Foreword

The pioneering sleep scientist Allan Rechtschaffen once said, “If sleep does not serve an absolutely vital function, then it is the biggest mistake the evolutionary process has ever made.” We now know that sleep serves many vital functions, yet it remains complex, fascinating, and full of secrets.

In 2017, the Nobel Prize in Physiology/Medicine was awarded in recognition of years of insightful work on biological rhythm that is now fundamental to sleep medicine and numerous other fields. But we are still far from solving the puzzle that is sleep. One thing is certain, if there is a way to tackle the growing poor sleep epidemic, it will come from a successful combination of the latest neuroscience discoveries and the greatest of technology. Our mission at dreem is to conduct this revolution at a large scale.

More than 30% of adults in industrialized countries struggle with sleep problems, ranging from poor quality sleep to clinical insomnia (Léger 2005, Roth 2007). Poor sleep has been linked to most of the leading causes of death in the U.S., including cardiovascular disease and diabetes, and its annual cost in the U.S. has been estimated at $411B (Rand, 2017). Existing solutions for sleep improvement range from motion and heart rate trackers, offering indirect and inaccurate measures of sleep, to addictive sedative drugs with unwanted side effects.

From 2014-2018, we developed and released 2 of the first of a new generation of sleep solutions; incorporating cutting-edge neuroscience and technology with a seamless user experience for monitoring and improving sleep of people suffering from nonrestorative nights. Through our 2 years of experience with a consumer product, we gathered feedback from thousands of users and iterated continuously to optimize our solutions.

We’ve made impressive progress in sleep science with the help of our prestigious scientific advisory board and the many scientific and medical partners who have supported us since the beginning to produce the best product possible. Following only 2 years of research and development, we conducted our first clinical trial at the Hôtel-Dieu hospital in Paris which focused on sound stimulation of deep sleep, a method requiring real-time detection of deep sleep to send pink noise at precise periods of neural activity. That study yielded positive results.
which were published in the journal Frontiers in Human Neuroscience (Debellemaniere et al. 2018). Two additional clinical trials are now under way to further improve our product, one at Stanford Sleep Medicine Center and the other at the French Armed Forces Biomedical Research Institute.

The objective of this whitepaper is to provide an overview of dreem’s sleep solution experience, including the hardware, software, and sleep enhancement techniques, and to outline our scientific validation process.
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Dreem Experience

Dreem is a complete solution consisting of the Dreem Band, Dreem Techniques, and Dreem Coach. These components work in concert to provide the most comprehensive sleep enhancement experience available. After many iterations and thousands of hours of discussion with our sleep experts and users, we developed a user journey with 3 critical steps:

i. Step 1 - Assessment: 7 nights to analyze your sleep

The first seven nights of your journey will be devoted to analyzing your sleep and lifestyle to understand how you sleep and why. During each of these nights, the Dreem Band will collect all of the physiological information necessary to objectively assess your sleep. And during the day, the Dreem Coach will complement this information by asking various questions about you and your sleep. At the end of the analysis phase, the Dreem Coach will deliver a detailed sleep report that includes a summary of your week’s sleep and its structure, and information on types of sleep-related problems and their causes. The Dreem Coach will also suggest a customized action plan to improve your sleep. This leads to the second step: restructuring your sleep.

ii. Step 2 - Restructuring: A crucial step

The best way to improve your sleep is often to change your behavior and your thinking about sleep. If the Dreem Band detects any structural or behavioral sleep irregularities during the assessment week, it will recommend personalized programs to restructure your sleep. Each sleep program addresses a specific problem: destructured sleep, bad habits, sleep loss, anxiety, etc. The duration of these programs can vary from a few weeks to up to two months for the Sleep Restructuring Program, our most advanced program. Using content and exercises suited to your needs, the Dreem Coach educates, motivates, and accompanies you in your journey to restructure your sleep. Once this crucial step is completed, Dreem will begin to further optimize your sleep.

iii. Step 3 - Optimization: When, for whom?
Before your sleep can be optimized, you must first have proper sleep hygiene and a regular sleep schedule. This is why the sleep restructuring step is so important. Once your root problems have been addressed and your sleep structure is normalized, if it is not already, Dreem will work to further optimize your sleep. Optimizing sleep means getting the most out of it. This is our goal during this last step. From sound stimuli that increase the quality of your deep sleep, to programs dedicated to periodic needs and relaxation techniques to better prepare your brain for sleep, we offer a suite of tools with proven efficacy to help you get the best quality night’s sleep possible.

At first, using Dreem can seem a bit intense. But bear in mind that a certain level of involvement is necessary. The Dreem Coach accompanies you through personalized programs and keeps you motivated on a daily basis to help you reach your goal. But it can't be done without regular use and honest input from you, the user.

Once you regain good sleep quality, you may use Dreem more occasionally. However, if new problems arise, know that you can repeat the assessment week and receive an updated action plan suited to your current needs.
Dreem Technical Overview

1. Dreem Band

i. Hardware

The Dreem Band is a wireless device that is worn on the head during the night to analyze sleep automatically and in real time. It is composed of foam, fabric, and TPU, with an elastic band behind the head to ensure the fit is tight enough to be secure, but loose enough to maximize comfort. Internal electronics include a variety of sensors, a microcomputer allowing analysis without bluetooth or Wi-Fi connectivity, and an audio system that 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 5 electroencephalography (EEG) sensors
- Heart rate and oxygen saturation via a pulse oximeter
- Movements and breathing frequency via a 3D accelerometer

Figure 1: Evolution of the Dreem Band. In 2014, EEG headset in a laboratory setup. In 2015, first functional prototype. In 2016, the beta version of the Dreem Band, used by 500 people for one year. In 2017, the Dreem Band.
**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. Our proprietary carbon-filled dry electrodes are made of high-consistency silicone, and can acquire signals through the user's hair. A patented mechanical system distributes the pressure of the electrodes to maximize comfort. The EEG sampling rate is set at 250 Hz.

The pulse oximeter measures the blood oxygen saturation and heart rate via a light which is reflected by body tissue (i.e., reflectance oximetry). This technique relies on the absorption characteristics of hemoglobin in blood. As the heart beats, the blood volume changes slightly and alters the amount of light transmitted through the tissue. The oximeter sampling rate is set at 50 Hz.

The 3D accelerometer is embedded in the top of the headband to ensure accurate measurements of your head position and breathing frequency during the night. The accelerometer 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 clarity while minimizing volume so as not to disturb a bed partner. The transducers are among the smallest on the market, and provide limited sound distortion.

Finally, there is a touchpad slider and a button located on the top arch which allows you to adjust the audio volume, terminate or re-start sleep induction techniques, snooze the alarm, and initiate and terminate sleep records, all without the use of the mobile app.
Electronics

The Dreem Band contains miniaturized electronics capable of running onboard calculations 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 of sensor data can be analyzed per second. An ultra-efficient power management of only 275 mW (on average) allows the system to have a consequent autonomy of more than 10 hours between charges.

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. Dreem Techniques include sound modulation based on EEG and respiratory signals, phases, and periods.
ii. Software

*Signal Analysis in Real Time*

**Algorithm Pipeline.** Signal analysis is processed in real time on the Dreem Band’s low-power processor (ARM CPU). The Dreem Band acquires signals from the following inputs:

- 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 is pre-filtered at the level of the sensor (see above). Each channel's data is processed independently, then combined and used to predict sleep stages and execute Dreem Techniques. The signal-processing parts are based on Fourier and wavelet transform filtering as well as signal combinations which enables the detection of sleep stages and 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-complexes, alpha waves, slow oscillations
and blinks are detected in real-time, and EEG features are extracted for sleep stages classification.

**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 are filtered in the respiration data frequency range, then combined with an online Principal Component Analysis to detect respiratory events and frequency.

**Pulse oximeter module.** A pulse oximeter is a noninvasive method for monitoring blood oxygen saturation and heart rate. 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 (Non-REM vs. REM sleep). Heart rate also provides information about the sleep onset process.

![Figure 4: Overview of real-time EEG, accelerometer, and pulse oximeter analyses](image)

**Offline Analysis**

Once records are uploaded to dreem’s servers, some of them are randomly selected and manually labelled for sleep stages, EEG patterns, and signal quality by our team of sleep experts. This time-consuming process is performed periodically to generate annotations that are used to train our machine learning and deep learning artificial intelligence (AI) algorithms. These algorithms combine expertly-crafted features and raw measurements to build predictive models.
A set of custom tools allows our sleep experts and AI specialists to examine large amounts of sleep data in detail. An example of such a tool is the signal viewer depicted in the following figure.

![Signal Viewer](image)

**Figure 5:** The “Signal Viewer”, a tool developed by dreem to visualize and interact with raw sleep data and computed labels.

**Dreem Mobile Application**

The Dreem Application is an integral interface with the Dreem Band. The application is separated into 3 main sections. The home screen shows snapshots of each night’s sleep data with metrics and hypnograms, and also contains Dreem Coach cards for additional information and questionnaires for specific programs. The headband tab is used to initiate relaxation or sleep records; view and change headband settings; and enable various sleep induction techniques, alarms, and deep sleep stimulation. Finally, the profile tab contains all of your weekly sleep summaries and aggregated metrics, and is your interface to any program you may have enrolled in. Some screen shots can be found below:
Figure 6: Screen shots from the Dreem mobile application.
2. Dreem Techniques

Dreem techniques are proven methods to help you fall asleep faster (relaxation techniques), improve the quality of your deep sleep (sound stimulation), and wake up more refreshed (smart alarm). This section highlights these techniques and their scientific rationale.

i. Relaxation

Let your stress melt away with breathing exercises, guided meditation (sophrology), neurofeedback, and a vast library of soundscapes. Dreem offers a wide range of techniques to help you relax and fall asleep faster. These techniques can also help you unwind and focus during the day. Just put on your headband, close your eyes, let the sound flow, and follow the guide.

Difficulty falling asleep is a frequent complaint among 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 frequency 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 found that 28% of a representative sample of the French working population took 30 minutes or more to fall asleep on average (INSV 2016). Common causes of trouble falling asleep can be physiological (e.g., hyperarousal), psychological (e.g., ruminations), or behavioral (e.g. poor sleep hygiene). Dreem Techniques deal with physiological and psychological causes; for more on behavioral (hygiene) causes, please refer to the Dreem Coach section, below.

In the following paragraphs, we will detail the four techniques that we have developed to help you relax and fall asleep faster: Ambiance, Meditation, Cognition, Respiration. These techniques rely on the real-time analysis of physiological signals which then influence audio feedback, operating in a closed-loop system. They have been designed to cope with the physiological and psychological causes of sleeplessness.
**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 you are completely asleep.

**Meditation**

Meditation is often characterized by brain activity and heart rate changes. Theta rhythms can also be observed in deep meditation states (Young et al., 1998). It has been shown that long-term practitioners of meditation change positively 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 in preparation for sleep.

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

**Cognition**

Cognitive hyperarousal due to stress increases the time to fall asleep, known as sleep onset latency. It can be related to daily stressors or to 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 Band. These words might be played with
relaxing background music. When the Dreem Band detects in the brain activity that you are starting to fall asleep and your attention is waning, it stops playing the sequence of words but continues to play the background music. The background music stops when you are completely asleep.

**Respiration**

It is well known that breathing deeply and holding your breath for few seconds increases physiological response of the parasympathetic nervous system, enabling a transition from a stressed and active state to a relaxed one. Notably, it has been shown that theta rhythms, characterizing sleep onset, are also more frequent with parasympathetic activation (Kubota et al., 2001). During Respiration, you will breathe at a specific pace indicated by the Dreem Band. Initially, alongside relaxing background music, a sound (e.g., an ocean wave) is synchronized with your breathing activity. After a few cycles, the headband progressively slows its pace based on the your breathing patterns. Most people follow the new pace unconsciously. **Respiration** can be useful if you are feeling some stress or tension, as focusing on your breathing at the beginning of the exercise also helps to distract the mind. The sounds gradually fade when the Dreem Band detects that you are falling asleep or you may stop this technique yourself with the touchpad when you feel ready to fall asleep.
ii. Sound Stimulation

Enhance the efficiency of your deep sleep. Once you have an adequate sleep profile, the Dreem Band can initiate **sound stimulations** at specific moments during deep sleep. Totally non-invasive, these sounds effectively increase the amplitude of your slow oscillations, the primary indicators of the quality of your deep sleep. This phenomenon is the major neuroscientific breakthrough discovery that led to the creation of Dreem.

Deep sleep is arguably the brain's top priority among the sleep stages. Interestingly, when sleep is restricted, the most preserved stage is deep sleep, also called slow-wave sleep due to its signature brain activity: "slow oscillations" (SO). SO correspond to a strong synchronous oscillation (from 0.75 Hz to 2Hz) among 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). In other words, when a brain is deprived of sleep, it attempts to make up for lost deep sleep first, before recouping other stages.

Accumulating evidence indicates that deep sleep plays a critical role in a variety of biological and cognitive processes. For instance, research supports a strong relationship between slow-wave sleep and insulin regulation (Tasali et al., 2007), growth hormone secretion (Cooper et al., 1995), cardiovascular health (Fung et al., 2011), and cognitive performance (Ngo et al., 2015, Walker 2009), and the brain’s clearance of toxic byproducts including beta amyloid implicated in Alzheimer's disease (Xie et al., 2013).

Due to the crucial role of the deep sleep stage, its enhancement has been intensely investigated by academic researchers over the last decade. Techniques used to boost deep sleep range from drugs (Walsh et al., 2006) to 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, Leminen et al. 2017).
This latter technique, audio stimulations, has emerged as the preferred noninvasive method of enhancing deep sleep slow oscillations. While random night sounds may perturb sleep, stimulating deep sleep slow oscillations with precisely-timed brief bursts of noise can strengthen and enhance them. Indeed, several rigorous scientific studies have demonstrated this phenomenon. The phase (exact timing) of slow oscillation stimulation is important and requires accurate monitoring to stimulate within an optimal window lasting only a few milliseconds. Behaviorally, some studies have reported that this enhancement of slow oscillation can increase memory consolidation of information learned the previous day (Ngo et al., 2013, Papalambros et al., 2017, Leminen et al., 2018). Dreem's Sound Stimulation technique involves stimulating the slow oscillations automatically detected by the Dreem Band with brief sounds in order to boost their activity.

Figure 7: 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.

To produce auditory stimulations at a precise moment, Dreem implements a complex pipeline of operations (see Fig. 8 A, B, C, D and E below). 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. 8B). 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. 8C). 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 (deeps) sleep vs. non-N3 sleep (Fig. 8D). 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 required 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, the Dreem Band does not stimulate if the quality of both channels is bad.

Figure 8: Simplified representation of the pipeline of operations underlying deep sleep sound stimulation.
iii. Smart Alarm

How you wake up influences your morning mood. The Dreem Band tracks your sleep in real time and triggers its Smart Alarm during the optimal sleep stage for an effortless, non-groggy wake-up.

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). This is potentially problematic when an alarm is set for a specific time. 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 have dramatic consequences.

Controlled laboratory studies 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 shown to be improved upon waking from light vs. deep sleep.

The Smart Alarm feature is designed to implement these findings to wake you at an optimal time. Classic alarms wake the user at a preset time, regardless of their sleep stage. The Smart Alarm, on the other hand, tracks sleep stages to wake you during light sleep if possible, within a predefined window of time before the preset time.

Figure 9: Dreem’s Smart Alarm
3. Dreem Coach

There are two levels of Dreem sleep coaching. At the more basic level, the Dreem Coach will share your hypnogram and key sleep data (actual sleep time, nocturnal awakenings, time to fall asleep, sleep stages, heart rate, and more) with you each morning, directly in the app. The Dreem Coach also keeps track of your sleep patterns over time, and gives you a detailed summary report every week.

The next level involves the Dreem Coach’s personalized programs tailored to your specific goals. Indeed, we have developed programs with varying objectives, durations, and intensities to meet your needs. After your first sleep assessment, the Dreem Coach will assign you to a specific program, which can be customized to you and your schedule. It will provide you with tailored information and exercises, motivate you, and measure your progress night after night. The most advanced program is dreem’s Sleep Restructuring Program. Developed with input from expert sleep therapists, dreem’s Sleep Restructuring Program is intended for those who experience regular and important difficulties to initiate or maintain sleep. It delivers progressive sleep consolidation and sleep efficiency improvement over 6-8 weeks.

Dreem’s Sleep Restructuring Program is inspired by the Cognitive and Behavioral Therapy for Insomnia (CBT-I), a first-line therapy for chronic insomnia that is recommended by both the American Association of Sleep Medicine and the European Sleep Research Society. It is a well-established drug-free treatment that is traditionally achieved through face-to-face sessions with a therapist, but it can also be administered remotely via a mobile application or website. CBT-I involves sleep education and it provides behavioral strategies aimed at reducing sleep-related anxiety and increasing sleep efficiency, including sticking to a regular wake time every day, restricting the amount of time in bed to only time spent sleeping, and avoiding stimuli that inhibit sleep. One of the main limitations of app- or web-based CBT-I is the high rate of patient dropout. Indeed, up to half of all patients who enroll in a remote CBT-I program drop out before finishing the program. Dreem’s Sleep Restructuring Program aims to engage its users by providing support and feedback to increase user’s commitment to the journey.
The Dreem Coach resides in the Dreem App, and is your companion on the journey towards improving your sleep. The app is also where you set up your headband, choose Dreem Techniques, and can view your own live physiological data. That’s why we paid particular attention to its design and made it both attractive and simple to use. Below are some screenshots:

Figure 10: Screenshots from the Dreem Coach
Dreem’s Research & Development Process

1. Dreem R&D Overview

At dreem, we are continuously developing, testing, and iterating on our product. This is achieved through two research pipelines. As is the scientific standard, we use traditional clinical trials which recruit patients who volunteer to validate our solutions either in a clinical setting or at home. But, traditional sleep clinical trials are costly and take considerable time. Therefore, we also conduct fast, iterative research using our Adventurer program, which allows Dreem users to participate in brief studies aimed at piloting new features and improvements from the comfort of their own beds.

The Adventurer program allows us to swiftly involve a large number of Dreem users in diverse study protocols. We explore, measure, and develop various hypotheses at once, on a large scale and under natural conditions, while being able to easily correct and reorient our work as necessary. The scope of the Adventurers program also allows us to identify and consider the smallest individual variations. It’s this level of personalization that separates a theoretical discovery from a practical and effective solution.

With this flexible iterative approach to research, we believe we can drive sleep science forward rapidly, in tandem with traditional research laboratories.

Importantly too, the Adventurer program affords us the unique opportunity to revise and refine our hypotheses before initiating more rigorous clinical trials - a major advantage when considering the immense cost and time investment that high-quality clinical trials involve.

Thanks to the over 25,000 nights’ of data and subjective feedback contributed by generous and dedicated Adventurers, we have gathered valuable insights to help us advance our sleep solution. For instance, we have used the results of Adventurer studies to enhance the efficiency of various parameters of our deep sleep stimulations; better understand the user experience through the assessment phase and Dreem Coach programs, including Sleep Restructuring Program; and evaluate and improve our relaxation techniques and Smart Alarm. These preliminary results provide initial support for our scientific hypotheses and confidence that we are moving in the right direction. This phase of our research and development paves the way for our confirmatory clinical trials.
Figure 11: Accumulation of nights recorded from users in the Adventurer program.
2. Dreem Validation Through Clinical Trials

Scientific research is at our core and enables us to confirm the accuracy of our measurements and efficacy of our sleep techniques. This requires gold-standard clinical trials, highly controlled and rigorously designed research studies with human volunteers that are verified and regulated by independent ethics boards, scientists, and doctors.

The clinical trials we have conducted to date are summarized below.

i. Hotel-Dieu Clinical Trial - STIMENPHASE (Completed)

**Background.** This was the first clinical trial following the production of the beta version of the Dreem Band. The aim was to assess the accuracy of real-time automated deep sleep detection and targeted deep sleep sound stimulation.

**Methods.** From September to November 2016, we conducted a randomized, double-blind, sham-controlled, crossover clinical trial under the supervision of Dr. Damien Léger at the Hôtel-Dieu Hospital Sleep Center in Paris to assess the beta version of the Dreem Band and deep sleep sound stimulation (NCT02956161). Twenty young healthy volunteers slept at home while wearing both the Dreem Band beta and an ambulatory medical polysomnogram device in both stimulated and sham conditions. Three experimental conditions were tested in each participant:

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

**Main results.** The Dreem Band beta was able to reliably detect deep (N3) sleep in real time with a sensitivity and specificity of 0.70 and 0.90, respectively; and sound stimulation during deep sleep was highly accurate (ascending phase of the slow oscillations targeted: $45 \pm 52^\circ$).
Figure 12: Representative 30-s epoch of (A) Wakefulness, (B) N1 sleep, (C) N2 sleep, (D) N3 sleep, and (E) REM sleep obtained with the simultaneous recording of the Dreem beta (blue) and the PSG (black).

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*FP, False Positive; FN, False Negative; TP, True Positive; TN, True Negative; Sens., Sensitivity; Spec., Specificity; Prec., Precision, Acc., Accuracy.*

Figure 13: (Top panel) Performance of Dreem Band beta for N3 automatic sleep stage algorithm in real-time. (A) Graphical description of phase angle. (B) Polar histogram showing 7,059 stimulations as a function of the phase of the signal. The targeted phase was 45° which represents the middle of the ascending
slope. 90° corresponds to the peak of the up state, 270° to the trough of the down state.

**Discussion.** The results of this study were consistent with previous laboratory-based findings showing a local enhancement of slow wave activity by auditory stimulation (Ngo et al. 2013, Leminen et al. 2017, B Ju et al. 2015, Papalambros et al. 2017, Cox et al. 2014); but for the first time, we demonstrated that these results could also be obtained remotely, in the home environment. Furthermore, the results show that Dreem’s stimulation accuracy is state of the art compared to studies conducted in sleep labs (Cox et al. 2014, Ju et al. 2015, Papalambros et al. 2017). This increase of slow oscillations may have functional consequences, as other groups have reported greater neuronal synchrony during slow oscillations is associated with enhanced memory consolidation. These results have been published in the peer-reviewed journal Frontiers in Human Neuroscience (Debellemaniere et al., 2018).
**Background.** This is the first clinical trial with the consumer version of the Dreem Band, which includes the addition of a 3D accelerometer to measure breathing frequency and movement, and a pulse oximeter to measure heart rate and blood oxygen saturation. With the addition of these components, we set out to evaluate the ability of dreem’s algorithms to detect apnea severity. Apnea is a prevalent form of sleep disordered breathing characterized by periods of breathing cessation that can have serious negative health consequences. Additional aims of this study include further training and validation of automated sleep staging algorithms and validation of Dreem EEG signal quality in comparison to the gold-standard in-lab polysomnogram (PSG).

**Methods.** This clinical trial is being conducted under the supervision of Dr. Emmanuel During at the Stanford Sleep Medicine Center (NCT03657329). In this prospective study, 70 patients referred with suspicion of a sleep breathing disorder complete an in-lab overnight sleep study while wearing the Dreem Band simultaneously with a full clinical polysomnogram (PSG). PSG records from the first half of participants will be manually scored by 5 certified sleep technologists, synchronized to their respective Dreem records, and used to train our deep learning algorithms. Then, the algorithms will render predictions of sleep stages and apnea severity on the Dreem Band records from the second half of subjects, and the accuracy of these predictions will subsequently be tested against consensus scoring of their associated PSG records. This study is estimated to be completed by November 2018.
Background. This clinical trial with the aims to validate dreem’s automated sleep staging and patterns detection and the Dreem Band’s physiological signal quality in comparison to a gold-standard in-lab PSG in healthy normal sleepers.

Methods. This clinical trial is currently ongoing under the supervision of Dr. Fabien Sauvet at the French Armed Forces Biomedical Research Institute (IRBA; NCT03725943). This study is enrolling 25 healthy volunteers with mild sleep complaints who will complete an overnight in-lab sleep study wearing both the Dreem Band and a full PSG. The primary objective of this study is to validate the performance of dreem’s automatic sleep staging and sleep patterns detection algorithms compared to the consensus of blinded sleep experts’ scoring of simultaneous PSG records. The automatic sleep scoring will be assessed for the total sleep time, N1, N2, N3, and REM sleep stage durations, wake after sleep onset (WASO) time, sleep efficiency, and sleep onset latency. The study also aims to validate the Dreem Band’s signal quality, automated detection of various sleep patterns (e.g., slow oscillations, spindles, eye movements), accelerometer measurement of breathing frequency, and pulse oximeter measurement of heart rate and oxygen saturation in comparison to PSG consensus scoring. This study is estimated to be completed by November 2018.
Conclusion

Together, the Dreem Band, Techniques, and Coach comprise an advanced solution that bridges scientific and technological breakthroughs and represents the culmination of 4 years of collaborative research and development across multiple disciplines. Together, our team of experts in electronics, embedded systems, material sciences, physics, mechanics, design, machine learning, software development, sleep, and neuroscience have developed a trailblazing device able to:

- Monitor sleep precisely through simultaneous recording and integration of high quality neural EEG, heart rate, oxygen saturation, and breathing and positional measurements
- Automatically analyze and interpret sleep data in real time
- Act on sleep in real time with discrete audio stimulation
- Gather subjective user data
- Provide useful and informative sleep information to the user
- Be comfortably worn regularly to acquire longitudinal sleep data
- Suggest personalized programs and strategies for achieving individualized sleep goals
- Be used remotely by a large number of people with personalized settings

Unlike activity monitors and sleeping pills, dreem provides the first comprehensive sleep solution. Not only does the Dreem Band offer detailed sleep measurement and assessment, but it can also improve multiple aspects of sleep, including sleep onset latency, deep sleep quality, morning refreshment, sleep hygiene, and overall sleep structure and efficiency. Furthermore, it enables unparallelled longitudinal sleep measurement; empowers researchers and clinicians with rich, accurate, and clear data; provides recommendations for personalized sleep programs and goals; and encourages, monitors, and supports you throughout your journey.

To date, we have collected more than 400,000 nights of sleep data from our users. Thanks to this large dataset, and to insightful input from our engineers, researchers, academic partners and scientific advisory board, we have already made significant advances in sleep science. And, it’s only the beginning.

With the launch of our new Dreem Coach steps, we will drastically improve our ability to offer customized solutions. It will also enable us to accelerate our research to further optimize and
individualize our programs. By embracing remote clinical trials, we can quickly conduct complex, large-scale sleep studies, and rapidly iterate and refine our hypotheses. This approach, in parallel with traditional clinical trials, will enable us to continue to make significant progress in sleep science and apply these discoveries to develop new and improved 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 Band, this is now a reality as our technology makes state-of-the-art neuroscience-based sleep solutions available to the masses. Building upon our achievements, we are more dedicated than ever to pursuing this mission further. By leveraging our uniquely precise technology, and with the benevolent contribution of willing Dreem users and research volunteers, we will continue to rapidly advance sleep science.
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