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Citation: Amores, Judith, Mae Dotan, and Pattie Maes. "An Exploration of Form Factors for Sleep-Olfactory Interfaces." 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), July 2019, Berlin, Germany, IEEE, 2019. © 2019 by IEEE

As Published: http://dx.doi.org/10.1109/embc.2019.8856805

Publisher: IEEE

Persistent URL: https://hdl.handle.net/1721.1/123847

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

An Exploration of Form Factors for Sleep-Olfactory Interfaces

Judith Amores[1], Mae Dotan, Pattie Maes

Abstract— **Releasing scent during sleep has been shown to influence the emotional valence of dreams, reduce cigarette smoking behavior, strengthen memories as well as enhance restorative slow-wave activity. Nevertheless, current scent technologies used in sleep laboratories are not portable and require the use of nasal masks and large olfactometers. In this paper we investigated the preferred form factor and acceptance of a set of biometric wearables that can release scent based on the user's physiological state. We conducted an online survey with 163 participants and evaluated 8 different form factors. The results showed that 73.5% of the subjects preferred the designs that are not wearable during the night but that can be worn during the day. We provide insights to take into account for the design of next generation sleep-olfactory technologies. We provide a literature review of sleep and scent studies and discuss the opportunities for well-being and memory applications.**

I. INTRODUCTION

There has been an increasing number of products and research that aims to create new solutions to quantify sleep and ultimately, improve sleep quality. Most of these efforts are focused on improving sleep stage detection and creating better sensors to track sleep. However, little research has gone into developing interfaces that can interact with the sleeping mind. Current interfaces are limited to smartphone apps that show your night of sleep as a diagram and provide tips to rest better. While the Machine Learning community aims to create new and better algorithms to improve sleep staging accuracy, the Human Computer Interaction (HCI) community has put their efforts into analyzing the effects of using technology right before going to sleep as well as creating comfortable sleep trackers to use at home. Still, most of the technology developed for sleep applications is exclusively focused on sleep tracking.

A typical setup for a sleep study or Polysomnogram (PSG) consists of a minimum of 22 wire attachments to the subject to track brain activity (EEG), eye movements (EOG), muscle activity (EMG), body movements, respiration, heart rhythm (ECG) and pulse oximetry. Sleep studies are conducted in hospitals or medical offices although in some cases the patient can take home some of the screening tools such as a blood oxygen monitoring device. The sleep technician or "scorer" observes in real-time the biometric signals of the subject while sleeping and interpret the results to diagnose sleep disorders and the quality of sleep.

Given the difficulties of conducting such PSG-based experiments, most of the efforts in HCI, biomedical engineering and machine learning have gone into trying to simplify scoring mechanisms and develop new sensors to track sleep at home. However, there is very little research that looks into what interventions we might use to interface with sleep. What stimuli could we make use of to improve sleep quality, increase the duration of deep sleep, reduce sleep onset latency, trigger lucid dreams, reduce nightmares and support other applications that might be beneficial for our well-being?

In our work we focus on scent as a sensory input during sleep because of its unique anatomical structure and its privileged connection to the memory and emotional parts of the brain (amygdala and hippocampus). Unlike other modalities, olfactory stimuli can be presented during sleep without arousing the subject. Olfactory interfaces are an interesting and yet to be exploited medium. Likewise, sleep interfaces offer a new way for humans to interact with technology that has not been fully defined nor explored. In this paper we combine both and propose sleep interfaces with olfactory cues as a new interaction opportunity.

A. *The Olfactory System and Sleep*

Olfactory perception takes an exceptional position in the neurological processing of sensory stimuli. When we smell, odor information goes from the olfactory epithelium to the olfactory bulb and then directly to the olfactory cortex while the other sensory systems go through the thalamus. This is an interesting neurophysiological aspect since a moderate sensation of touch, light or sound is enough to wake us up. Interestingly, the awareness of odors during sleep is in all but extreme cases, absent. Some studies show that the use of very putrid, fish-like odors like Pyridine, as well as arousing scents like peppermint that activate the trigeminal nerve, can wake people up in certain sleep stages given sufficiently high intensity [1].

Although sleep interfaces and olfactory interfaces have not yet been widely explored, the combination of scent for sleep has been researched extensively in the fields of Neuroscience and Psychology. Studies have shown how memories can be reactivated during certain sleep stages with smells [2], [3], [4] or sounds [5], [6]. Interestingly this is not effective when that same stimulus is only presented during wakefulness [7], [8] or during rapid eye movement (REM). Recent studies [9] have shown that there is no effect of memory reactivation using smell during REM. Therefore, the reactivation of memories while sleeping seems to be specifically linked to deep sleep (also referred to as SWS or N3). Similarly, if a scent is continuously produced these effects will not occur, as the user will habituate and desensitize.

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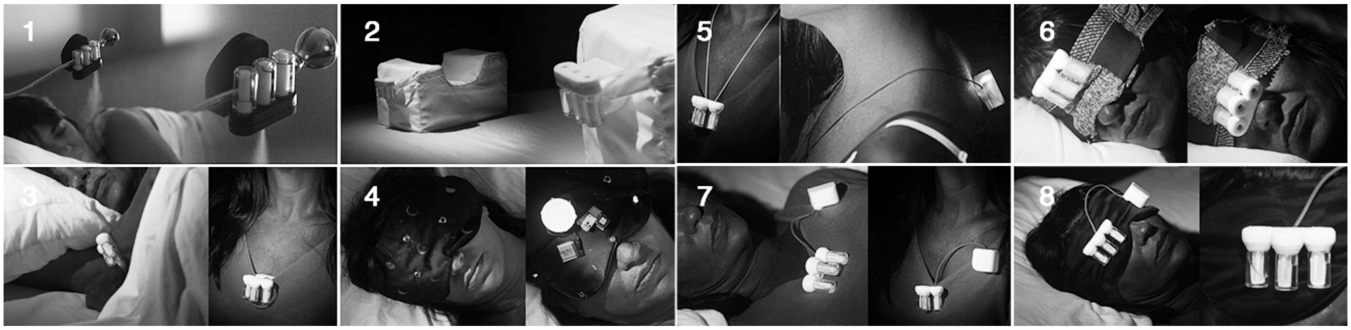

Fig. 1. Showcase of the prototypes and its form factors designed to be used while sleeping. Pictures are organized in order preference after conducting the survey. 1) Wall/clamp spot-scent. 2) Pillow. 3) Magnetic clip. 4) Padded mask. 5) Magnetic necklace. 6) Integrated mask. 7) Magnetic brooch. 8) Mask with magnetic brooch.

II. RELATED WORK

There has been a significant amount of research and development in scent displays for interactive applications [10], [11], [12], [13]. However, as far as we are aware of, there is no related work on interfacing with the sleeping mind using scent for HCI applications. Most of the related work is focused on scientific studies conducted in research labs or hospitals that use large olfactometers that are neither portable nor wearable.

Prof. Sobel's research group has conducted several studies using scent while sleeping. In one study they showed how olfactory aversive conditioning during sleep can reduce smoking behavior [14]. In another study they showed how odors influenced respiration (decreased inhalation and increased exhalation following an odor release) [15] and could be used as a potential mechanism for treating sleep apnea without waking the sleeper nor inducing arousal. Another interesting study found that triggering scents during sleep increased delta frequencies and sleep spindles proportional to the smell duration [16]. They found effects when scent was triggered every 10, 30, 45 and 60 seconds but not every 15 seconds. They did not observe a long-lasting effect when the smell was presented for longer periods of time. If the odor was presented for only 5 seconds, there was increased Slow Wave Activity but not increased spindle activity.

There have been several studies that show how scent can help induce sleep and improve its quality [17]. Other researchers have used the smell of roses to influence the emotional valence of dreams to be more positive. Schredl et al [18] compared the results of using the smell of roses, placebo or smell of rotten eggs during REM. The emotions of the dreams were significantly affected positively in the case of rose scent, and negatively with rotten eggs. The same authors conducted a more recent study that shows that if an odor is associated during wakefulness with certain images, and replayed while the person is in REM, subjects report having dreams of those images [19].

Born et al [2], [20] used odor cues to enhance learning of visuo-spatial locations. The odor was first exposed during wakefulness and re-exposed again during SWS. They showed how after sleep (only for 40 minutes), memory retrieval of 2D object-location tasks was enhanced.

In all of the studies described above, scientists used a full PSG setup and a nasal mask or nasal cannula that is connected via long Teflon tubes to a computer-controlled olfactometer. The scent release device is usually placed in an adjacent room so the noise does not disturb the subject. The device uses pumps to release scent with air flow, which are loud enough to wake up the subject if they were in the same room. In order to make sure that there is no cross-contamination between fragrances, the nasal mask pulls clean air from the environment and pushes it between scents.

One of the motivations for this paper was to explore a new form factor that would allow conducting these types of studies and development of novel HCI applications without the need for nasal masks or burdensome olfactometers.

III. OLFACTORY INTERFACES FOR SLEEP

We have created a set of biometric scent wearables that are designed to be used during sleep. The wearables detect heart rate and respiration by monitoring subtle body vibrations associated with the beating of the heart and the movement of the blood (i.e., ballistocardiography and seismocardiography). They are also synchronized with external sensors, such as the Muse wearable EEG and Empatica Wristband to monitor HR, HRV, EDA and body temperature (based on previous work [21], [22]). We took into consideration some of the current limitations of PSG setups, as well as of scent delivery systems used for sleep applications in the medical field. We came up with multiple form factors and conducted a survey to better understand users' preferences.

A. Design Rationale

Figure 1 showcases some possible wearable form factors that could offer a more comfortable solution for scent delivery during sleep. We aimed to have a silent mechanism that can release bursts of scent at a specific sleep stage and that can also be worn during the day. Therefore, some of the form factors we designed can be clipped to a pillow, lamp, textiles, or magnetic/metallic surfaces. Another design consideration was that the device needed to either detect the physiological signals of the user, or be synchronized with body sensors to properly do sleep staging and track sleep quality.

There are several parameters to be considered when releasing scent as already described by previous work [11], [22]. We gathered some of these guidelines and included insights from sleep studies, as well as new findings that we discovered after conducting our survey.

*1) **Silence**:* A typical neuroscience study uses nasal masks with a long tube that is connected to an olfactometer in a separate room to prevent disturbing the sleeper. One of our main goals was to design a device that was silent and small enough to be used as a sleep wearable. Therefore, we used ultrasonic piezoelectric transducers instead of solenoid valves, fans, or heat. Piezoelectrics are capable of triggering scent with a frequency that is not audible to the user. In comparison with heat-based scent release, which is also silent, they trigger faster with a directional burst that reaches the user's nose more quickly and do not change the chemical structure of the molecule.

*2) **Multiple Scent Release**:* The prototypes that we have created can release up to 3 different types of fragrances that can be combined and released at different frequency and duration. Our goal was to use one scent as a placebo/vehicle and another with a pleasant or unpleasant aroma for future applications around olfactory conditioning during sleep. The third scent can be an odor masking fragrance that can serve as a neutralizer. Other types of studies and HCI applications are also possible as the user can change and refill the containers with different scents. We avoided cross-contamination by designing completely independent channels for each scent.

*3) **Scent Lingering**:* Researchers tackled the problem of scent lingering by conducting their studies in ventilated rooms [23] and minimizing the amount of scent released in the air [24]. Most neuroscience studies use nasal masks to prevent cross-contamination of fragrances in the environment and pump air stream. However, nasal masks can be uncomfortable to use during sleep and might cause awakening. The most common solutions in HCI consist of releasing small doses of scent and having good ventilation in the room. Therefore, timing and minimizing the distance between the device and the nose are an important parameters to take into account when designing sleep-olfactory devices.

*4) **Scent-Device distance**:* Our aim was to design a device that could be placed close enough to the nose while still being comfortable to use while sleeping. Some previous work released odors between 3 and 10 cm away from the user's nose and used larger distances when using compressed air [25]. The distance varies according to the odor strength, fragrance dilution as well as age or sex of the participant. One of the virtues or problems of using scent while sleeping is that the user cannot consciously report the distance preference. It is therefore necessary to integrate biometric sensors for real-time adaptation of scent regulation based on the user's unique preferences, as well as being able to change the position of the prototype. To meet the needs of multiple users, we decided to embed magnets in the prototype so that they can easily clasp it and move it depending on their preferences. We chose to design form factors that are close to the nose so a higher concentration of scent can reach the olfactory receptors with a lower quantity of scent, therefore reducing the number of times the user needs to refill the container, as well as increasing battery life.

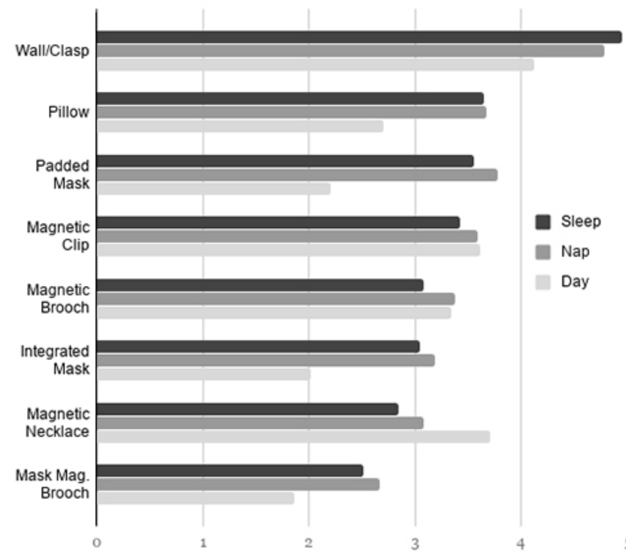

Fig. 2. Participants were asked to rate the prototypes based on how convenient they seemed for sleeping, napping and daytime. 1= Very poor, 2= Poor, 3 = Fair, 4 = Good, 5 = Very Good, 6 = Excellent, 7=Exceptional. Magnetic Brooch average STD: 0.30, Wall avg. STD: 0.54, Pillow: 0.27, Integrated Mask: 0.29, Mask Magnetic Brooch: 0.22, Magnetic Clip: 0.33, Magnetic Necklace: 0.27, Padded Mask: 0.33

*5) **Time and intensity control**:* In order to avoid habituation and desensitization [26], the prototypes release bursts of scent at specific times as opposed to a constant release. Releasing scent using a humidifier or placing some drops of oil on a pillow before sleeping will habituate the user in the first sleep stage.

*6) **Biometric Information**:* The wearables that we have designed can link the individual's physiological state and the physical location with an olfactory response, supporting emerging approaches for self-monitoring and self-awareness. They are based on the designs described in BioEssence clip [21] and Essence necklace [22]. In this paper we focused on expanding on these designs for sleep applications.

B. Form Factors

We designed a set of form factors that can be clipped onto pajamas, textiles, sleeping masks, pillows or clasps on the wall or the bed frame. Some form factors such as a nightstand scent release were not considered, as the quantity of smell required to be released in order to reach the nose would be hard to control. Cross-contamination of fragrances across the room and control of how much scent the subject has inhaled would also be difficult to quantify. Therefore we limited our design to a wearable/attachable device that can be placed in proximity to the user's nose. The olfactory wearable can release up to 3 different fragrances, designed to contain a positive fragrance, a negative fragrance and a neutral one. The neutral fragrance can either be used as a placebo or as a masking odor, releasing it to camouflage the previous scent. The containers can be refilled with other fragrances resulting in an efficient and convenient setup for performing sleep studies.

The form factors we considered were designed to optimize the distance between the burst of scent and the nose. Figure 1 shows a series of prototypes that are synced with sensors that track heart rate, respiration, electrodermal activity and brain activity to release scent just-in-time during sleep and wakefulness. The user is in control of the type of scent released and when it is triggered. We used similar electronics as the ones in previous work [21]. One difference between the designs are the piezoelectrics. We decreased the size of the piezoelectrics for the *Padded Mask* design. We also changed the microporous internal size of the piezoelectric so that it would be capable of triggering a higher quantity of fragrance in less time (20um). The industrial design varies from previous work in the case of all the magnetic prototypes (brooch, mask, clip, necklace). The Wall/clamp spot-scent was based on BioEssence and manually attached to an Ikea spotlight. In the case of the pillow, we customized a commercial pillow and sewed 2 textile strips on its sides to hold the prototype. In the following section we describe the different form factors which were the subjects of our survey as seen in Figure 1.

1) Magnetic Brooch, Magnetic Necklace, Magnetic Clip, Mask with Magnetic Brooch: These 4 designs are the same prototype in 4 different form factors. It can be attached to textiles or metallic surfaces. For the *Magnetic Clip*, the frontal part of the prototype has the smell actuation, and the back part the electronics. They are both encapsulated in 3D printed cases (see Figure 1, 3) and can be magnetically connected to form a clip and ensure that the device stays in place while sleeping. For the *Magnetic Necklace*, the frontal part triggers scent (Figure 1, 5), and the back part, sitting around the neck, contains most of the electronics. One can also attach the prototype to a regular sleeping mask using magnets (*Mask with Magnetic Brooch*, Figure 1, 8).

2) Wall/clamp spot-scent: The user can attach the prototype to the adjustable arm and direct the scent where they want. The components are encapsulated in a 3D printed case (see Figure 1, 1), with the frontal part of the prototype (smell actuation) and the back part (electronics) connected to form a clip that the user can also wear.

3) Padded Mask: We designed our own sleeping mask with 2 layers of textiles. We embedded the electronics in between the layers, and sewed flat, 3D printed containers to the back of the first layer for the smell actuation. (see Figure 1, 4).

4) Integrated Mask: We digitally knitted a sleeping mask with various types of stitches and waterproof yarns. The knitted sleeping mask holds the scent release containers. The electronic components are inserted in one of the padded pockets of the sleeping mask (see Figure 1, 6).

5) Pillow: This customized neck pillow allows the user to clip the prototype on the sides of the pillow. The frontal part of the prototype (smell actuation) and the back part (electronics) are both encapsulated in a 3D printed case (see Figure 1, 2), and are connected forming a clip that they can also wear.

IV. SURVEY

We conducted a survey to study what the preferred form factor may be for scent release systems that could be used during sleep. The survey consisted of a set of questions to rate the prototypes on how comfortable and convenient they seemed to the user if worn while sleeping, napping and during the day. A total of 163 subjects participated; 91 females, 68 males, 1 transgender and 3 not listed. The mean age was 32; the youngest person was 16 and the oldest 72 years old. The participants had to rate a series of scent prototypes based on their sleeping habits or disorders. There were some other questions about frequency of wearing sleeping masks, brooches, lapel pins and necklaces (never, once a year, once a semester, monthly, weekly, daily). The survey was anonymous and took less than 10 minutes to complete.

We expected to find more negative results for those participants that did not wear sleeping masks or fashion accessories. We also hypothesized that form factor preferences would depend on sleeping position. 71% of people said that they never wear sleep masks. ≈80 % said they never wear brooches/label pins. In the case of necklaces, the results were slightly different. 45 % of people reported to never wear necklaces, while ≈17.64 do so daily.

A. Results

Approximately 60% chose the wall/clamp spot scent as their favorite design (97 out of 163). 13.6% chose the pillow, 9.3% the magnetic clip, 8.6% the padded mask, 5.6% the magnetic necklace, 1.9% the integrated mask and 1.2% the magnetic brooch. No one chose the mask with magnetic brooch. The results show that there is a clear preference for form factors that are not worn while sleeping. 73.5% of participants chose the two designs that are not worn on-body while sleeping, but that can be used during daytime as a wearable clip or necklace.

We used a 7 point Likert scale to evaluate the comfort and convenience of the devices to be worn while sleeping, napping and daytime. As shown in Figure 2, people ranked the *Wall/clamp spot scent* the best for sleep (4.95), nap (4.7) and daytime (4.1). Contradictory to these results, participants rated the *Pillow* for daytime with an average of 2.69. We suspect that the participants were not aware that the *Wall/Clasp spot scent* was the same design as in the *Pillow*, but with a different way of attaching it.

The second highest ranked design to be worn during daytime was the *Magnetic Necklace*, with an average of 3.7. As expected, lower ratings (average of 1.9) were given to the Padded Mask and Integrated Mask for daytime use, as they are not meant to be used during the day. However, participants also rated poorly the *Mask Magnetic Brooch* for daytime, even though the brooch is the same as in the magnetic clip or necklace. We suspect that when asked for ”daytime” they did not think about walking on the street, but rather resting on a bed or sofa, which could explain why they might have rated the wall/clamp and the magnetic clip and brooch positively but not the *mask magnetic brooch*.

Overall, people ranked the comfort and convenience of the prototypes higher for sleep than for daytime, except for the case of the *Magnetic Necklace*, *Magnetic Brooch* and *Magnetic Clip*. All the form factors were ranked more positively for napping than for sleeping, except for the case of the *Wall/clamp spot scent* and the *Pillow* with almost the same values.

Overall, we received positive feedback and participants offered very interesting ideas such as combining the wall/clamp and the pillow prototypes. The sensors would be embedded in the pillow while the wall/clamp would trigger the scent. Another idea was to have liquid filled pouches that can also be used with the pillow or even as the pillow. Another participant mentioned a version that magnetically attaches to the bed sheet/mattress or is hosted inside a standard pillow.

V. Conclusions

We presented a literature review of sleep research with a focus on odor stimuli, after which we discussed guidelines for the design of sleep-olfactory displays and reported on the results of a survey to evaluate desirable form factors. We focus on the sense of smell due to the olfactory system's unique anatomical structure and its privileged connection to memory and the emotional parts of the brain. The present findings support the development of off-body olfactory interfaces and physiological sensors for use while sleeping. The results of the survey showcase positive attitudes towards this new technology and encourage further quantitative analysis of the preferred form factor (Wall/Clasp prototype). Other design considerations should be considered such as off-body physiological sensing for sleep staging. We hope that this work will foster interest in the biomedical engineering and HCI community to develop scent technology and conduct studies outside of sleep laboratories. We believe that sleep-olfactory wearables are a promising medium for real-time sleep interventions to be used in translational clinical research.

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