Whitepaper

The Somnox Sleep Robot

Scientific background

somnox®
realizing dreams

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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

Unlocking human potential by improving the sleep of 100 million people 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 22% 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 [1]. 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 comprised quality of life, lower productivity and illnesses such as depression, hypertension and diabetes mellitus [4-8]. The prevention and treatment of sleep disorders are therefore imperative to increase human health and happiness. Moreover, sleep deprivation has a large economic impact. In the US and Japan, a real sleep-loss epidemic is happening. The economic loss in the US due to insufficient sleep is around 411 billion dollars (2.28% of GDP). Japan loses on average 4.8 million working hours per year due to lack of sleep [9].

Definition of insomnia
Dr. Thomas Roth defines insomnia as follows: "A disorder with the following diagnostic criteria: (1) difficulty falling asleep, staying asleep or nonrestorative sleep; (2) this difficulty is present despite adequate opportunity and circumstance to sleep; (3) this impairment in sleep is associated with daytime impairment or distress; and (4) this sleep difficulty occurs at least 3 times per week and has been a problem for at least 1 month" [10].

The reasons why one may suffer from disordered sleep need to be understood in order to find a solution for this worldwide sleep problem. This is very challenging, because the underlying causes of disordered sleep 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 [11]. In addition, lightdark cycles of contemporary societies have been altered significantly due to artificial lighting 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 [12].

Another important risk factor of sleep disorders is psychological distress [13, 14]. Especially in today's society, excessive workload and frantic lifestyle causes chronic stress in individuals. We take this mental stress with us even when we go to bed, thus stress deprives us of a good night's rest. This results in lower resilience to stress, which further worsens sleep quality [15,16]. 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 turned to pharmaceuticals. With sleep disorders on the rise, the use of medication to aid sleep has increased over the past few decades. Sleep medication come in a variety of forms, but they all help the user to fall asleep artificially. While sleep medication may provide temporary relief, there is a range of side effects associated with its use. Examples are headaches, drowsiness and dizziness [17]. Long term use of sleep medication is strongly not recommended, as people can easily become dependent on it [18,19]. In contrast, with the Somnox Sleep Robot it may be possible to improve people's sleep quality in a natural way without such side-effects. Although the Sleep Robot cannot eliminate the anxieties of everyday life that prevent us from having a good sleep, it can support users in finding relaxation in bed despite the presence of worrying thoughts.

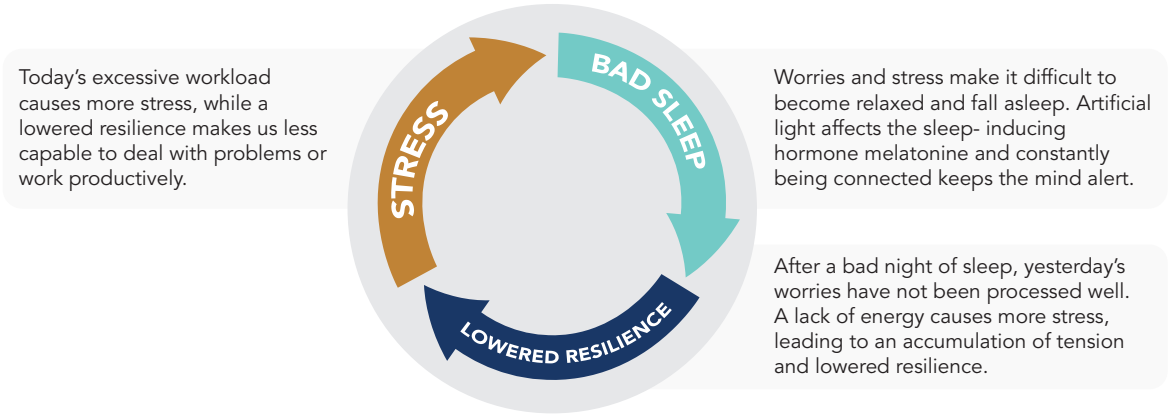


Figure 1: an example of a vicious circle of stress-induced sleep loss

WHAT IS SLEEP?

A sleep cycle consists of different stages. Light sleep (NREM 1 + 2) is the transition from being awake to being 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 you normally do 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 [20].

Sleep can easily be disturbed by many influencing factors, such as bad sleep hygiene (e.g. light, temperature, and consumption), stress and medical conditions [21].

SLEEP DISTURBERS

Caffeine | Light | Noise | Alcohol | Stress

1 out of 5 people suffers from

SLEEP PROBLEMS[3]

Insomniacs may have problems with..[10]

- Initiating sleep
- Frequent awakings
- Early morning awakenings

CONSEQUENCES

Sleep problems have a large impact on health and quality of life [4, 9, 22-24]

- Obesitas, diabetes, immune system suppression
- Less productivity
- Stress, depression
- (Car) Accidents
- Economic burden

INTERVENTIONS

In order to improve sleep quality and overcome sleep problems, several solutions exist. We will only take into account some solutions that can help in a natural way [11].

- Sleep hygiene
- Stimulus control
- Cognitive behaviour therapy
- Relaxation exercises
- Technology

The Somnox Sleep Robot

The Somnox Sleep Robot is designed to relieve the mind and body of stress, which is provided by three elements: breathing, sounds and affection. In this section, these aspects are explained in relation to physiological responses of the body.

Breathing simulation

The Somnox Sleep Robot mimics the rise and fall of the breath, which is similar to our physical breathing movement. The user can feel this by holding the Sleep Robot and will follow the breathing rate of the Sleep Robot. The following paragraphs explain how the breathing function of the Sleep Robot can help you fall asleep.

Autonomic nervous system
Breathing can have an effect on a person's relaxation state by influencing the Autonomic Nervous System (ANS). The ANS is regulated by the hypothalamus and controls internal glands and organs [25]. It consists of three different parts: the sympathetic, parasympathetic and enteric nervous system [25]. The sympathetic nervous system is responsible for the body's "fight or flight" reactions [25]. Secretion of epinephrine (adrenaline) helps to protect the body in times of stress: the heart rate increases, pupils dilate and gut motility decreases [25]. This allows blood to be distributed to areas that the body needs in stress situations [26]. In contrast, the parasympathetic nervous system is responsible for the body's "rest and digest" mode, for example when you are sitting and resting [26]. Lastly, the enteric nervous system is responsible for digestion functions, which can act independently of the sympathetic and parasympathetic systems [27].

For relaxation and a good night's sleep, the body should maintain a stable and constant internal environment: homeostasis. In order to achieve this, the ANS must 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.This results in shallow breathing, increased heart rate and poor sleep quality [28]. Thus, in order to attain relaxation and improve sleep, a balanced ANS is important. In figure 2, this balancing mechanism is shown.

> *"To sleep we need to become like someone else who is sleeping. Many people try to slow their breathing in order to prepare for sleep, as if synchronising their body rhythms to those of a virtual or a real companion."* - Darian Leader, author of Why Can't We Sleep

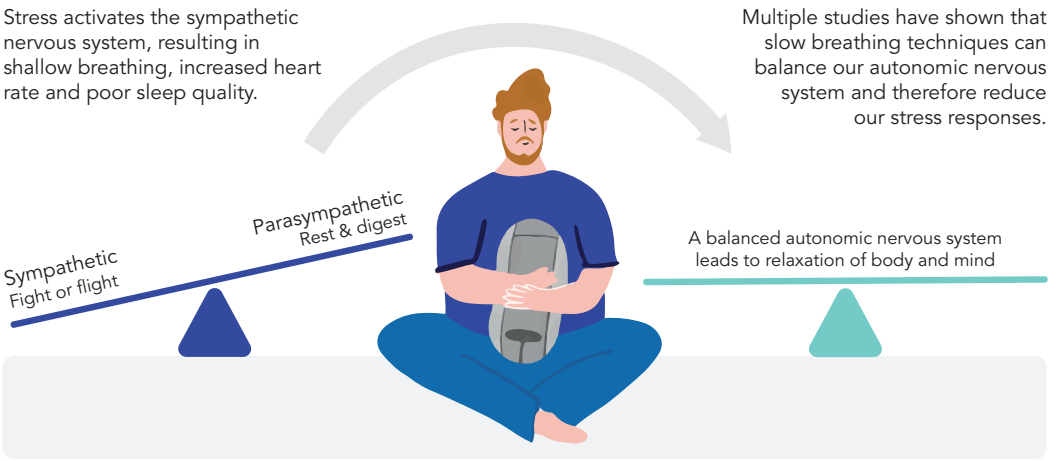


Figure 2: balancing the autonomic nervous system by slow breathing

Breathing techniques for relaxation

The actions of the ANS are not under voluntary control. For instance, one cannot decrease or increase the heart rate, pupillary response and digestive function of the intestines by conscious will. These functions are automatic [25]. However, breathing is an automated function of the ANS that can also be controlled consciously. Conscious slow breathing techniques can therefore play a role in achieving a relaxed state by balancing the ANS [29-32].

Pranayama techniques are conscious breathing exercises that are exerted in yoga practices or relaxation methods. The father of modern yoga, Patanjali, described Pranayama as a way to smoothen and lengthen the stressful or shallow breathing patterns. As a result, Pranayama can activate the parasympathetic nervous system and decrease sympathetic dominance [29, 33].

Pranayama

Pranayama techniques can be subdivided based on inhale-exhale ratios and breath retention. The underlying mechanism of the relaxation effect of slow pranayamic breathing techniques on autonomic responses is not entirely known. However, a hypothesis on the mechanism has been proposed by Jerath et al. (2006) [33]. Slow pranayamic breathing activates stretch lung receptors and cells 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 [32, 33]. Thus, slow pranayamic breathing can reduce stress responses [33].

> *"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 also used the Sleep Robot to meditate or to relax during the day."* - Test user, Feb 2019

Breathing function of the Somnox Sleep Robot

The Somnox Sleep Robot has been designed to lower the breathing frequency of the user. As a result, the user will feel more relaxed which can help with falling asleep. The Sleep Robot guides the user towards a slower breathing pattern by synchronization of the user's breathing with breathing movements of the Sleep Robot. The concept of synchronization of breathing patterns was based on a scientific study in which premature infants slept with a breathing bear. During sleep, infants usually have chaotic breathing, which can result in poor sleep. By using the bear, infants adapted to the regular breathing pattern of the bear resulting in an improved sleep quality [34]. 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 shown in figure 3. The synchronization of the human body to the Sleep Robot will further be studied in future research.

The current version of the Sleep Robot has two options in which the user can set preferred breathing patterns. 1) Users can set the breathing frequency (breaths per minute) manually. They can select a start rate and end frequency. The Sleep Robot will gradually slow down towards the selected end breathing frequency. 2) When turning on the "adaptive breathing" feature, the Sleep Robot will automatically adapt to the breathing frequency of the user. The breathing frequency will be measured by a motion sensor. The Sleep Robot adapts to the user's breathing and will gradually slow down, while constantly measuring the breathing frequency.

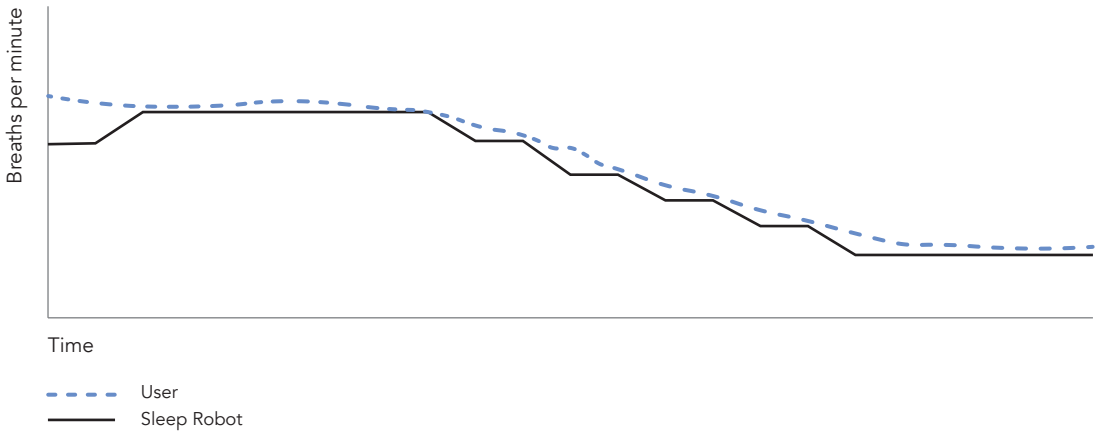


Figure 3: Gradual synchronization of a user's breathing with the Sleep Robot. After synchronization has been identified by the robot, it will start to slow down its breathing rate.

Soothing sounds

Besides breathing synchronization, music and sounds are used in the Somnox Sleep Robot. The Somnox Sleep Robot can play music, white noise, pink noise and ambient sounds to help the body achieve full relaxation mode.

Music
Listening to music at bedtime, showed to have a positive impact on subjective sleep quality in adults with insomnia symptoms [35, 36]. Another study supported this result in individuals aged 60 years and older [37]. Moreover, music interventions are very safe and easy to perform [35, 36]. Especially meditation music is known to induce a calm state and reduce feelings of stress [38]. Therefore, meditation music is integrated into the Somnox Sleep Robot. As of July 2019, users can add their own music to the Sleep Robot as well.

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 [39]. It can be used to mask unwanted or noisy sounds. For example, it can mask traffic sounds for people that live close to a highway. White noise can help to fall asleep by masking distracting noises [40]. Like white noise, pink noise contains all sound frequencies that are audible to humans. However, the intensity of pink noise is not constant for all frequencies: the intensity of pink noise decreases with increasing frequency. Researchers have shown that pink noise can induce a more stable sleep time with less sleep fragmentation and awakenings [41].

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 with falling asleep by reducing muscle tension and decreasing their heart rate [42]. 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" [43]. The nature sounds can be selected through the Somnox mobile application (figure 4). Samples of the audio designed by our partner Manglemoose are shared on our website.

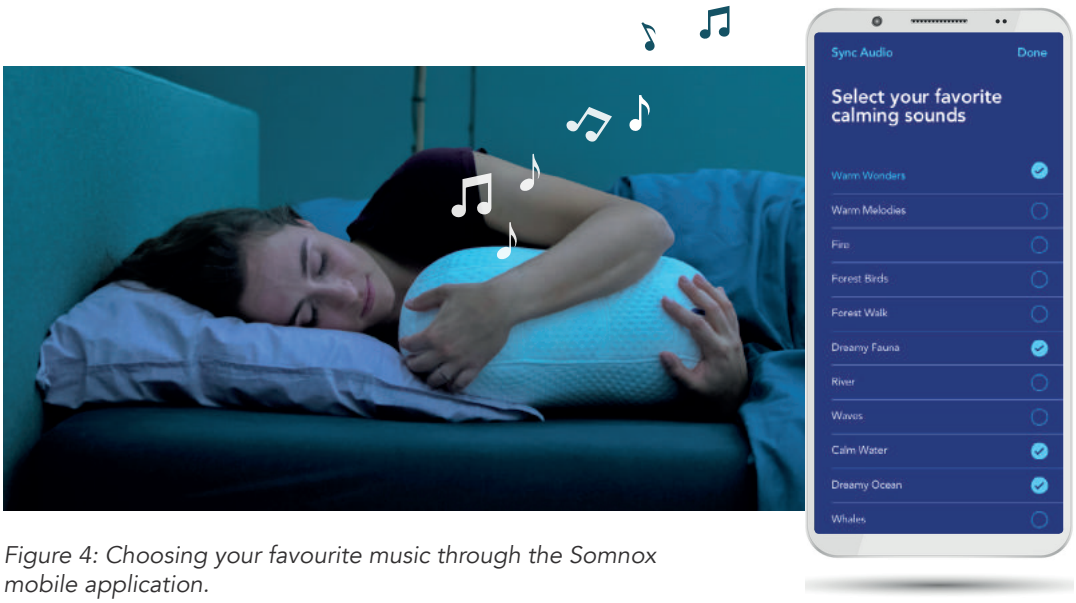


Figure 4: Choosing your favourite music through the Somnox mobile application.

Affection

The Sleep Robot has been designed to be a comfortable, useful, and easy to use product. The shape is designed to allow sleepers comfortably place the Sleep Robot to their chest, wrap their arms around it and hug it. In this way, the user can get feelings of affection by holding the Sleep Robot.

Sleep position
In order to physically feel the breathing movements of the Sleep Robot and fall asleep easier, users should hold the Sleep Robot. The shape is designed such that users can maintain a natural sleeping position when hugging the Somnox Sleep Robot, without deviating from their natural neck and shoulder alignment. It accommodates the fetal sleep position, which is the most common sleep position. However, it is also possible to hold the Sleep Robot in other positions.

> *"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

Soft robotics and ergonomic shape
The Somnox Sleep Robot is designed to be a sleep companion during the night like a living being instead of a mechanical robot. This is achieved by designing an ergonomic shape and cover the Sleep Robot with soft materials. In this way, our soft-robotic huggable Sleep Robot overcomes the archetype of robots.

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 larger surface-area-to-volume ratio. The dimensions of the Somnox Sleep Robot have been determined based on DINED, the TU Delft anthropometric database [45]. The most important body parts 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 sleepers to comfortably place it next to their chest and hug it with their arms (figure 5).

Figure 5: Sleeping with the Sleep Robot in fetal position

Research and Development

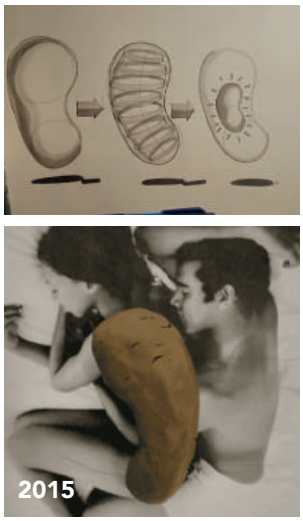
Since the start of the development process of the Somnox Sleep Robot, the technology and design have been iterated on constantly. Since 2015, over 100 people have tested prototypes at home and feedback was given by hundreds of people through surveys and interviews. Now that the Sleep Robot has been launched, development and validation of the Sleep Robot will continue.

Development

September 2015 - July 2019

The Sleep Robot was developed by four students at the robotics institute of Delft University of Technology. 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). After introduction of the Sleep Robot, software updates have been launched, including an adaptive breathing feature and the possibility to add your own music to the Sleep Robot.



The idea of a soft sleep robot was found by four engineering students. They wanted to find a natural solution for sleep problems.

The first working prototype already included a breathing mechanism and LED light. The weight of the robot was about 5 kg and the mechanism was found too noisy by test users.

After user tests, fabrics were redesigned, the size decreased and weight decreased to 2.3 kg. Furthermore, a solution was found to reduce the sound of the breathing mechanism.

Prior to launch, iterations on usability of the control panel and intensity of the breathing movement were done. A washable sleeve was designed for hygiene and protection.

Figure 6: development of the Sleep Robot. From a shape analysis through clay models (left) towards 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 a heterogeneous group of 39 people selected through a submission form. 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. Prior to the user test, 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 prelaunch 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 study set-up was explorative and observational: how do people perceive the Sleep Robot, what effects can be identified? During this study, qualitative, subjective data were gathered through weekly questionnaires, a focus group and in-depth interviews. The participants received the Sleep Robot, including the user manual, at home (figure 7). They were free to use the Sleep Robot according to their own expectations, habits and needs. In total, four participants dropped out of the study due to personal circumstances.

Results

Results are based on self-reported measures and show anecdotal evidence on the perceived effect of the Sleep Robot. The final 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.

> *"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."*

Results on the effect of the Sleep Robot

Falling asleep - Difficulty falling asleep is the most reported sleep problem amongst participants in this study. They had tried multiple other solutions already (eg. medication, cognitive behaviour therapy), without satisfying results. More than half of the participants (54%) reported to fall asleep faster when using the Sleep Robot.

Relaxation - In general, the relaxing effect of the Sleep Robot has been rated positively. The Sleep Robot was not only used during the night, but to calm down during the day as well. Most participants (83%) who used the Sleep Robot for more than three weeks reported that the Sleep Robot helped them to relax.

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

Results on 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 breathing. 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 (this featture was added to the Sleep Robot's software in July 2019).

Sounds

Several test users liked to listen to sounds or music to let go of their own thoughts. 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 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). A participant mentioned: "I have experienced the Sleep Robot as a pet".Participants who usually do not sleep in fetal position had more difficulty finding a comfortable position to sleep with the Sleep Robot. Furthermore, the Sleep Robot was experienced heavier than expected.

> *"I perceived the Sleep Robot as a pet."*

Discussion

This study showed feedback and results 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.

Usability and satisfaction on the Sleep Robot were influenced by technical problems. Feedback was analyzed by our Research and Development team during the user test and problems were immediately 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. This could have had an impact on the functionality of the Sleep Robot and therefore

> *"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." - One of the first users, May 2019*

on the results. Due to these influencing factors, the results of this pilot only show indicators for satisfaction and effect of the Sleep Robot. However, the indicators are promising and inviting for further research and clinical trials.

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 validated 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

Relaxation is essential for balancing the autonomic nervous system and falling asleep. From our first user test, we found that multiple users have experienced a positive effect on relaxation and sleep quality when using the Sleep Robot. Especially the breathing mechanism stimulates relaxation and has been rated as a 'natural' and 'relaxing' movement'. Conclusions on effectiveness cannot be drawn from this explorative study and more research will be done to validate the effect on specific target groups. In the near future, we will validate the relaxation effect of the Sleep Robot on the human body.

Final word

We have already received stories from test users and customers who could reduce their sleep medication dosage, experienced better sleep quality and were more energized during the day. Many people reviewed the Sleep Robot as a relaxing tool, sleep buddy or solution for their 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.

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