are optimally fitted to generalize well on new records thereafter. A set of custom tools allows our sleep experts and AI specialists to examine in detail large amounts of sleep data. An example of such a tool is a signal viewer depicted in the following figure.

Figure 8: The “Signal Viewer”, a tool developed by Rythm to visualize and interact with raw sleep data and computed labels.
1.2.3 Mobile App

Dreem interfaces with a mobile app which serves two purposes:

i. The app is the headband’s graphical user interface, allowing the user to:
   a. select night settings such as sleep-inducing features or the Smart Alarm
   b. display live EEG signal and heart rate data
   c. launch a sleep session

ii. The app acts as a “sleep coach” by providing useful metrics and insights about the user’s sleep. At the end of each record, the headband provides the app with a night report, which includes a set of metrics computed in real time. Key metrics are displayed in the app to the user, including:
   a. hypnogram
   b. sleep-onset duration
   c. sleep duration
   d. wake-up stage
   e. sleep score (proprietary way of describing a night’s quality on a 0-to-100 scale)

The night report is also uploaded to Dreem servers. New data is combined with metrics from the user’s previous nights to update a set of aggregated metrics and baselines that feeds algorithms generating sleep cards. Sleep cards are personalized sleep tips or contextualized metrics. The app displays customized sleep cards to the user every morning.
2. DREEM’S FEATURES

Dreem’s current features focus on three crucial periods of the night: sleep onset, deep sleep and wake up. Future features and techniques will be released in the future so users can develop a personal portfolio of features that fit best for their usage. This section highlights these initial features and their scientific rationale.

![Figure 10: Dreem’s features during the night](image)

2.1. Sleep Induction

Difficulty falling asleep is a frequent sleep-related complaint amongst the general population (Roth, 2007). The transition from wake to sleep is characterized by a modification of EEG frequencies with fewer beta and alpha rhythms and more theta rhythms. Concomitantly, heart rate and breathing decrease and stabilize their rhythms, facilitating this transition. In general, healthy sleepers often take 15 minutes or less to fall asleep. However, the National Institute of Sleep and Vigilance reports that 28% of a representative sample of French active population took 30 minutes or more to fall asleep on average (INSV 2016).

Common causes are physiological (e.g., hyperarousal), psychological (e.g., ruminations) or behavioral (e.g., bad sleep hygiene). The diversity of these factors therefore requires an individualized approach.

Dreem treats the behavioral cause of insomnia with sleep coaching (see 1.2.3.). Today, sleep coaching, or cognitive and behavioral therapy, is considered the reference treatment for insomnia (Rieman et al., 2017).

In the following paragraph, we will detail the four techniques that we have developed to help reduce time to fall asleep: Cognition, Ambiance, Respiration and Meditation. These techniques rely on the real-time analysis of physiological signals which are then influenced by audio feedback, overall forming a closed-loop system. They have been designed to cope with the physiological and psychological causes of insomnia.
2.1.1 Cognition

Cognitive hyperarousal due to stress increases sleep onset latency. It can be acute stress or stress due to not having enough time to sleep. Moreover, actively trying to fall asleep becomes counterproductive. If the mind is distracted by a demanding cognitive task to balance the bad thoughts generating their waking state, the person may fall asleep faster (Beaudoin, 2014).

The principle of the Cognition technique is to stay focused on a sequence of words played by the Dreem headband. These words might be played with relaxing background music. When we can see in the brain activity that the user is starting to fall asleep and his attention is decreasing, Dreem stops playing the sequence of words but continues to play the background music. When the user is completely asleep the background music also stops.

2.1.2 Ambiance

The Ambiance technique uses audio environments (musical or natural) that are associated with sleep and relaxation to facilitate falling asleep. At the beginning of the exercise, salient audio content related to the chosen environment is added to the music background to avoid circular mental rumination. Gradually, based on brain activity changes, sounds fade and only the background remains, only stopping when the user is completely asleep.

2.1.3 Respiration

It is well known that breathing deeply and holding your breath for few seconds increases physiological response of parasympathetic system. Interestingly, it has been shown that theta rhythms, characterizing sleep induction phase, are more frequent with parasympathetic activation (Kubota et al., 2001).

During Respiration, the user breathes at a specific pace indicated by the Dreem headband. Initially, alongside relaxing background music, a sound (e.g. a wave) is synchronized with the user’s breathing activity. After a few cycles, the headband progressively slows its pace based on the user’s breathing patterns. Most of the time the users follow the new pace unconsciously.

Respiration can be useful when the user feels some stress or tension, and focusing on their respiration at the beginning of the exercise also helps to distract the user’s mind. The sounds gradually fade when the Dreem headband detects the user is falling asleep or the user may stop this technique themself when they feel ready to fall asleep.

2.1.4 Meditation

Meditation is often characterized by a hypometabolic state with parasympathetic dominance. Theta rhythms can be also observed in deep meditation states (Young et al., 1998). It has been shown that long-term practitioners of meditation change their brain activity during deep sleep and REM sleep (Mason et al., 1997). Thus, meditation is a good option for influencing physiologic and behavioral states prior and during sleep.

In Meditation, alongside background music, vocal instructions invite the user to focus on their body’s physical sensations. Successively the user is asked to concentrate on their breathing with biofeedback or on different body parts. Periods with no vocal instruction are integrated to give the user time to focus and measure their physiological state with Dreem sensors. If the user is falling asleep the next vocal instruction is not played and only the music background continues until the user is completely asleep. Meditation is for users feeling tension in their body however focusing on the vocal instructions also helps to distract the user’s mind.
2.2. Deep Sleep Stimulation

Interestingly, when sleep is restricted, the most preserved stage is deep sleep, also named slow-wave sleep due to a brain signature: the “slow oscillations” (SO). SO correspond with a strong synchronous oscillation (from 0.75 Hz to 2Hz) between many neurons in the thalamo-cortical loop (Massimini et al., 2004). In a recent study on sleep restriction (Rabat et al., 2017) it was shown that when the duration of sleep was reduced by a factor two (i.e., four hours of sleep per night for five consecutive nights), deep sleep duration was only reduced by a factor of 1.15, whereas the duration of other sleep stages was reduced by a much higher factor (3.75 for N1, 2.8 for N2 and 2.5 for REM sleep).

The central role of deep sleep could be explained by the physiological mechanisms occurring during deep sleep. Some research indicates a strong relationship between slow-wave sleep and brain clearance (Xie et al., 2013) or with insulin regulation (Tasali et al., 2007).

Due to the crucial role of the deep sleep stage, its enhancement has been intensely investigated by academic researchers during the last decade. Techniques used range from pharmacological stimuli (Walsh et al., 2006), transcranial electric stimulations (Marshall et al. 2005), transcranial magnetic stimulations (Massimini et al., 2007) and audio stimuli (Ngo et al. 2013, Ngo et al. 2015, Papalambros et al. 2017, Cox et al. 2014, Leminén et al. 2017).

This latter technique has emerged as a noninvasive way to enhance deep sleep slow oscillations. While random night sounds may perturb sleep, stimulating the deep sleep slow oscillations periodically strengthens slow oscillations. Indeed, studies have reported an increase of them amplitude when stimulated at precise moments. The phase of slow oscillation stimulation is important and requires accurate monitoring to stimulate within a few milliseconds optimal window. Behaviorally, some studies have reported that this enhancement of slow oscillation can increase memory consolidation. New techniques, such as targeted memory reactivation (replaying during deep sleep words learned during the day), seems also to be promising for improving memory consolidation, but is not implemented currently on the Dreem headband.

The Deep Sleep Stimulation feature of Dreem consists in stimulating the slow oscillations automatically detected by the Dreem headband, with auditory stimulations, in order to boost their activity.

![Figure 11: Effect of the auditory stimulation on deep sleep. The red vertical lines represent the audio tones. After the stimuli the slow wave activity increases and the sleep is deepened.](image-url)
To produce auditory stimulations at a precise moment, Dreem implements a complex pipeline of operations (see Fig. 12 A, B, C, D and E right).

Three checks are needed before sending stimulation:

- The quality gate allows the signal to proceed to the next stage if it reaches a threshold quality (Fig. 12B). This quality detector is a machine learning predictor (forest of decision trees) applied to a binary classification task on a large database of 2 seconds windows, labeled by sleep experts to specify which parts of the signal correspond to good or bad quality signal.

- The channel switcher selects the channel with the highest quality (Fig. 12C). This selected channel is referred to as the ‘virtual channel’. A hysteresis switcher avoids frequent switching from one channel to the other, if they have similar qualities.

- The N3 sleep gate classifies 30 seconds windows of ‘virtual channel’ in N3 sleep vs else (Fig. 12D). This N3 sleep detector is composed of a machine learning predictor (forest of decision trees) fed with numerous features computed on the ‘virtual channel’ and on the accelerometer. If the signal is detected as N3 sleep and meets hard conditions (applied to avoid awaking the user), then it is broadcasted to the next stage. In other sleep stages, the data is not sent to the stimulation stage and no stimulation can be played. Notably, Dreem does not stimulate if the quality of both channels is bad.

Figure 12: Simplified representation of the pipeline of operations to produce deep sleep stimulation.
2.3. Smart Alarm

Sleep-to-wake transition cannot be characterized as an immediate change from one state to another, but instead as a progressive transition that takes some time to complete (Ferrara et al., 2000). The characteristics of this transitory phenomenon, called sleep inertia, involve many factors, including prior sleep duration, time of day and sleep stage at the awakening time. Obviously, sleep loss and drugs also have an impact on sleep inertia. In some professional arenas (e.g., drivers, pilots, etc.), sleep inertia can induce dramatic consequences.

Although most studies focus on sleep inertia after short naps, they show that abrupt awakening during light sleep produces less sleep inertia than abrupt awakening in deep sleep (Cavallero et al. 2003, Tassi et al. 2001). Both subjective (e.g., sleepiness) and objective (e.g., attentional performance) measures are impacted by wake-up sleep stage.

The Smart Alarm feature is designed to implement these findings to wake the user at an optimal time. Classic alarms wake the user at a preset time, regardless of a user’s sleep stage. The Smart Alarm, on the other hand, tracks light sleep to wake the user in this stage if possible, within a 20-minute window before the preset time.
3. TESTING & EFFICACY OF DREEM’S FEATURES

3.1 Testing

We tested the Dreem features in the following three separate contexts: Clinical Trial, Dreem First beta Program, Internal Tests.

3.1.1 Clinical Trial

A randomized, crossover and double-blind clinical trial has been conducted at the Hôtel-dieu Hospital sleep center, in Paris, from September to November 2016. The main objective was the performance of Dreem to detect N3 sleep automatically and to send auditory closed-loop stimulations on SO. Test were conducted on 20 young healthy subjects who slept with both Dreem and a miniature commercial polysomnography device in both stimulated and sham nights. Three experimental conditions were performed:

- Ascending condition, where auditory stimulations were delivered in synchrony with the ascending phase of slow oscillations during the N3 sleep stage.
- Sham condition, where the device was worn though no auditory stimulations were delivered.
- Random condition, where auditory stimulations were randomly delivered during the N3 sleep stage.

The results of this clinical trial have been submitted in peer-reviewed journal (Debellemamerie et al., 2017). 20 young healthy subjects for a total of 60 nights have been analyzed (35% women, averaging 23 years old).

3.1.2 Dreem First Program (Beta program)

This observational study included 500 users selected to represent our customer base (83% men, average age 43 years old, 31% with sleep problems) from November 2016 to June 2017 (criteria detailed in part 3.2). During this Beta program, we:

- Tested the efficacy of the Deep Sleep Stimulation (N = 90 users for a total of 1000 nights).
- Tested the efficacy of the Smart Alarm (N = 230 users for a total of 3980 nights).
- Gathered user feedback on product use.

3.1.2 Internal Preliminary Tests

From March to August 2017, we assessed the efficacy of newly-developed sleep induction techniques of Dreem on users representing our customer base. These preliminary tests have been conducted on 11 users in a first exploratory campaign designated to quickly improve Dreem’s feature. A second campaign on N=15 users (2/15 women, averaging 40 years old, 60% with poor sleep quality), assessed the efficacy of Dreem’s features on industrialized pre-mass production units of Dreem at home for a total 132 nights.
3.2. Efficacy of Dreem’s Features

3.2.1 Deep Sleep Feature

This feature has been tested in a Clinical Trial and during the Dreem First Program.

In the Clinical Trial the ability of the algorithm to target the positive half-wave (i.e. the ascending phase) of the slow oscillation was tested. All the stimulations were summed up in a circular “polar plot” histogram by using a zero-phase digital filter with transfer function coefficients of a second order band-pass Butterworth filter in the delta band (0.4 to 4Hz). The phase angle at each pulse delivery was identified and a Hilbert transform was applied on the EEG signal to identify the instantaneous phase at each pulse delivery. Circular histograms were created with 72 bins of 5° where 90° represents the peak of the upstate and the ascending targeted phase of stimulation delivery 45°.

The Dreem First Program has been conducted to assess the electrophysiological impact of the stimulations on the EEG after 1 and 10 consecutives nights to increase the statistical power by the important size of our sample (90 subjects, 10512 stimulations and 9872 sham triggers). To filter out the inherent bad recordings in the Dreem First Program, due to the home environment which is not as controlled as in laboratory, the nights have been selected based on the following criteria:

- recordings with a minimum duration of 5h,
- a minimum effective sleep time of 3h with a good EEG signal quality (higher than 60% of the time)
- to avoid the impact of outliers, recordings without N3 sleep or with more than 3h of N3 sleep were removed from the analysis

The power increase in the delta band was computed between stimulated and non-stimulated slow oscillations. More precisely, we computed the delta power in the 0.4 to 4 Hz frequency band in a 4s window after the first stimulation (or sham) in each train of 2 stimulations (or shams). We used the squared norm of the discrete Fourier Transform of the 1024 time steps after the first trigger convolved with a Hann function. This provided 2 distributions of delta power: one after stimulations and one after sham. We then computed the percentage of increase between the mean of these two distributions. The significance threshold was set at p<0.001.

Results

The average time of stimulation for the 7059 pink noise at the ascending phase was 45±52°.

The targeted phase was 45° which represents the middle of the ascending slope. 90 degrees corresponds to the peak of the up state, 270 degrees to the trough of the down state. Across all nights and all stimulations a total of 10512 stimulations were considered.
stimulations and 9872 sham triggers were displayed, the power increase in the delta band in the 4s following the first stimulation was of 39.5 % when stimulating as compared to sham triggers (Fig. XX). This increase of slow oscillation response to auditory stimulations remained at the same level after 10 consecutive nights.

To sum up, the stimulation accuracy is state-of-the compared to studies led in sleep labs (Cox et al. 2014, Ju et al. 2015, Papalambros et al. 2017). We confirmed previous findings on a local effect of auditory stimulation reported in the scientific literature (Ngo et al. 2013, Leminen et al. 2017, Ju et al. 2015, Papalambros et al. 2017, Cox et al. 2014). This increase reflects an higher neuronal synchrony during slow oscillation that has been linked to a slight memory consolidation enhancement (Ngo et al. 2013, Leminen et al. 2017, Papalambros et al. 2017). We reported a novel finding which is the absence of adaptation effect after 10 consecutive nights of auditory stimulations.

**Figure 15 A**: Averaged power in the delta band in the 4s following the 1st stimulation (Stim) or sham trigger (Sham). **Figure 15 B**: Averaged electrophysiological response time locked to the first stimulus for the stim (orange line) and sham (blue line). **Figure 15 C**: Resulting ERP of the 1st (light blue line) and 10th night (purple line) stimuli where the “1st night” and the “10th night” refer to the difference between the stim and the sham of the first and tenth night respectively. Black line indicates the stimulus trigger. Black bars indicate time points where differences between the two conditions were statistically significant (p<0.001).
3.2.2 Efficacy of Smart Alarm

The objective of Dreem’s Smart Alarm is to wake the user up in a good sleep stage within 20 minutes of the user’s pre-set alarm time. Good sleep stage refers to a stage of light sleep (N1 and N2 stages), avoiding waking users in deep or REM sleep.

The analysis of Smart Alarm performance was performed on data from the beta program on 230 users for a total of 3980 nights. The nights were selected based on the following criteria:
- Nights with the Smart Alarm activated
- Nights with a minimum duration of 4 hours
- Nights when the user did not remove or turn off the headband during the night.

For each night, the hypnogram (indicating the sleep stage of the user every 30 seconds) was computed. Nights where the alarm rang when the user was already awake (corresponding to a natural awakening) were removed from the analysis. As a comparison, we used the results obtained when users used the classic alarm (8 users and 133 nights).

Results

We observed that the Smart Alarm woke users up in light sleep 88% of the time compared to 59% of the time with a classical alarm.

The Smart Alarm feature is very successful in waking the user up in light sleep compared to a classic alarm. Waking up in light sleep leads to reduced sleep inertia, in other words, a more frequent feeling of waking up refreshed (Tassi and Muzet 2000, Cavallero & Versace 2003).

Figure 16: Effect of Dreem Smart Alarm on the Sleep stage on which alarm rings.

Percentages over bar exclude nights where alarm rang when the user was already awake.
3.2.3 Sleep Induction Feature

Methods

This test aimed at assessing the efficacy of different sleep-inducing techniques (SIT) on sleep latency. This test is based on the data collected from the Insider Program. The 15 testers included in the SIT efficiency tests were aged from 21-53 years old (average 40 years old). Two of the fifteen testers were women. Their sleep quality has been assessed via the Insomnia Severity Index or ISI (Morin 93, Bastien et. al. 2001) and ranged from 8 to 24 (average 15.5). Hence, this program includes both people having trouble falling asleep and people who don’t. Each user was free to use any SIT they liked, whenever they liked. Every morning, a very short questionnaire was prompted in the mobile app prior to the user accessing their sleep data. Questions included asking how long the user took to fall asleep.

For each night, we compute the relative variation of the current sleep onset duration (SOD) relative to the user’s baseline SOD. For each user, we compute their average relative reduction in SOD relative to baseline. The values we provide as average efficiency are computed by averaging user’s own averages (not by pooling all nights together) so as to have an equal weighting of all users.

![Figure 17: Effect of Dreem Sleep Induction Techniques (Insider tests). Each red marker corresponds to a user average.](image)
Results

Overall SIT efficiency: On average, users need 31 (± 14) minutes to fall asleep when they do not use Dreem, with a large variability. When using Dreem, users need 18 (± 7) minutes to fall asleep and they display a narrower distribution, meaning the average of the mean time to fall asleep decreases by 43% (FIG. 17). If we decide to compute the average reduction of the individual self-reported sleep onset duration, there is a 32% decrease when using Dreem. (p-value =0.0027, wilcoxon signed-rank on user average durations with exact method).

Efficiency of SIT in relation to difficulty falling asleep: Concerning users who have an ISI below the clinical significance (i.e., not considered as having sleep difficulties, ISI<15), the average sleep onset duration was 19.6 minutes (± 9.1) without Dreem. The average sleep onset duration with Dreem was 17.2 minutes (± 5.6), a decrease of 12%. Yet when we consider the average individual decrease for this population, we found a 5.5% decrease. For people with a low SOD, the level of imprecision in self-estimation of SOD represents an important proportion of the SOD.

We see a significantly higher efficiency for people suffering from moderate or severe sleep difficulties (ISI>14). Using Dreem decreases the average self-reported sleep onset duration by 52% (from 38.8 (± 11.1) to 18.1 (± 7.6) minutes). The average individual decrease in SOD for users with moderate/severe sleep difficulties is 49.4% (FIG. 18).

Effect of Dreem Sleep Induction Techniques depends on the level of sleep difficulties (ISI<15 vs ISI>15, Insider tests). Each red marker corresponds to a user.

These preliminary results are interesting and show that the usage of SIT narrows the distribution of the sleep onset duration around 18 minutes, independently of severity of the insomnia of the user. Indicating strong interest for people suffering from severe insomnia. This reduction of the variability of sleep onset duration is consistent with the fact that SIT guide successively the user through a process of relaxation, mind distraction and transition to an asleep state.

This test campaign on sleep induction techniques efficacy yields congruent results with previous tests and provides further indications on the pool of users benefiting the most from it. Being based on self-reported durations, these results represent users’ perceptions of the efficiency of SITs. A measurement of SIT efficiency from objective measurements will be carried out in the coming months but it requires testers to use the headband for a significant length of time and to spend control nights without SIT, something which can really degrade their experience. This constraint was incompatible with the general objectives of the Insider tests. Therefore, a specific tests program is necessary and will be conducted once the Dreem is shipped. We launched a specific research program called the Adventurer program which will include such a test.

Figure 18

Sleep Onset Duration with or without Dreem (min)

Figure 18: Effect of Dreem Sleep Induction Techniques depends on the level of sleep difficulties (ISI<15 vs ISI>15, Insider tests). Each red marker corresponds to a user.
Dreem is an advanced solution designed to improve many aspects of sleep: reducing sleep onset latency, improving deep sleep quality, waking up in optimal condition, empowering the user with precise information and improving its sleep habits.

Over the past three years, our multidisciplinary team, gathering experts in electronics, embedded system, material science, physics, mechanics, design, machine learning, software development and sleep science have developed a unique device able to:

- Monitor sleep precisely through EEG, heart rate and breathing measurement,
- Automatically analyze and interpret sleep data,
- Act on sleep in real-time with audio stimulation,
- Gather subjective user data and give precise information to the user,
- Be used remotely on a large number of people with personalized settings.

So far with the beta version of the Dreem headband we have recorded and analyzed more than 32,000 nights on 680 users, for the latest version of Dreem, we have already more than 5,000 nights on 250 users. With all this information and with our engineers, researchers, academic partners and scientific advisory board, have made significant progress in sleep science.

With the new version of the Dreem headband we want to go one step further. We are now able to run complex and large-scale sleep studies in a short period of time and we plan to publish all the results in the scientific literature. We aim to confirm and improve the preliminary results that have been presented in this document. Moreover, we believe that on many other topics, we will be able to make significant progress in sleep science and apply the discoveries to Dreem to create new and better solutions to tackle the diversity of sleep problems.

Our company was built by bringing together neuroscience discoveries and advanced technologies to solve sleep problems. With the Dreem headband, this is now a reality as our technology brings state-of-the-art neuroscience solutions for everyone. Building upon our achievements, we are more than ever dedicated to pursuing this mission further. By leveraging our uniquely precise technology and with the benevolent contribution of willing Dreem users, we will collectively push further knowledge boundaries in sleep science.
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