

A scientific overview of Rythm's technology: the Dreem headband.

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Abstract

Sleep is a universal phenomenon which takes part in the well-being of our bodies in many respects. Rythm is a neurotechnology startup designing the Dreem headband which aims at improving sleep quality. This document explains the scientific roots and the technological context of the Dreem headband. We also show some preliminary results with our technology.

1 Scientific roots

1.1 What is sleep?

Sleep is one of the most puzzling human and animal behavior. Its function remains elusive despite increasing interest and research in this field. Even if this state consists on an almost total disconnection with the environment (and thus being potentially dangerous for survival), sleep was found in every mammal studied so far [Cirelli and Tononi, 2008]. It is not known when this state appeared in the evolution process, but sleep deprivation often cause vital perturbations.

Contrary to what one might think, recent advances in neuroscience have shown that sleep is an active state [Moorcroft and Belcher, 2003]. The brain is always on the go. It never rests. During sleep, it follows a well orchestrated sequence of patterns. When falling asleep, the leading frequencies in the brain activity slowly decrease from 12-40Hz to 1-8Hz. After a small duration of light sleep, which depends on the overall health of the sleeper, deep sleep is achieved. In the context of brain activity patterns, this deep sleep phase is characterized by slow oscillations, which are spectacular synchronous oscillations between a large number of neurons at a frequency of 1Hz. After an hour or so of deep sleep, the brain transits to another state called REM (rapid-eye movement) sleep. Beyond muscle atonia and a characteristic motion pattern for the eyes, this state is characterized by strong similarities in the EEG signal with the awake activity. This is the phase when most dreams occur. After this first sleep cycle, another one begins with light sleep and the brain reaches again deep sleep but for a shorter time than previously. It then goes to a slightly longer REM sleep phase. One night is made up of multiple sleep cycles, with increasingly shorter deep sleep and increasingly longer light sleep and REM sleep along the night [Bliwise, 1993].

Deep sleep is characterized by a special brain activity signature: the slow waves (or slow oscillations) [Massimini et al., 2004]. They correspond to a strong synchronous oscillation between many neurons in the thalamo-cortical loop. The cortex is thought to be a representation structure. The thalamus is the sensory gate to the cortex and is strongly linked with attention. Thus, structured sensory information is roughly ignored by the brain in deep sleep [Strauss et al., 2015]. The large oscillations observed are due to most neurons of the prefrontal cortex layer V being strongly excited during roughly 0.5 seconds and then going quiet for a shorter amount of time, and so on. This slow oscillation is thought to be the time for communication between cortex and hippocampus and for the transfer of information from short term to long term memory [Diekelmann and Born, 2010].

A compelling observation of deep sleep is that this process is homeostatically regulated. The longer one has been awake, the more frequent and larger are the slow oscillations during the subsequent sleep. Thus, the amount of deep sleep is elevated in early sleep, when the sleep pressure is physiologically high and decreases progressively to reach low level in late sleep [Bliwise, 1993]. Moreover, deep sleep increases further after sleep deprivation and is reduced by naps [Borb and Achermann, 1999].

A lot of physiological mechanisms are triggered during deep sleep:

- Brain energy restoration - A significant positive correlation was observed between the surge in ATP (the essential energy molecule of cells) and EEG slow oscillations during spontaneous sleep [Dworak et al., 2010]. Thus, it can be said that deep sleep may be a time when the body repairs itself and builds up energy for the day ahead.
- Memory consolidation - A type of memory which is particularly consolidated during deep sleep is called declarative memory. This latter corresponds to explicit memories that one can explain, as opposed to procedural memory which is often linked to movements. For instance, remembering a book corresponds to declarative memory, whereas knowing how to play tennis corresponds to procedural memory. Deep sleep is also the time when recently acquired memory (stored in the hippocampus) is transferred to long term memories (in the cortex). Deep sleep is linked to our ability to learn and retain new information [Stickgold, 2005]. In other words, this is a key mechanism to make us one-shot learners when we face really sparse stimuli.
- Hormones releasing - Deep sleep plays a major role in hormones releasing such as the growth hormone and hormones implicated in the glucose metabolism [Van Cauter et al., 2008]. Notably, a lack of deep sleep is correlated with chronic diseases like obesity [Patel and Hu, 2008] and high blood pressure [Peppard et al., 2000].
- Preserving degeneration - A lack of deep sleep was linked to the accumulation of beta-amyloid, a protein responsible of Alzheimer's disease [Mander et al., 2015].

Deep sleep amplitude and its total duration generally decreases with age, stress, use of psychotropic drugs, and various neurological degenerative diseases.

[Ancoli-Israel, 2009, Åkerstedt, 2006, Scullin, 2013] . This is typically caused by reduced synchronization and the loss of neurons. Sleep also varies considerably at an individual level: some have nights with deep restorative sleep while others get barely any deep sleep. Today, a lack of deep sleep can lead to a vicious circle: stressful work, poor nights, and poor performance.

1.2 The means for stimulating deep sleep

During the last decade, the process of stimulating the brain in order to increase deep sleep efficacy has been intensely investigated by academic researchers. These processes range from pharmacological stimuli, [Walsh et al., 2006], visual stimuli [Gackenbach and LaBarge, 2012], electric / magnetic fields, [Huber et al., 2007, Massimini et al., 2007] and audio stimuli [Ngo et al., 2013, Bellesi et al., 2014].

A number of drugs was shown to improve sleep efficacy by promoting slow oscillations. Notably, both gaboxadol and tiagabine (two molecules acting on neurons) increased the duration of deep sleep and tiagabine also improved performance on cognitive tasks [Walsh et al., 2006]. Although these results seem promising, pharmacological approaches to sleep enhancement often raise issues related to dependence and tolerance, and are commonly associated with residual daytime side effects.

Several studies have been devoted to measuring the impact of imposing electric or magnetic fields during slow wave sleep [Huber et al., 2007, Massimini et al., 2007, Marshall and Born, 2011, Bergmann et al., 2012]. With the development of transcranial direct-current stimulation (tDCS) and transcranial magnetic stimulation (TMS), researchers now have had several tools to strengthen and prolong the slow oscillations during deep sleep. When tDCS delivers direct low current to specific regions of the brain, TMS can stimulate the brain briefly with pulses. These periodic pulse trains at the frequency of slow oscillations (1Hz) leads the slow oscillations to lock on this magnetic metronome. This has resulted in a significant increase of the duration and amplitude of the slow oscillations [Marshall et al., 2006]. The energy pulses (electric or magnetic) can activate neurons and trigger action potentials at a precise moment increasing the synchronization of the brain activity and the production of slow waves. The main problem with these stimulation devices is their inherent limited use due to the unknown risks of imposing electric / magnetic fields frequently.

In the recent years, a more acceptable possibility has emerged through stimulation via sounds in the human audio range. While random sounds during the night may perturb sleep, stimulating the deep sleep slow oscillations periodically has proven to be an effective way to strengthen slow oscillations. Interestingly, this stimulation process induces a large and significant increase in declarative memory for vocabulary learning tasks [Ngo et al., 2013]. In some ways, the slow oscillation is like a swing on a windy day and the stimulation is similar to repeated pushes to help the swing oscillate. It is believed that audio stimulation activates neurons mainly in the temporal lobes, thereby modifying their excitability and increasing the chances to have a slow wave propagating through the brain [Bellesi et al., 2014]. Much remains to be understood regarding this process, in particular because it involves designing an advanced closed loop system in order to stimulate accurately based on time, and with the best stimulation. So far the biologists have only considered periodic stimulation or basic closed loop schemes, without considering the efficient tools used in control

theory, machine learning, or deep learning.

2 Technological context

Brain recording techniques have a relatively long and rich history. Among the non-invasive options, electroencephalography (EEG), magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI) are the ones that are used most commonly. Both MEG and fMRI require expensive and large devices. On the other hand, EEG devices are cheap and small enough to be embedded on the head. EEG records electrical activity of the brain and provides us with information about the local synchronization of the surface neurons. It has been used for decades to identify sleep stages, mental state, or diseases. It has a remarkably good temporal resolution, providing measurements to the order of the milliseconds. Hence, it is often used for measuring strong and fast cerebral patterns such as epilepsy and sleep. However, EEG has its own limitations. Compared to other techniques, EEG has a poor spatial resolution: it is difficult to locate the source of a signal even with numerous densely packed electrodes. It is also significantly impacted by artefacts, mostly from movements.

Sleep monitoring is particularly adapted to EEG because it is the only technique which allows people to sleep at the same time. Moreover, although this technique has to be carefully used during wakefulness because of movements artefacts, sleeping implies few movements and, therefore, few artefacts. Finally, sleep patterns occur at very specific frequencies that require high temporal resolution, conveniently in the range of the EEG recording technique.

Another important thing to note is that EEG recordings allow large amounts of data to be collected during sleep (up to 1GB per night). This gives us the opportunity to study and analyze sleep on a broader scale using fundamentals of 'Big Data'. Until recently, neuroscience was a field dominated mostly by biology. But today, it is at the crossroads of neurophysiology, cognitive science and data science. We strongly believe that the recent developments in data-mining and machine learning will bring a tremendous progression in how we understand sleep and the deeper functioning of the brain. Indeed, efficient automation of pattern detection has been shown to be heavily based on the quantity of available data. In other words, a huge amount of data necessarily leads to robust algorithms for pattern detection.

The recent progress of the technology in term of electronics, sensors, computing, storage, bandwidth and miniaturization have allowed us to develop small and inexpensive EEG devices which can be embedded with ease. It is now possible to create comfortable sleeping devices, which can lead to many recorded nights, and lead to a rigorous quantification of sleep. The data generated can also lend itself to uncharted and thorough neuroscience research. In Europe, most experiments are currently conducted with a minimal set of about 10 to 20 different subjects with few recordings per subject. With a comfortable embedded device, one can go beyond these laboratory limitations and allow greater possibilities for research projects like the Human Brain Project or the Brain Initiative. Most notably, recording the EEG of the same person during many nights opens up new scientific and medical perspectives.

Of course, collecting data is one thing, getting useful information from it is another. One can find a lot of research in data mining and machine learning

concerning visual processing or text mining, but less about temporal biosignals. Hence, there is a real challenge in creating new algorithms that will provide relevant bio-medical information, health advice, help disease diagnostic, predict future problems, and suggest solutions.

A major opportunity provided by comfortable embedded devices is to use them for stimulating sleep according to the methods described above. We can expect a convergence between EEG measurement, embedded calculators, and algorithms for generating appropriate brain stimulation. We believe that audio stimulations are ideal, since they are harmless and they have shown good performance in laboratories.

As a consequence of this technological environment, we strongly believe that sleep studies will be the cradle of neurotechnology.

3 What Dreem does

Rythm is designing a comfortable, smart headband to monitor and enhance sleep: the Dreem headband. It allows us to monitor and record overnight EEG data and stimulate deep sleep acoustically. Compared to most of similar commercial devices, the Dreem headband records good quality and relevant data at a large scale. We use a proprietary technology of sensors based on cutting edge electronics, removing most of the artefacts and which are able to detect accurately the low frequency data produced during sleep. This is very important when you want to record brainwaves accurately and stimulate the brain at an exact time. Combining this with machine learning and deep learning algorithm, our headband is able to determine specific strategies to stimulate the brain in an optimal way.

Sleeping with the headband has to be natural and comfortable. In order to maximize the user experience, we have put a strong focus on creating a headband that is optimized for ergonomic, design and technology needs. We are and will continue to address this ongoing effort with extensive anthropomorphic / design studies and countless tests.

To build this technology, Rythm relies on a multidisciplinary team. With strong links to the academic world and skilled employees in computer science, electronics, design, chemistry and neuroscience - Our vision is not to only ensure quality of sleep, but is also to take brain science one step ahead.

4 Proof of concept

The efficiency of audio stimulations during deep sleep has been assessed in various studies from different independant laboratories over the last few years [Ngo et al., 2013, Bellesi et al., 2014]. We have reached identical results with our headband prototypes. The rigorous analysis of all sleep related and cognitive impacts of the headband is in preparation for an academic publication.

Here, we show the typical impact of audio stimulation(s) on a single night in figures 1 and 2. The two figures show the average of the EEG signal over all the time windows centered around a stimulation time. Note that in the non stimulated case, the stimulation has not been sent and the potential stimulation times are just recorded for fair comparison between stim and sham.

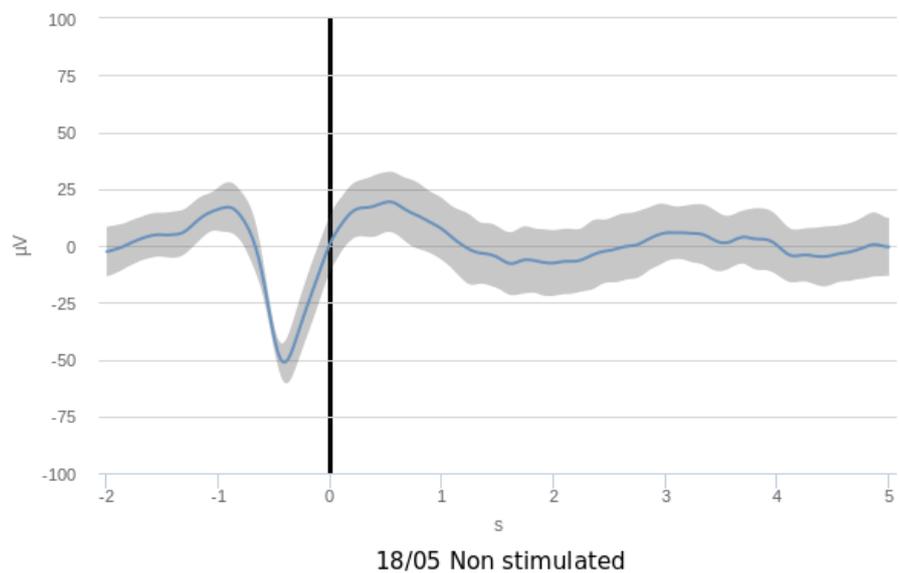


Figure 1: Mean (\pm SEM) EEG signal averaged for each potential stimulation time during a sham night. The black vertical axis at $t = 0$ s corresponds to the stimulation which would have been sent if it was a stimulated night.

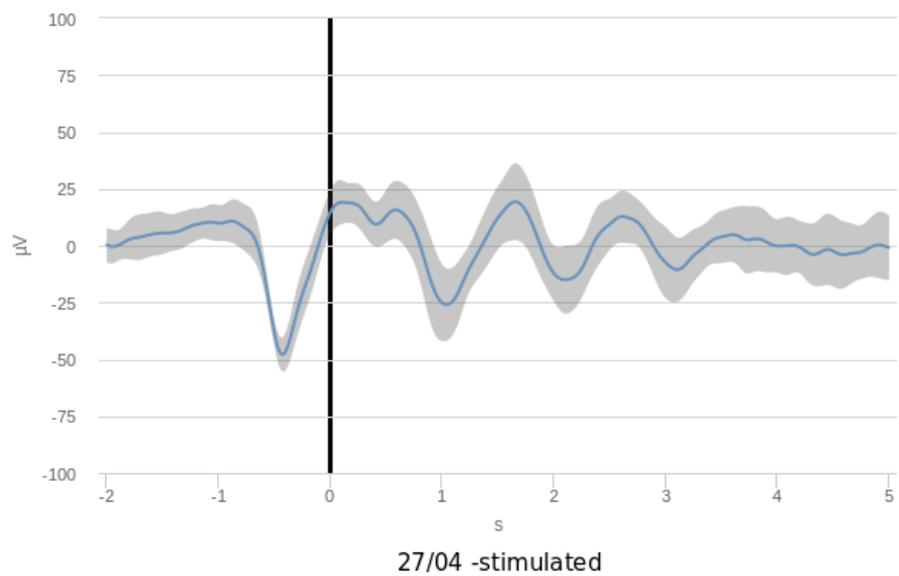


Figure 2: Mean (\pm SEM) EEG signal averaged for each stimulation time during a stim night. The black vertical axis at $t = 0$ s corresponds to the stimulation time.

This example strongly shows that a single stimulation pushes the brain os-

cillation for several cycles.

The overall impact of the whole stimulation procedure is not reported here because of the heterogeneity of prototypes used for our tests: the results have not been obtained with full scientific rigor so far. However, our preliminary tests have shown an increase of deep sleep amplitude and duration in the order of magnitude of 10%.

5 Conclusion

The recent discoveries and growing awareness of sleep confirmed the importance of good quality of sleep in all the aspects of our lives. The understanding of the different physiological mechanisms that occurs during the different stages of sleep highlighted the fact that the quantity of sleep is not everything, quality matters as well.

The structure of our sleep seems to have adapted to an environment where survival during the night was the main criterion. The biological evolution has not followed the same suit when it comes to social evolution. While technology has filled the gap between our prehistoric body and our modern world in many fields like communication, health, security or traveling - it has not done so for how we sleep. With the Dreem headband, we believe that our stimulation process allows us to use technology to understand sleep and modify the structure of sleep.

The preliminary results show the impact of audio stimulations on the number and amplitude of slow oscillations. As our current research initiatives mature, we are improving our learning algorithms and stimulation processes.

But beyond the modification of the structure of sleep, building a massive EEG data base with homogeneous data collected on the same people for a long period of time opens the possibility to early diagnostics of chronic diseases, personalized learning and even personalized treatments.

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