

Whitepaper

Somnox Sleep Robot

Scientific Background





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Preface

We believe that we can make a major impact on the daily wellbeing of millions of people through soft robotic companions. That is why we designed the Somnox Sleep Robot, a soft robotic device that helps people improve their sleep and wake up more refreshed. We will continue improving our products in order to achieve our goal.

Our mission

Help 100.000.000 people sleep naturally by 2030

Introduction

Sleep is undoubtedly one of the most valuable things in life. One-third of a person's life is spent sleeping. Sleep is as important for our mental and physical health as good nutrition and physical activity. However, a good night's sleep is not as easy as it might seem.

Around 20% of the Dutch population aged 12 years or older, suffer from symptoms that are related to sleep disorders [1]. These symptoms include: difficulty initiating sleep, maintaining sleep and waking up too early. But even more shocking, the prevalence rate of insomnia, which is a chronic sleep disorder, in the Dutch population is 8,2% [2]. Sleep problems do not only occur frequently in The Netherlands. Around the globe, approximately 10 to 20% of the population suffers from insomnia [3]. This is a cause of concern, as sleep disorders are associated with major health risks. Sleep deprivation can result in devastating consequences, including compromised quality of life, lower productivity and illnesses such as depression, hypertension and diabetes mellitus [4-8]. Moreover, sleep deprivation has a large economic impact. It has a minimum yearly impact on Dutch economics of 1.5% of the Dutch Gross Domestic Product, which corresponds with approximately 12 billion euros [9]. The prevention and treatment of sleep disorders is therefore imperative to increase human health and happiness.

In order to find a solution for this worldwide sleep problem, the reasons why one may suffer from disordered sleep need to be understood. What makes this challenging is that the causes vary considerably from person to person. They can be of a physiological and psychological nature. A disrupted biorhythm, poor sleep hygiene and worry about being able to fall asleep can all lead to disruption of sleep [10]. In addition, light-dark cycles of contemporary societies have been altered significantly due to artificial lightning and screens of

electronic devices. Artificial light exposure suppresses the production of melatonin, one of the most important hormones of sleep, and therefore affects natural circadian rhythms [11].

Another main risk factor of sleep disorders is stress [12]. Especially today's society, due to excessive workload and frantic lifestyle, causes chronic stress in individuals. We take this stress with us even when we go to bed, thus depriving us of a good night's rest. This results in lower resilience to stress, which further worsens sleep quality [13,14]. As shown in figure 1, a vicious circle forms. Breaking this circle is crucial to reducing stress-induced sleep deprivation.

In order to combat sleep problems, many have turned to pharmaceuticals. With sleep disorders on the rise, the use of medication to aid sleep has increased over the past few decades. Sleeping pills come in a variety of forms, but have in common that they all help the user to fall asleep artificially. While they may provide temporary relief, there is a range of potentially harmful side-effects associated with their use. Examples are memory disorders, reduced alertness and psychomotor problems [15]. People who abuse sleeping pills can easily become emotionally or physically dependent on the drugs [16,17]. In contrast, the Somnox Sleep Robot can help improve people's sleep quality in a natural way without such side-effects. The Sleep Robot can not eliminate the anxieties of everyday life that prevent us from having a good sleep, but it can support users in finding relaxation in bed despite these worries.

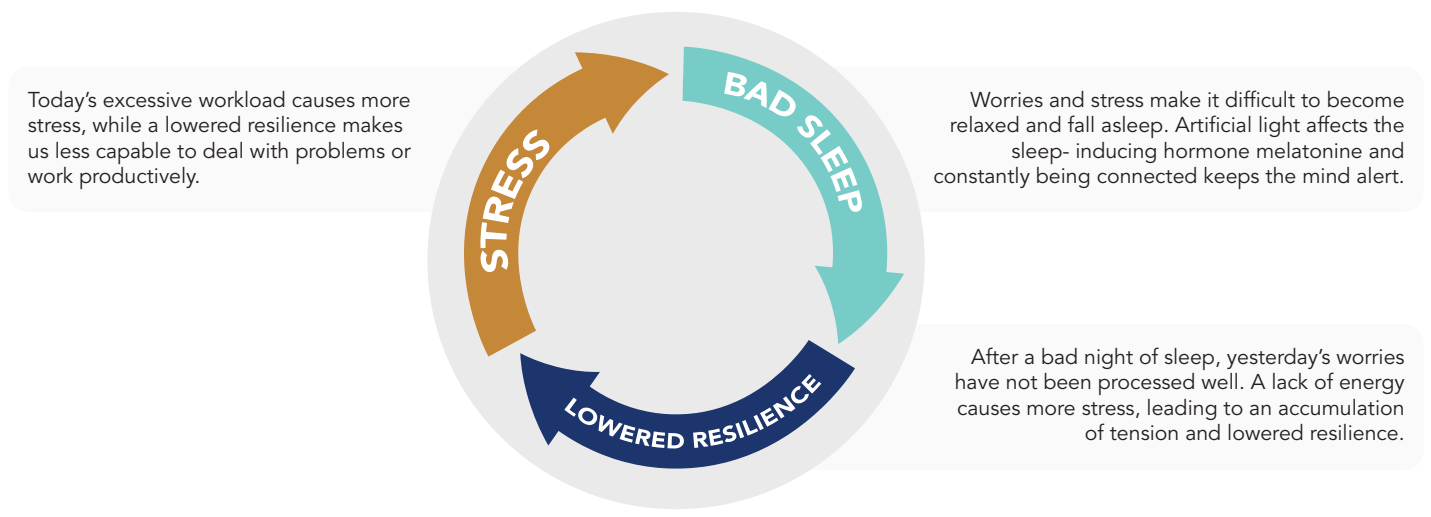


Figure 1: vicious circle of stress-induced sleep loss

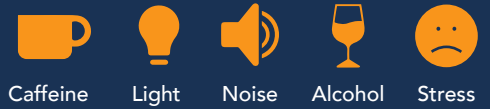
WHAT IS SLEEP?

A sleep cycle consists of different stages. **Light sleep** (NREM 1 + 2) is the transition from being awake to asleep. Brain waves slow down towards **Deep sleep** (NREM 3 + 4), during which your body repairs muscles and tissues, and your brain processes information and impressions. Your dreams happen during deep sleep phase **REM** (rapid eye movement). You will wake up multiple times a night, but one normally does not notice or remember these **onsets**. A healthy sleep pattern consists of 4-5 full sleep cycles, which is essential for restoration of body and mind and building up energy for the next day.

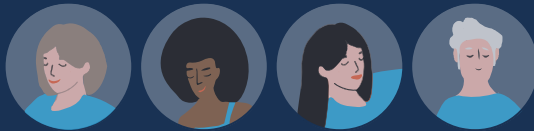


Sleep can easily be disturbed by many influencing factors, such as bad sleep hygiene (e.g. light, temperature, and consumption), stress and medical conditions.

SLEEP DISTURBERS



1 out of 5 people suffers from **SLEEP PROBLEMS**

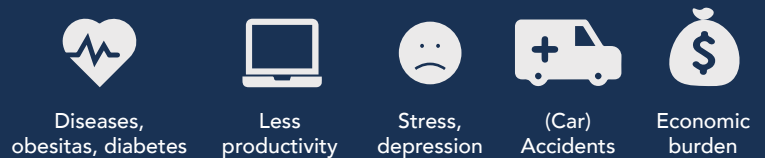


Insomniacs may have problems with..

- 🕒 Initiating sleep
- 🔄 Frequent awakenings
- 🕒 Early morning awakenings

CONSEQUENCES

Sleep problems have a large impact on health and quality of life.



INTERVENTIONS

In order to improve sleep quality and overcome sleep problems, several solutions exist. We will only take into account solutions that can help in a natural way.



The Somnox Sleep Robot

The Somnox Sleep Robot is a bean-shaped pillow that has been designed to relieve the mind and body of stress, which is provided by three elements: breathing, sound and affection. In this section, these aspects are explained in relation to physiological responses of the body.

Breathing simulation

The Somnox Sleep Robot automatically synchronizes the user's breathing to that of the Sleep Robot, guiding the body towards a relaxed mode. The following paragraphs explain how breathing can help achieve relaxation and improve sleep during the night.

Autonomic nervous system

The Autonomic Nervous System (ANS) is part of the peripheral nervous system and primarily innervates the smooth musculature of internal organs. The actions of this system are not under voluntary control. For instance, one cannot consciously decide the heart rate, pupillary response and digestive function of intestines. These characteristics distinguish the ANS from the somatic nervous system, which is subject to voluntary control [18].

The ANS consists of three different parts: the sympathetic, parasympathetic and enteric nervous system. The sympathetic nervous system is responsible for the body's "fight or flight" reactions. Secretion of epinephrine (adrenaline) helps to protect the body in times of stress: the heart rate increases, pupils dilate and gut motility decreases. This allows blood to be

distributed to areas that the body needs in stress situations [19]. In contrast, the parasympathetic nervous system is responsible for the body's "rest and digest" mode. It is responsible for the internal functions when you are sitting, resting or relaxing for example [20]. In rest, the heart rate is lowered and intestine motility is enhanced for digestion through the parasympathetic nervous system. The vagus nerve is the most important anatomic structure by which the parasympathetic nervous system exerts its influence. Lastly, the enteric nervous system is responsible for digestion functions of the gastrointestinal tract [19].

For a good night's sleep, the body should be in a relaxed condition: homeostasis. In order to achieve homeostasis, the ANS has to be in balance. However, if a person is stressed, the sympathetic nervous system will be continuously activated without normal counteraction of the parasympathetic nervous system [21]. This results in shallow breathing, increased heart rate and poor sleep quality [22]. Therefore, in order to attain relaxation and improved sleep quality, a balanced ANS is important. In figure 2, this balancing mechanism is shown.



Figure 2: balancing the autonomic nervous system by slow breathing

Breathing and relaxation

Slow breathing techniques, characterized by extended exhales and a breathing frequency of 4-10 breaths per minute, can balance our ANS and therefore reduce our stress responses [23-26]. Stress is one of the main risk factors for sleep problems [24-26]. Thus, slow breathing can possibly break the vicious circle of stress-induced sleep problems.

Slow breathing techniques that have been shown to be effective are Pranayama techniques [24]. Pranayama is used in yoga as a practice of voluntary breath control. Researchers showed that pranayamic breathing causes decreased sympathetic dominance and enhances parasympathetic activation [23, 27]. Through rhythmic slow breathing exercises, the cardio-respiratory system can be normalized [28]. Moreover, melatonin production increases and induces a sense of relaxation [29]. Also brain wave synchronization can provoke delta wave activity in the brain, which indicates parasympathetic dominance [31].

The underlying mechanism of the effect of slow pranayamic breathing techniques on autonomic responses is not entirely known. A hypothesis on the precise mechanism has been proposed by Jerath et al. (2006) [27]. According to this hypothesis, slow pranayamic breathing activates stretch receptors in the lungs and stretches fibroblasts surrounding the lungs. This generates inhibitory impulses in neural tissue and a hyperpolarization current, leading to decreased action potentials in neural tissue and decreased metabolic activity. This results in increased parasympathetic dominance and therefore decreased blood pressure, heart rate and oxygen consumption [26, 27]. In conclusion, slow breathing can reduce perceived stress and in this way improve sleep [27]. Therefore, slow breathing is the main feature of the Somnox Sleep Robot.

Breathing function of Somnox Sleep Robot

As mentioned in the previous paragraph, slow breathing can possibly interrupt the vicious circle of stress-induced sleep problems. The Somnox Sleep Robot has been designed to lower the breathing frequency during the night and bring the body to a relaxed state.

The breathing patterns that are used in the Somnox Sleep Robot are inspired by the slow breathing pranayama techniques. The Sleep Robot guides the user towards slow breathing by synchronization of the user's breathing with the breathing frequency of the Sleep Robot. The concept of synchronizing breathing patterns was based on a scientific study in which infants slept with a breathing bear. During sleep, infants usually have dysrhythmic and chaotic breathing, which can result in poor sleep. The infants adapted to the regular breathing pattern of the bear, improving their sleep quality [31]. User test results with one of the first Somnox Sleep Robot prototypes showed that the Sleep Robot successfully achieved slow breathing patterns through gradual synchronization. A visualization of this synchronization concept is visualized in figure 3.

"Using the Sleep Robot helps me calm down and I notice that my heart rate slows down. I fall asleep quicker and more gently. I have also used the Sleep Robot to meditate or to relax while sitting on the couch."

Test user - February 2019

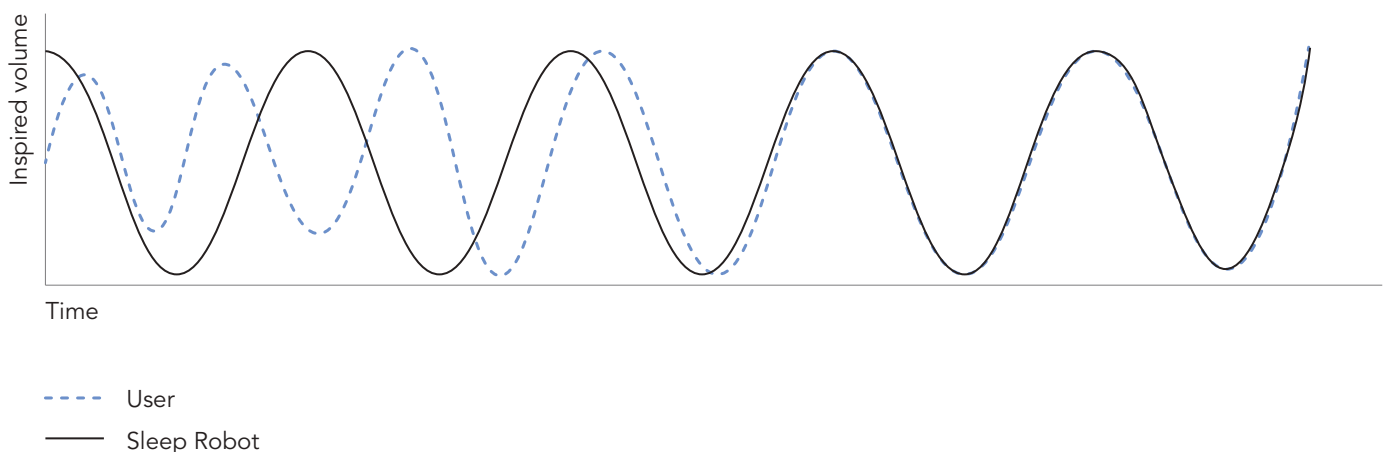


Figure 3: gradual synchronization of a user's breathing with the Sleep Robot. After synchronization has been identified by the robot, it will start to slow down its breathing rate.

Soothing sounds

Besides breathing synchronization, music and sounds are used in the Somnox Sleep Robot as a source of relaxation. The Somnox Sleep Robot can play music, white noise, pink noise and ambient sounds (such as wind, rain and waves) to help the body achieve full relaxation mode.

Music

Listening to music at bedtime, appeared to have a positive impact on sleep quality in adults with insomnia symptoms. Researchers showed that musical interventions improved perception of sleep and quality of life [32, 33]. Another study supported this result in individuals aged 60 years and older [34]. For this reason, slow-paced meditation music is integrated in the Somnox Sleep Robot. Meditation music is known to induce a calm state and reduce feelings of stress [35]. In a future update, users can add their own music to the Sleep Robot.

White and pink noise

White noise is the signal created when all different sound frequencies (20 Hz - 20 kHz) that the human ear and brain can perceive are put together at an equal intensity [36]. It can be used to mask unwanted or noisy sounds. For example, it can mask traffic sounds for people that live closeby a highway. Because white noise can mask distracting noises, it can be useful for helping people fall asleep [37].

Just like white noise, pink noise contains all sound frequencies that is audible to humans. However, in contrast to white noise, the intensity of pink noise is

not constant for all frequencies: pink noise's intensity decreases with increasing frequency. Pink noise is known to reduce brain wave complexity and induce a more stable sleep time. Therefore, it can improve sleep quality of individuals [38].

Nature sounds

Nature sounds, such as rain, wind or waterfalls naturally contain white noise. As described above, white noise can be used to mask distracting sounds. Moreover, nature sounds can calm people and support them in falling asleep. They may also reduce muscle tension, heart rate and stress [39]. As Orfeu Buxon, Biobehavioral Health Associate Professor at Pennsylvania State University, explained: "These slow, whooshing noises are sounds of non-threats, which is why they work to calm people. It's like they're saying: Don't worry, don't worry, don't worry" [40]. Therefore, nature sounds can strengthen the calming effect of the Sleep Robot's breathing pattern.

The sounds can be selected through the Somnox mobile application (figure 4). You can listen to samples of the audio designed by our partner Manglemoose [on our website](#).

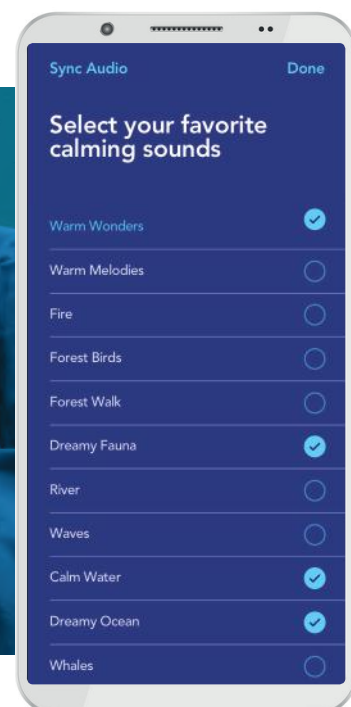


Figure 4: Choosing your favourite music through the Somnox mobile application

Affection

The Sleep Robot has been designed to be a comfortable, useful, and easy to use product. The Sleep Robots' shape is designed to allow the sleepers to comfortably place it to their chest, wrap their arms around it and hug it. In this way, the Sleep Robot is able to give you affection.

Fetal position

The shape is designed such that users maintain a natural sleeping position when hugging the Somnox Sleep Robot, without deviating from the natural neck and shoulder alignment. The sleep companion is molded in such a way that the shape of the Sleep Robot accommodates a natural fetal position, which is the most common sleeping position. A study of sleep expert Christopher Idzikowski, author of "Learn to Sleep Well", showed that 41% of participants slept in a fetal sleep position [41]. However, it is also possible to cuddle the Sleep Robot in other sleep positions. The goal of holding the Sleep Robot is to physically feel the breathing rhythm and fall asleep easier.

Soft robotics and comfort

Somnox developed a soft-robotic huggable Sleep Robot which can relax the body and mind of the user. Its shape is meant to be a sleeping companion through the night, like a living being instead of a mechanical robot, as shown in figure 5. Therefore the Somnox Sleep Robot overcomes the archetype of robots. The shape is designed to be comfortable, useful and easy to use. Comfort is mainly ensured by the ergonomic shape of the robot and the material used to cover it. The shape of the Somnox Sleep Robot has

been carefully designed to be both easy to hug and enjoyable to see. The material that is chosen to wrap it has been selected carefully after visiting several mattress factories including Auping. The material is very soft, yet it is also easily washable.

"Yesterday, I had to return the Sleep Robot to Somnox, and it felt quite lonely in bed. The Sleep Robot is like a teddy bear for adults, you get used to it."

Test user - March 2019

Shape and dimensions

The curved shape of the Somnox Sleep Robot and the absence of sharp edges give a sense of peace and calmness. The two-sphere-connected shape creates the impression of harmony because it allows higher volume over surface area ratio. The dimension of the Somnox Sleep Robot have been determined based on DINEN, the TU Delft anthropometric database [42]. The most important limbs that are in contact with the Somnox Sleep Robot are the arms and the chest. Therefore, the Somnox Sleep Robot's dimensions are chosen carefully to allow the sleepers to comfortably place it on their chest and hug it with their arms.



Figure 5: Sleeping with the Sleep Robot in fetal position

Research and development process

Since the start of the development process of the Somnox Sleep Robot, we have been constantly testing and iterating our technology and design. Since 2015, over 100 people have tested (early stage) prototypes of the Sleep Robot at home. We selected 'test sleepers' through our list of volunteers and feedback has been given by hundreds of people through surveys, interviews and test nights. Now that the Sleep Robot has been launched, we will continue developing by gathering user feedback and validating the Sleep Robot through clinical trials.

Development

September 2015 - March 2019

The Sleep Robot was developed by four students of Delft University of Technology at the robotics institute. Inspired by soft robotics, they started to think of ways how robots could solve problems and make life easier. In six months, they made the first prototype of the Sleep Robot and after positive feedback from people suffering from insomnia, they decided to further develop this concept. In an early stage of the design process, Auping got involved by producing some prototypes. Together with Auping, Somnox took the development from proof of concept to an actual working product that has been launched on the international market. Read more about the collaboration between Somnox and Auping [here](#).

The first design was based on the shape of the human body and therefore much bigger than the final product. After early-stage user test results, it was decided to decrease the size to a shape that is more comfortable to hold and moves along in bed (figure 6).

Other improvements during the design and development process were:

- **Fabrics:** soft and high quality fabrics by Auping
- **Sleeve:** a washable sleeve was added for hygiene and protection
- **Weight:** the weight of the Sleep Robot has been reduced from approximately 5 kg to 2.3 kg
- **Sound:** the sound intensity of the Sleep Robot's mechanism has been reduced
- **Usability:** several iterations have been done on the control panel based on user testing and prototyping
- **Breathing movement:** the breathing movement became more intense and larger

In 2019 software updates will be launched to improve the first Sleep Robot, among which adaptive breathing and adding your own audio to the Sleep Robot.

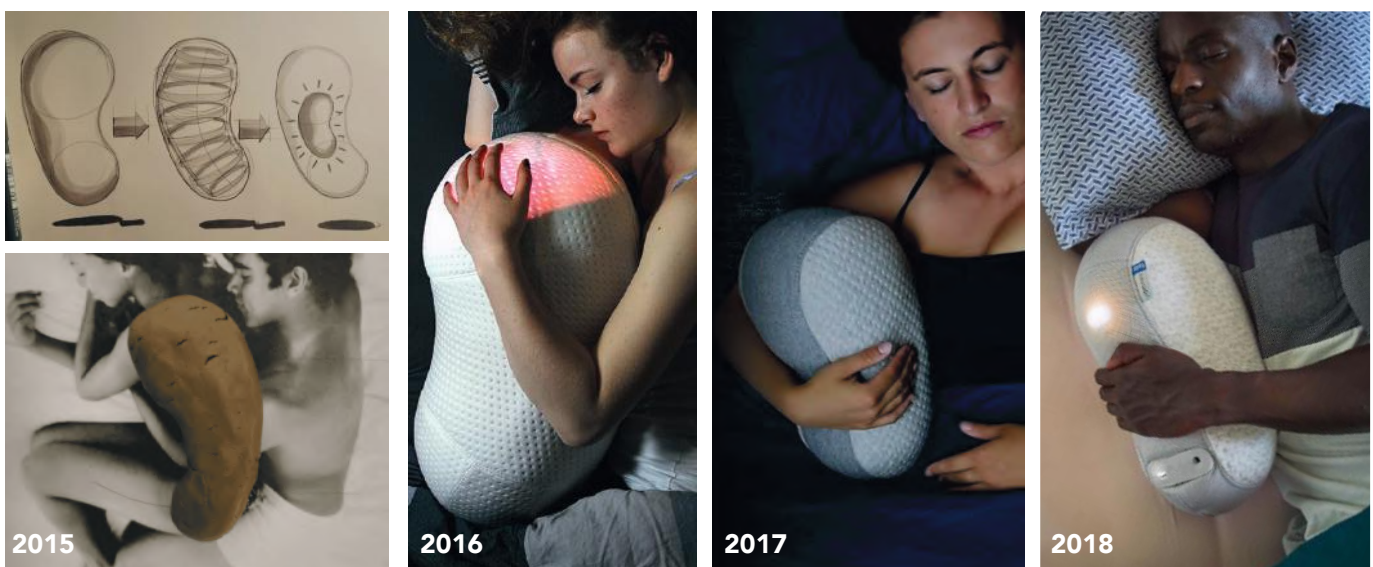


Figure 6: development of the Sleep Robot. From a shape analysis through clay models (left) towards the first and second prototype, and the final product (right). The Sleep Robot has been developed through technical iterations and user feedback.

Research

Pre-launch user tests: January-March 2019

The first production-line Sleep Robots (Jan 2019) have been tested for one month by 39 people selected through a submission form for participation in user tests at Somnox. The main inclusion criterion was the presence of self-reported sleep problems, e.g. trouble falling asleep, not being able to sleep through the night and/or not waking up refreshed. Participants reported to be interested in the Sleep Robot as a possible solution for their sleep problems.

Goals and set up

The goals of this study were: (1) gather feedback on usability of the Sleep Robot in order to make pre-launch improvements on the Sleep Robot, (2) evaluate whether the perceived sleep quality improved within one month of using the Sleep Robot and (3) observe the functionality of the Sleep Robot's features.

The participants received the Sleep Robot at home including the user manual. They were free to use the Sleep Robot according to their own expectations, habits and needs. The test was split in two test groups of both 19 and 20 participants. In both groups, two participants quit the study due to personal issues.

The study set-up was explorative and observational: how do people perceive the Sleep Robot, which effects can already be identified? During this study, qualitative, subjective data was gathered through weekly questionnaires, a focus group and in-depth interviews.

Results

Data from the different test methods can be split in results on usability, effect and the Sleep Robot's features.

1) Usability

Several usability errors and software bugs were identified during the first test months. In advance of the product launch in April 2019, improvements have been made on breathing intensity and control panel interaction, visualized in figure 7. After these improvements, an increase in satisfaction was measured during the user test.

Next to improvements on the Sleep Robot, the washable sleeve, mobile application, customer support services and the onboarding process were improved by user test results.

The Sleep Robot's breathing intensity appeared to be insufficient. After software improvements, improved satisfaction was measured.

Small changes have been made on usability of the control panel and LED indications.

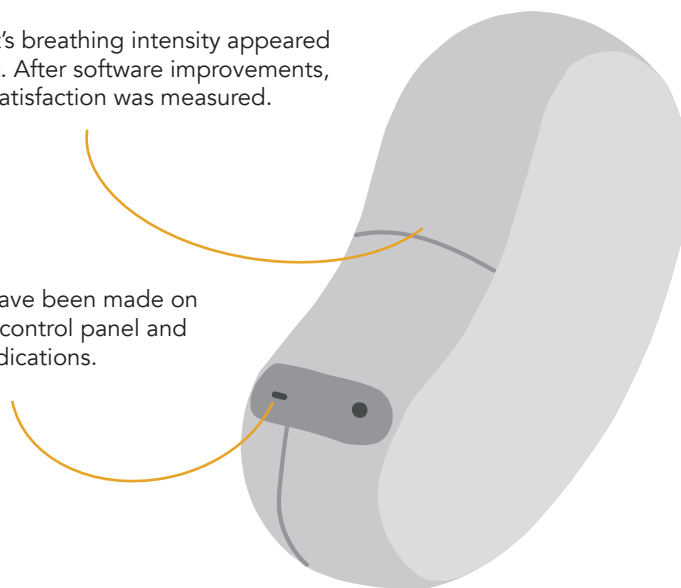


Figure 7: improvements that have been made to the Sleep Robot before the product launch.



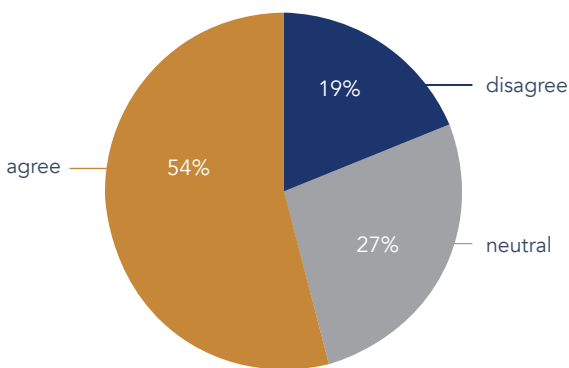
2) Effect

Because of the small and explorative set up of this study, conclusions on effectivity can not yet been drawn. Results are based on individual self-reported measures and show anecdotal evidence on the perceived effect of the Sleep Robot. Results are promising and exciting.

The final and most extensive questionnaire (after one month of use) was answered by 35 participants, of which 22 indicated to have used the Sleep Robot for more than three weeks in total. More than half of these 22 participants reported to fall asleep faster when using the Sleep Robot. Another astonishing result was that 83% reported that the Sleep Robot could help them relax. A visualization and further explanation and interpretation of these results are shown below.

“The Sleep Robot helps me to fall asleep faster”

54% of the participants who used the Sleep Robot (>3 weeks) perceive it as a solution to help them fall asleep faster.



“The Sleep Robot helps me to relax”

83% of the participants who used the Sleep Robot for more than three weeks reported that the Sleep Robot helps them to relax.

“When I’m stressed at work, it’s great to have a 10 minute break and breathe along with the robot. I think it’s very relaxing”

Feedback from our test users

“I set the Sleep Robot’s duration for 30 minutes and always fell asleep within that time. That’s amazing, because it normally takes hours to fall asleep. I actually don’t want to return the Sleep Robot after this test period!”

“I can let go of my worries by focussing on the Sleep Robot’s breathing rhythm. Initially, I tried to force myself towards breathing exactly the same, but when I just comfortably lie down and think of nothing but feeling and listening to the rhythm, I started to calm down automatically.”

Falling asleep

Difficulty with falling asleep is the most common sleep problem amongst participants in this study. They had tried multiple other solutions already (eg. medication, cognitive behaviour therapy), without satisfying results. Therefore, these first positive results are exciting.

Relaxation

In general, the relaxing effect of the Sleep Robot has been rated positively. 83% of the participants who used it for more than three weeks is positive about the relaxing effect of the Sleep Robot. The Sleep Robot was not only used during the night, but to calm down during the day as well.

As stated in this whitepaper, relaxation is essential for balancing the autonomic nervous system and falling asleep. In the near future, we will validate the relaxation effect of the Sleep Robot on the human body.



3) The Sleep Robot's features

When looking into the three main aspects of the Sleep Robot: breathing, sounds and affection, the following results have been derived.

Breathing

Two-thirds of the test users experienced their breathing rate slowing down when using the Sleep Robot. In general, the breathing movement was experienced as a realistic simulation. Furthermore, the Sleep Robot helped in becoming aware of the breath. However, difficulty was experienced in setting the breathing rate via the mobile application. An adaptive breathing movement (the Sleep Robot adapts to the user) was mentioned as a desired feature. Next to that, support on this aspect (e.g. videos or tips & tricks) can be improved.

"The Sleep Robot made me feel more in control of my breath"

Sounds

Several test users liked to listen to sounds or music to let go of their own thoughts. The possibility to add personal music to the Sleep Robot has not been launched yet, but will probably increase satisfaction. Reasons that were mentioned for not listening to the sounds or music: "since my partner would be bothered" and "I prefer to listen to my own music".

"I have tried them all and especially like the nature sounds"

Affection

Participants mentioned to get used to the Sleep Robot as a 'bed partner' and named it as if it was their pet (Robbie, Sommi, etc). As a participant also mentioned: "I have experienced the Sleep Robot as a pet". In order to improve comfort when sleeping in positions apart from the fetal position, the shape will be iteratively redesigned in future versions. Moreover, the weight of the Sleep Robot will be further reduced.

"I have experienced it as a pet"

Discussion

This user test study showed self-reported measurements of 35 participants from the user test executed in the pre-release phase of the Sleep Robot. It has been set up as a subjective exploration into the perceived effect on a heterogeneous population that showed interest in the Sleep Robot as a possible solution for (self-reported) sleep problems. No correlation could be found on demographics, sleep problems and/or causes, and the results on effect and satisfaction. In future studies, the effect on different target groups will be studied.

Due to several teething problems, usability and satisfaction have negatively been influenced. Feedback was immediately analyzed by our Research and Development team and problems were solved when possible. During the test month, participants received two over-the-air updates to improve the software of the Sleep Robot. Furthermore, the app has been updated several times. Therefore, the results of this user test cannot be quantified and can only be used as indicators for satisfaction and effect. More research on satisfaction and effects has to be performed when issues regarding the Sleep Robot are solved.

Multiple studies have shown that slow breathing techniques can balance our autonomic nervous system (ANS) and therefore decrease our stress responses. We have received positive experiences on this aspect, but have not clinically proven the effect yet. In the near future, we will execute a clinical trial in which the effect of the Sleep Robot on the ANS will be studied.

Conclusion

The Somnox Sleep Robot can have a positive effect on relaxation and sleep quality, as reported by multiple test users. Conclusions about effectivity cannot be drawn from this explorative study and more research will be done to validate the effect on different populations. Furthermore, improvements on usability and support will constantly be made.

Final word

The Somnox Sleep Robot can have a positive effect on relaxation and sleep quality, as reported by multiple test participants and first users. We have already received stories from customers who could reduce their sleep medication dosage, experienced better sleep quality and were more energized during the day. Therefore, Sleep Robot provides a solution for people suffering from insomnia or related sleep problems.

The Sleep Robot was founded by four students with a mission: helping people sleep naturally. From their vision on soft robotic companions, they did not only develop the Sleep Robot as a natural solution for sleep deprived people, but found an innovative method that can have an impact on the daily well being of millions of people in the future.

The Somnox team will constantly iterate on both hardware and software of the Sleep Robot in order to increase usability and - consequently - improve effectivity and user experience. We will run clinical trials to validate the effect of the Sleep Robot and study specific value for different groups of people.

We hope you will sleep well tonight.

First user experiences

In April 2019, the Somnox Sleep Robot was officially launched. We are happy to share first stories of our users.

It has done wonders to me

"The 'pillow' has done wonders for me. I can not remember the last time I slept without sleep medication, but this pillow has brought a solution. Yes, it is quite expensive, but the benefits definitely outweigh the costs. I think it's a pity not all people with sleep problems can get the possibility to use the pillow."

I slept like a baby

"I have reduced my sleep medication and set the Sleep Robot from 10 to 4 breaths per minute. I slept like a baby and did not have any troubles falling asleep. If I woke up during the night, I turned on the Sleep Robot again. It worked perfectly! I am so happy! My mindset: I don't let myself be fooled by anyone or anything. I have a goal and I will reach that goal: improve my sleep."

Confident enough to try it without sleeping pills

"Marvin (the name I gave to the robot) is going to improve my quality of life substantially. As my insomnia started to affect my job and my daily routine, I became so desperate that I had my doctor prescribe me a sedative. However, the sleeping pill made me drowsy for the next day. Like a gift from the universe, Marvin arrived 3 days after that point of desperation and now I feel confident enough to try to fall asleep sober tonight. Thanks again, so much more than I can describe in words."

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