ESSENCE

Olfactory Interfaces for Unconscious Influence of Mood and Cognitive Performance

by

Judith Amores Fernandez

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, in partial fulfillment of the requirements for the degree of Master of Science in Media Arts and Sciences at the Massachusetts Institute of Technology

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Abstract

Our sense of smell is perhaps the most pervasive of all senses, as it has the ability to evoke memories and emotions in a vivid and subtle manner. While olfactory communication is one of the most basic methods of communication, it is also one of the least understood and one of the least exploited in human computer interaction. In this thesis we describe the hidden power of scent along with the design and implementation of “Essence”, a custom made olfactory wearable device and its stationary version. Essence is a necklace that can be used by any person in their daily life for the purpose of altering one’s mood, as well as affecting cognitive and psychological conditions. It can influence the user’s behavior through consciously perceivable as well as subliminal bursts of scent released while the person is asleep or awake. The device can be remotely controlled through a smartphone and can vary the intensity and frequency of the released scent. The system can also potentially be triggered by physiological data such as brain signals, heart rate, or galvanic skin response, etc. The types of scent that can be placed in the necklace can range from essential oils to odorless scents like hormones and pheromones. We conducted a set of preliminary studies that show an overall satisfaction, comfort and ease of use of the system. We also demonstrate the effectiveness for mood enhancing and cognitive performance during wakefulness and sleep state.

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Chapter 1

INTRODUCTION

1.1. Initial Remarks

A considerable amount of effort in human-computer interaction has been aimed at making the user experience more seamless, natural and integrated with our physical lives. When designing user interfaces, we aim to create tools that will allow the user to accomplish a certain "job" with a minimum effort, time and difficulty. When evaluating these tools, we take into account the individual's perception of the system such as utility, ease of use and efficiency. In all of our UI designs, we tend to consider the user as a conscious, thinking mind. In reality, a lot of our perception of the environment and our behavior is unconscious and does not involve deliberate rational thinking [1]. We perceive the world indirectly by processing and interpreting the raw data from our senses. Among the so-called "five senses", olfactory perception takes an exceptional position in the neurological processing of sensory stimuli. Research shows that smell influences the unconscious and differs from other forms of perception in the direct connection between the two brain areas that control emotions and memories: the amygdala and hippocampus. Interestingly the sense of sound, sight and touch do not pass through these brain areas, they are routed through the thalamus.
Our sense of smell is perhaps the most pervasive of all senses, as it has the ability to evoke memories and emotions in a vivid and subtle manner. Olfactory communication has been one of the oldest methods of communication and chemical communications is of the least understood forms of communication. In a physical social interaction, people are constantly using their sense of smell. Even though we are not very aware of doing so, our brain is responding to the odor [2][3][4][5][6]. Pheromones are like invisible social magnets to communicate below the level of consciousness.

In this thesis we explore the unconscious power of scents in the fields of psychology and neuroscience and apply this knowledge to HCl. The main motivation of this thesis is to create an olfactory device that does not stay in the realms of scientific laboratories. A technology that is comfortable enough to use for any person in their daily life for the purpose of altering one's mood, cognitive, psychological or physical conditions.
1.2. Contribution

Kahneman [7] describes two different ways the brain forms thoughts: System-1: Fast, automatic, frequent, emotional, stereotypic, unconscious. System-2: Slow, effortful, infrequent, logical, calculating, conscious. Most of today’s interfaces assume that our decision-making is done only by system-2 (rational thinking). However, we have an unconscious understanding that affects our interactions in a more primitive and instinctual way.

In this thesis we focus on creating interfaces that play an important role in the unconscious mind and send information to and receive control signals from the rest of our body. We explore the creation of a technology that targets system-1 information processing, or subliminal perception and instinctive processing rather than conventional system-2 user interfaces.

We describe the hidden power of scent and present the design and implementation of a custom made olfactory necklace (Essence) and its stationary version. We also present a proof-of-concept system that integrates brain activity signals, ambient lights and automatic scent release to subliminally influence the user’s mood and behavior.

We collect qualitative and quantitative data from users and show the effectiveness of using Essence during wakefulness and sleep state. We analyze users’ interaction with the system and present the overall satisfaction, ease of use and comfort of Essence in a real-life context.
1.3. Motivation

Current technologies are very good at connecting people remotely, but when it comes to being emotionally connected at a distance, existing technologies offer limited ways for people to feel close. All these systems require ways for expressing empathy, sharing memories, and showing intimacy and affection for deep and personal connection. During this kind of experiences, we usually involve 5 senses, however, current technologies are purely vision’s dominated over other senses. In a daily life social interaction, people interact with their entire physical environment using all of their senses, however, when it comes to the digital world, our interactions are restricted to an audio-visual experience and limited to the small screens of our computers and smartphones. Therefore, we become isolated from the environment and the rest of our senses are in “standby” mode.

Before the wide use of telecommunications, letters were one of the few ways for people to remain in contact and keep memories, especially during wartimes. People often used to spray their own perfume on letters to recreate the intimate and physical connection they had while being together. During my time as a graduate student I explored several ways for people to better communicate at a distance, mostly using the sense of sight, touch and sound (Showme++, Tagme, Social Textiles) [8][9][10][11][12].

By supporting some of these additional means of communication, ShowMe++, TagMe or Social Textiles can make people feel more closely connected and enables more effective means of communication. Over the period of my
Masters research, these projects lead me to think about other ways of communicating at a deeper and more connected level. Subliminal perception, unconscious information processing, nonverbal communication, olfactory communication, etc. Essence was the inspiration to create a system that would be less an extension of oneself but rather a part of ourselves, enhancing existing perceptions by subliminally affecting human behavior to help focus, relax and communicate better.
1.4. Thesis Overview

This thesis starts by providing an overview of the importance of scent in our life. We present a summary of established research in psychology and neuroscience; how smell influences memory and emotions, strengthens interpersonal ties and can be used for early cancer detection (Chapter 2.1). We then provide an overview on the physiology of the olfactory system and how the sense of smell works; how the olfactory bulb is directly connected to the two brain areas that control emotions and memories and why it can influence the unconscious (Chapter 2.2).

In Chapter 2.3, we explain what does olfactory communication mean, the differences between hormones and pheromones and its role in mate selection and survival.

In Chapter 3 we provide background into olfactory interfaces, from the ancient history of scent (Chapter 3.1) to related work in the human computer interaction field (Chapter 3.2).

We then describe the Essence system, the implementation of both the wearable and stationary device and how the design and fabrication was made (Chapter 4). In Chapter 5 we describe a range of different applications that make use of Essence while asleep, learning or interacting with another person. In Chapter 6 we present the evaluation of the system in two different case scenarios: (1) sleep and post-traumatic stress disorder and (2) real-life context situation while performing a cognitive task of memorization. We show the effectiveness in both cases and explain the ease of use, satisfaction and overall comfort of the users while using the system.
Chapter 2
THE HIDDEN POWER OF SCENT

Scent is invisible, intangible, yet the most pervasive sense with strongest emotions and memories attached.

2.1. The Importance of Smell

It had been widely accepted for nearly a century that a typical person can discriminate no more than 10,000 odors, but in 2004, C. Bushdid, M. O. Magnasco, L. B. Vosshall and A. Keller discovered that humans are able to discriminate at least one trillion or 1,000,000,000,000 different odors [13]. The study was published in the Journal Science, and involved the creation of unique combinations of smells derived from mixtures of odor molecules. This discovery makes the human sense of smell more discriminatory than human color vision, which can distinguish between 2.3 million and 7.5 million color variations, or human hearing, which can discriminate about 340,000 sound tones. Nevertheless, as humans we don’t tend to perceive the sense of smell as all that important in our lives. In fact, in a survey of 7000 young people around the world, about half of those between the age of 16 and 30 said that they would rather lose their sense of smell than give up access to technology like smartphones or laptops [14]. This willingness to sacrifice one of our human senses to stay connected shows not only how intrinsic technology has become to us, but also how little we are aware of our use of smell and its impact upon our daily life.
2.1.1. Memory and Emotions

Smell has a primary connection with our memory and how we feel. When we first smell a new scent, we link it to an event, a person; we link it to the feelings and sensations that we are experiencing at that time. Afterwards, our brain forges a permanent association with that memory and when we encounter the smell again, the link is already there [15][16][17]. That might be one of the reasons why we have so many smell-based memories associated to our childhood (Figure 1).

Figure 1. Scented memories are kept forever, like the fragrance of someone special, the smell of playdoh during kindergarten, vanilla ice-cream, the smell of an old book, etc. Photos by Pinterest.
Previous work has demonstrated that memories evoked by odors differ from memories evoked by words and pictures [18]. Specifically, events triggered by odors are older, more emotional, and evoke stronger feelings of being brought back in time. Odor-evoked memories produce stronger emotional arousal than events triggered by other sensory modalities [19] (e.g., Chu and Downes 2002; Herz and Cupchick 1995; Herz et al. 2004; Herz and Schooler 2002; Willander and Larsson 2007).

Scent has a hidden power in our behavior and the unconscious. The first study to demonstrate a relationship between empathy and smell dates back to 2002 [20]. Positive and negative emotions not only transfer between individuals through mimicry of vision and hearing but also through smell. Happiness can be communicated through the sense of smell via chemical signals. Humans are able to smell feelings of fear and disgust through sweat and then experience the same emotions [4]. Researchers took body odor samples from users in a happy state and then released them to the receivers, which lead to positive facial expressions and the feeling of happiness [6]. A recent study published in Chemical Senses Journal has proved that the body odor of a stranger with the intention to harm induces an affective modulation compatible with an anxiety reaction in test subjects [5].

Other studies show that stress and anxiety can be reduced with the use of essential oils. Researchers administrated Heliotropin (a vanilla fragrance) to patients undergoing cancer treatment [21]. The results reported that the administration of fragrance was associated with 63% less anxiety versus placebo effect.
Another study examined aromatherapy effects on feelings of relaxation, anxiety mood and alertness and on EEG activity and math computations [22]. The group that used scent of lavender performed the math computations faster and more accurately following aromatherapy and reported feeling more relaxed. Other studies showed that the use of peppermint do not create significant trends in memory performance, however, there were significant differences in the speed and accuracy of the tasks. The results suggest that peppermint scent promotes a general arousal of attention, and people stay focused on their task and increased their concentration [23][24].

While essential oils and fragrances have been widely used in aromatherapy for therapeutic purposes as a form of alternative medicine (Figure 2), there has been little research and there is still a lot of controversy regarding its scientifically-proven medical evidence. A limited number of clinical trials have concluded that essential oils do provide a
potentially effective treatment for psychiatric disorders, including Alzheimer’s disease and related dementias [25][26]. Unfortunately, judging by the clinical trial’s literature, the use of aromatherapy is rarely considered by the medical profession. Most of the controlled trials that have been conducted are only in relation to mental disorders but not so much in other application areas. This fact might reflect the lack of effective treatments and drugs for people with dementia, leading to innovative research and alternative treatments for some of the symptoms.

2.1.2. Strengthening Interpersonal Ties

From the time we are born, to the moment of our death, smell pervades every aspect of our lives and guides our behavior in ways that we are not conscious of. Until recently, it was believed that the ability to smell depended on breathing in air, however in the uterus, babies breathe in only amniotic fluid. The inhalation and swallowing of amniotic fluid are the first chemosensory experiences we perceive. The chemical senses, smell and taste, are ancient sensory modalities and provide crucial information for survival. Although a baby’s nose is formed by the 8th week of gestation, the fetus can recognize flavors and scents related with the food her mother has eaten. This might be one of the reasons why newborns after birth recognize their mothers and are drawn to the scent of breast milk although they have never been exposed to it before [27][28].

The sense of smell is intimately connected to nutrition and allows us to reject foods that might be harmful and seek out those that are beneficial and pleasurable. This rejection is
triggered by strong emotional reactions. The sense of smell differs from the other forms of perception in the direct connection between the olfactory and the limbic system, our emotional center. Evolutionary pressure has produced elaborate olfactory systems that contribute to the survival of both the individual and the species. Body odor is strongly influenced by diseases or psychological conditions; a clear example is the smell of death. In many animals, body odor plays an important role in survival function. For example, Opossums, when threatened or harmed fake their own death. They mimic the appearance and smell of a dead animal. Skunks release a powerful foul odor when they feel attacked. Bombardier Beetles, Wolverines, Stink Bug, Musk Ox, Tasmanian Devil, Lesser Anteater, Millipede, are only some of the many other animals that use scent mechanisms to survive.

Animals rely heavily on the sense of smell for communication. Many of them also rely on the sense of smell to determine sex, social rank, territory, reproductive status and even the identification of individuals, such as their own mates or hatchlings via pheromones (see Chapter 2.3).

Some of these metabolites are volatile organic compounds (VOCs) and are present in the exhaled breath, feces, urine, blood, sweat or skin. Dogs have an exquisitely sensitive sense of smell and can pick up these VOCs.

2.1.3. Cancer and Disease Detection

Over the years there have been many anecdotal reports from people suggesting that their dogs and cats saved their lives and were able to "sniff" their cancer or diseases. In the case of dogs, this fact has been finally scientifically proven and argued
with robust evidence [29][30][31]. Recently the National Health Service (NHS) has introduced new innovative methods to detect prostate cancer in its early stages using trained dogs [32] (Figure 3). Their studies demonstrate that dogs can detect urological cancer earlier, and with greater accuracy than current test methods. Initial studies have found that they can successfully detect this cancer in 93% of cases. Current research is looking into other diseases that dogs might be able to detect from scent such as Breast, Lung, Colorectal Cancers and Parkinson Disease. There is even a case of a woman whose super sense of smell detects Parkinson disease [33].

Figure 3. Dogs are being trained specifically to detect different types of cancer. This method is still used in airports as well to sniff out drugs. Photos by Telegraph and BBC Video.

On the other hand, recent studies found that loss of smell can be an early identification of an increased risk of Parkinson’s disease [34] or Alzheimer [35]. Losing the sense of smell predicts death within five years more accurately than did a diagnosis of cancer, lung disease or heart failure [36]. The explanation is that the production of new smell cells declines with age, and this is associated with a gradual reduction in our ability to detect and discriminate odors. Interestingly, loss of smell may indicate that the body is entering a state of disrepair, and is no longer capable of repairing itself.
2.2. Human Physiology

2.2.1. Olfactory System

The sense of smell was the hardest of the senses to crack; in 2004 Linda Buck and Richard Axel Land won the Nobel Prize for their discovery of how smell works and how the brain interprets it [37]. Their discoveries of odorant receptors and the organization of the olfactory system revolutionized the field. Buck provided evidence in support of a combinatorial model for odor coding: an odorant can activate multiple receptors, and a receptor can be activated by multiple odorants.

As humans we have around 400 different kinds of scent receptors in the nose. These receptors are nerves that are exposed to the outside air in the nose cavity. When we sniff, volatile organic compounds (VOC) come into our nose and meet with these receptors. For example, when we smell brewed coffee, VOC are in the air, specific receptors are going to detect the molecular components of the coffee and send the message to the brain. The brain knows what we smell because of the combination of receptors and nerve cells that they trigger, sending messages up to the brain in a combinatorial fashion (Figure 4).

There are two ways of perceiving smell, the Orthonasal and the Retronasal. The most common way of understanding smell or sniffing is Orthonasal smell perception. As described above, it is when volatile molecules bump into the nose and it is usually used to sense odors in the environment. Retronasal perception happens while we are
eating food and volatile molecules are released inside the mouth. In this case, the receptors are activated only when breathing out through the nose between mastication and swallowing. This is the reason why food loses its aromas and flavors when we have a cold and our nose is stuffed up.

Figure 4. The olfactory bulb is located in the forebrain that receives neural input about VOC detected by cells in the nasal cavity and processes the odor information. Design by Judith Amores.

2.2.2. Neural Pathways

Smell is a very complex and deep sense, very different from the other four senses. The sense of smell differs from the other forms of perception in the direct connection between our olfactory receptors and the limbic system, our emotional center.

There are three general areas of the brain, the first and most basic is the brain stem, which controls basic functions such as breathing and heartbeat. The next higher area is the
limbic system in the central area of the brain. The limbic system is where emotional responses are concentrated. When various areas of the limbic system are activated, a person feels intense emotions. Some limbic areas cause feelings of peace, contentment, attraction while other areas causes feeling of anger, rage, hostility, loneliness and so on.

The conscious brain is the topmost and outer area of our brain. This is where we spend our time thinking, but the conscious mind is not where emotions develop.

The olfactory bulb has direct connections to the two brain areas that control emotions and memories: the amygdala and hippocampus (Figure 5). Interestingly the sense of sound, sight and touch do not pass through these brain areas, they are routed through the thalamus [2]. This particularity of traveling through the thalamus is also responsible for the ability of sound, sight and touch to interrupt sleep.

Olfactory perception takes an exceptional position in the neurological processing of sensory stimuli. In all other sensory systems, a moderate sensation of touch, light or sound is enough to wake us up. Unlike the other senses, a smell is not enough to wake us up unless it is so strong that it becomes stinging (and therefore is more like a touch sensation). This makes smell an especially interesting modality to use in human-machine interaction during sleep as well as wake states. It is processed by the brain but does not disrupt the ongoing brain processes as easily.
Olfactory bulbs: The connection of these structures with the Limbic system helps explain why the sense of smell evokes long-forgotten memories and emotions. Amygdala: This structure influences behavior and activities so that they are appropriate for meeting the body's internal needs. These include feeding, sexual interest, and emotional reactions such as anger. Hippocampus: This curved band of gray matter is involved with learning and memory, the recognition of novelty, and the recollection of spatial relationships.

Figure 5. Image of a human brain, in color is the structure of the Limbic System. Design by Judith Amores.
2.3. Pheromones and Hormones

A special category of scents is pheromones and hormones. Neuroscientists and chemists have found that our bodies instinctively react to oxytocin, dopamine, endorphins, serotonins and other chemicals to form close, nurturing, and happy relationships.

Oxytocin (Figure 6) is a hormone produced in the brain that is then transported to the pituitary gland. It is often referred to as the "love hormone" for its role in sex, birth and breastfeeding. It is also important for controlling food intake and weight. Oxytocin stimulates attachment and creates feelings of calm and closeness. Higher oxytocin levels help you create deeper connections to friends, family, and romantic partners. It's a powerful happiness and love hormone.

For biologists, olfactory communication refers to the exchange of pheromones within one species. Pheromones are volatile components that cause instinctive reactions within one particular species. They are commonly known as the sex scents. Animals, plants and even bacteria produce pheromones. For example, ants establish their trails with a succession of pheromones deposits that results in a complex network of interconnected...
routes (Figure 7). You can easily test this by drawing an invisible line with your fingertip in between an ant trail. The ants will immediately get confused and loose their clue as to where to go and you will see them all going in random directions.

Male dogs can respond to pheromones from a female dog at distances up to three miles and at concentration that the dogs are unlikely to consciously smell.

While the effects of pheromones in animals are more obvious than in humans, growing evidence suggests that human body odors carry chemical signals that affect mood and menstrual cycles [38]. Until recently, pheromonal communication was only identifiable in animals, but since 2006 there has been research around the possibility that humans may also communicate via pheromones [39].

One of the reasons why scientific research on this topic has been delayed is because of cultural roadblocks, which made people reluctant to study the existence of human pheromones. On the one hand, westerners tend to think negatively of smell. Social sniffing is considered animalistic; we also combat body odors and attempt to cover our natural aromas by using fragrances and a variety of deodorants and perfumes. On the other hand, most of the studies so far focused on looking for human pheromones only in armpit sweat. Probably the reason why researchers have been doing so is...
because it is the less embarrassing when asking for samples. However, almost one-third of the world population does not have smelly armpits - Chinese, Koreans and Japanese have fewer apocrine sweat glands. Therefore, human armpits might not be the best body part to look for human pheromones.

The first mammalian pheromone to be identified was Androstadienone (Figure 8). Is a VOC that can be found in human sweat and it has been reported to significantly affect the mood of women and men [40][41][42][43].

Much study has been devoted to the possibility of a universal sexual attraction pheromone but because of the existence of genetic compatibility (such as immune system specificity) another layer of complexity is added. Each person’s immune system is resistant to a unique array of diseases (histocompatibility complexes or MHC). Humans can identify if a person genetically correlates to their own DNA by checking his or her body odor. The first study to prove this was the famous "sweaty T-shirt experiment" [44]. Several men were asked to wear the same t-shirt for two days. Various women were then asked to rate the top most sexually attractive t-shirts. The results showed that women were most attracted to men with most opposite MHC.

Pheromones also play a role when mothers recognize their babies and vice versa [45]. A recent
study found that newborns experiencing pain were soothed by the smell of their mother's breast milk [46]. Newborns also respond to the smell of breast milk by making mouthing movements. In one experiment, newborns were presented with the smells of different breast milk samples (by their mothers and by random women). The babies mouthed more in response to the scent of their own mothers' milk [47].
Chapter 3

OLFACTORY INTERFACES

3.1. The Ancient History of Fragrances

The word perfume comes from the Latin words “per” meaning “through” and “fumus” meaning “smoke”. Over 4000 years ago the Mesopotamians began creating incense. Throughout the ancient world Egyptians were also famous for their scents and perfumes (Figure 9).

Figure 9. On the left, Egyptian Museum of Turin: cosmetic box and various vessels of Merit. On the right, a representation of Egyptian women with cones of wax and perfume on their heads. The wax would melt from their body heat over the course of the evening, releasing the fragrance over time. Images by Wikipedia.

Egyptians associated perfumes with the gods and recognized their positive effect on health and wellbeing. They often carried perfume with them from birth and right into the grave, or tomb for the afterlife. They even had a god of perfume “Nefertum”, who was also a god of healing.
In ancient Rome, gladiator sweat was considered an aphrodisiac and was sold to rich women for cosmetics (Figure 10). As mentioned in others sections of this thesis, the odorous steroid compound Androstadienone, found in axillary sweat has been proven to influence the perception of facial and vocal attractiveness [48]. Interestingly, the gladiator reference is still used as an icon in modern perfumery (for ex. Jean Paul Gaultier Le Male Gladiator Cologne).

Figure 10. On the left, strigil or scraper. Romans didn’t use soap, but oil (hence the bottle) in a public ritual of oiling up, exercising, steaming, sweating and then scraping with the strigil across the sweaty skin. Slaves would keep gladiators scrapings to sell them afterwards. On the right, scraping off the oil with a strigil (480BC attic red-figure kantharos). Images by Classical Association and Knead to Write.
3.2. Olfactory Interfaces in HCI

While scent has been widely explored in art [49], the olfactory system has been rarely appreciated in the technological world. We have found ways to reproduce and sense audio-visual and haptic experiences but olfactory reproduction is fundamentally different from that of reproducing visual or sound stimuli. Olfaction and taste are chemical senses, whereas the relatively well-developed sensory interfaces (visual, auditory, and haptic) are related to physical stimuli. Visual reconstruction consists of spatial distribution of its wavelength and luminance; audio consists on pitch, volume and timbre. In modern computer systems, visual and auditory interfaces are highly developed, and there are numerous ways for users to obtain information through visual and auditory channels, however, olfactory interfaces still remain novel and unexplored.

Figure 11. Smell-O-Vision by Hans Laube and InStink by Joseph Kaye.

The history of olfactory technological research can be first dated to the late 50's, when scents were released during the viewing of a film, so that the viewer could associate certain smells with scenes of the movie (Smell-O-Vision [50] and Sensorama [51]).
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Fig. 12. Sensorama was one of the first Virtual Reality systems. It was an immersive, multi-sensory device that had stereo sound, smell, vibrations on the seat and wind simulation. By Morton Heilig.

A decade ago, the Human Computer Interaction (HCI) research community started looking into the challenges and possibilities for smell-based technology [52][53][54]. One main challenge is the complexity of producing arbitrary smells on demand. Humans have a thousand different olfactory receptors in their nose, each sensing a different chemical bond [55]. Reproducing arbitrary smell would therefore require a thousand-dimension space, which presents significant challenges compared to the 3-dimensional space of vision (RGB). Another challenge is the difficulty of creating a systemic and reproducible classification scheme for smell. As humans refer to smells through ambiguous descriptions, it is difficult to create a rigorous categorization for universal reference.
Recent HCI research and product developer efforts have focused on enabling scent to become part of digital communications rather than facing the chemical engineering challenge of capturing odors. Most systems use off the shelf aromas in their prototypes, focusing research efforts on the device itself.

Ranasinghe et al. [56] explored the use of smell for digital communication, enabling the sharing of smell over the Internet. By recreating smell through form, Clayodor [57] explores the possibility of form as a user-controlled navigator for smell. A recent commercial product is the Ophone [58]; it has 32 unique smells that can be combined to create tags for a message or a photo and be sent through Internet and reproduced on the other side. A similar idea is Scentee [59] which emits a fragrance when a notification is received in your smartphone (Figure 13).

SensorWake (Figure 14) is a crowd-funded project that serves as an olfactory alarm clock and it is meant to wake you up using scent. Another display system is "The Smelling Screen" [60] that can generate smell distribution on a 2D screen.
Brewster et al. [61] developed a smell-based photo-tagging tool (Olfoto) that aimed to find out if smell could play a role in photo searching and compared it to text tagging.

While a lot of research and commercial products focus on transmission and reproduction of smell [56][57][58][59][60][61], there are still a lot of unsolved problems regarding the sensing part of digital scent technology. Researchers have been trying to overcome the limitations and challenges of smell-based technology by using olfactometers and building electric noses [62]. However, in order to reach sensing capabilities similar to the human olfactory system, significant advances and experimentation with chemical sensors will be necessary.
3.2.1. Wearable Olfactory Displays

Current personal, wearable devices that promote wellbeing, such as fitness and sleep trackers, are mostly designed for physical stimuli (visual, auditory and haptic). The exploration of smell-enhanced technologies is mostly limited to bulky and burdensome devices that are neither portable nor comfortable to use in everyday life situations. Moreover, the smells used are often arbitrary and not related to experiences, using off the shelf oils and scented aromas. Consequently, artificial olfaction is a technology that sits stubbornly beyond our reach.

Some artists have explored the idea of using scent in fashion or even using the body as atomizers [63][64]. The “Smoke Dress” by artist Anouk Wipprecht [65] releases a cloud of smoke when it detects a person approaching. Although they do not use scented smoke, we can easily imagine a similar system releasing fragrance (Figure 15).

Figure 15. Smoke Dress by Anouk Wipprecht.
A Danish design company called "Diffus Design" created the "Climate Dress" that has an array of LEDs that light up depending on the CO2 levels in the air [66].

Google recently filed a patent proposal for a wearable sensor that detects physical movements and automatically emits pleasant-smelling odors (Figure 16). The wearable is supposed to be connected with social networks and predict an alternate tour to avoid social interaction in case the user is smelly.

Finally, one of the closest related projects to Essence is the ICT Scent Collar. It is a scent delivery device in the form factor of a collar or bib. (Figure 17, 18). Although the main application and patent is oriented to be used in a virtual environment, the idea of using a wearable-style olfactory display is relevant for the focus of this thesis and might serve for similar applications. Essence was purposely designed to be lightweight, fashionable and comfortable enough for people to be used during their daily life. The main aim of Essence is to design and fabricate a technology that can influence human behavior through consciously perceivable and subliminal bursts of scent released while the person is sleeping or awake.
In this thesis we gather related relevant research from the fields of Psychology and Neuroscience and apply it to HCl. The main contributions that are distinct from previous work are: (1) Design of a wirelessly-controlled, olfactory necklace to be used in every-day life situations. (2) Subliminal bursts of scent using non-off-the shelf scents like hormones and pheromones in a wearable device. (3) Synchronization between the physiological data of the user and the necklace. (4) Preliminary user studies that show the effectiveness of using Essence during wakefulness and sleep state for mood enhancing and cognitive performance.
4.1. Introduction

Essence was inspired by the idea of using scents to store, encode and retrieve memories. A message in a bottle was the metaphor used for both the idea and the form factor of the wearable (Figure 19). This rudimentary form of communication whereby a message is sealed in a container reflects the scented memory encapsulated in the necklace. When the scent is released, the memory will be retrieved.
4.2. System Description

Essence (Figure 20) is a necklace that can be used by any person in their daily life for the purpose of altering one's mood, cognitive, psychological or physical conditions. It can influence human behavior through consciously perceivable and subliminal bursts of scent. The wearable can be remotely controlled through the smartphone and can vary the intensity and frequency of the released scent. The system can also be automatically triggered by physiological data such as certain brain activity (described in the following paragraphs) or heart rate.

Figure 20. Accessories like rings can be used as decoration elements and personalization of the necklace (first and second image starting from the left). Photos by Judith Amores.
4.2.1. *Essence* Wearable and Stationary Device

We designed and developed a portable smart necklace called *Essence* (Figure 21, Figure 22.AB) and a bigger stationary prototype that has larger containers for six different types of scent (Figure 22.C).

*Figure 21.* On the left, close up of the *Essence* necklace. On the right, the *Essence* necklace and the stationary device. Photos by Judith Amores.

*Figure 22.* (A) Front part of the *Essence* necklace. (B) Closing and back part of the necklace – the case contains the electronic components that control the system. C is a big stationary version of the prototype that has 6 different scents and can be controlled through the same mechanism.
Both the necklace and the stationary device can trigger scents using a custom-made smartphone application. The current prototype works with Android and has been tested with several smartphones such as Nexus 6P and Samsung Galaxy S6. The software runs with API 23: Android 6.0 (Marshmallow) and communicates through Bluetooth with the necklace and the stationary device. The app runs in background, so unless the user wants to specifically change some parameters such the frequency or amount of the desired scent, there is no need to open the app. The default parameter is 1 second of burst every 20 seconds, additionally the user can manually release extra burst of scent by pulling the necklace down. The app is also capable of detecting location (GPS), date and current time.

4.3. Implementation

4.3.1. Wireless Communication

To endow the necklace with communication capabilities to be remotely controlled through the smartphone application, we used a microprocessor that controls the whole system and a Bluetooth Low Energy (BTLE) board that implements the wireless communication with the smartphone.

In order to make the prototype portable, the system is powered with a 3.7V Lithium Ion Polymer Battery (350mAh). The user can easily charge the necklace through a small USB micro connector. Additionally there is a turn on/off button.

The microprocessor is an ATmega32u4 clocked at 8Mhz and at 3.3V logic. The chip has 32K of flash and 2K of RAM with built in USB so it can be debugged either with USB-to-Serial program or directly through the same micro USB used to charge the necklace.
The BTLE module is an nRF51822 chipset from Nordic. The hardware interface to transfer the commands, events and data packets is UART (Universal Asynchronous Receiver/Transmitter).

Although the prototype is currently working with Android, the system uses the 2.4GHz spectrum wireless protocol so it can be used with iOS without needing special certification and it is supported by all modern smart phones. This makes the necklace easily portable to iOS devices (iPhone, iPad, etc) or other Android phones and tablets. It also is supported in Mac OS X and Windows 8+.

In order to make the prototype aesthetically appealing and as light as possible, most of the electronic components and the battery of the necklace are placed at the back of the neck so as to be hidden (see figure 22.B, figure 23, figure 24).

![Image](image.png)

*Figure 23. (A) Front part of the necklace. (B) Back where the electronics are placed. Designs by Judith Amores.*
Figure 24. Starting from the two images on the right: one of the first prototypes implemented using soft electronics. We sewed an Adafruit FLORA board with a piece of textile and controlled an LED when pulling the necklace. On the left, final electronics and case that controls all the system. We made a 3D printed case to robustly cover the electronic components. Photos by Judith Amores.

4.3.2. Scent Release

The front part of the necklace holds a container with an encapsulated piezoelectric transducer that controls the release of the scent (Figure 23, 25, 26).

Figure 25. The piezoelectric transducer contains a small metal plate that vibrates in ultrasonic high frequency to release the fragrance. Photos by Judith Amores.

In order to make the piezoelectric vibrate, it needs a frequency of 100KHz, 10VAC (20Vpp). Alternating current (AC) voltage makes the plate oscillate at the same frequency and produce ultrasonic sound. These ultrasonic sounds are inaudible to the user, but they are capable of breaking the water into small particles that look like vapor. Therefore, the device transforms the fragrance/essential oil
from the container into a fine mist, instantaneously distributing the scent all around the necklace (Figures 26, 27).

Figure 26. Scent container diagram. The cap contains a piezoelectric transducer that vibrates on top of the cotton stick filter, soaking up the fragrance. The piezo then is connected to the rest of the electronics through the thread (GND and Vcc correspondingly). Design by Judith Amores.

Figure 27. Once the fragrance is depleted, the user can easily unscrew the cap and refill the container. Photos by Judith Amores.
4.3.3. Conductive Thread

Usually jewelry string serves only as a decorative element, the materials used for necklaces or other wearable jewelry do not include electronic components or cables. In this prototype we braided two cables (Vcc and GND) with a conductive rubber cord stretch sensor (Figure 28). Therefore, the thread not only serves as a decorative component but also as a connector between the microcontroller and the piezoelectric.

Figure 28. On the left, conductive rubber cord stretch sensor by Adafruit Electronics. The cord is 2mm diameter made of carbon-black impregnated rubber. On the right, close up of the different braided cables and cords of the Essence necklace (including conductive cord and Vcc/GND cables). Photo by Adafruit (left) and Judith Amores (right).

The necklace thread is a key element in the design of the wearable since it transfers power and data from the back part of the necklace to the piezoelectric (front part). The sensor measures stretch forces: as you pull on it, the resistance increases (the particles get further apart). When these values go over a certain threshold the scent is released. As mentioned previously, the necklace can also release the scent without stretching the cord (manual activation) but can also be released through the smartphone or physiological signals.
4.3.3. Stationary Device

The stationary device is an extended version of the necklace. It integrates an array of six piezoelectric transducers that vibrate and release subtle bursts of the desired scent in the same way as the necklace (Figure 29). The piezos generate ultrasonic waves to break down the liquids deposited in each one of the containers and turn them into small droplets.

Figure 29. Electronic assembly of the stationary device. Photos by Judith Amores.

The current prototype is able to release 6 different types of scent (one per PIN and piezoelectric), but it has been designed so we can easily add more. In order to make the prototype scalable, we used only one DC to AC converter for all piezoelectrics.

In order to switch between each one of the piezoelectric by only using one DC to AC, we used three PhotoMOS relay OPTO AC/DC 400V 120MA 8DIP with high sensitivity and low on-resistance (each one of the relays controls two piezos). The relays chosen are one of the smallest ones we could find before starting to design a PCB board. We are currently using only 6 pins that are directly connected to the board (Figure 31), however, if more piezoelectrics need to be added, the 16-Channel Analog/Digital Multiplexer can connect up to 16 sensors only using 5 pins of the board.
4.3.4. Schematics

Figure 30. Schematic of the necklace. Design by Judith Amores.

Figure 31. Schematic of the stationary device. Design by Judith Amores.
4.4. Design and Fabrication

4.4.1. Inspiration

Figure 32. Mood board of the style we wanted to pursue. The trend is simplistic pendant bottles with minimal garments. Photos by Pinterest.
4.4.2. Concept Design

Necklace

Figure 33. The original idea of the Essence necklace was to chemically create unique scents so the user would associate a memory with it. Designs by Judith Amores.
Figure 34. A variety of form factors were considered to make the prototype pretty, functional and comfortable. Different bottled shapes were considered depending on the kind of scent or emotion associated with it. Drawings by Judith Amores and Lucia Liu.
Figure 35. Mechanisms and visualization of what the final prototype could look like. The electronics are covered and fit underneath the lid. Designs by Judith Amores and drawings by Lucia Liu.
4.4.3. Fabrication

The necklace and stationary device were designed using SolidWorks (Figure 36, 37, 39), and 3D-printed with Ultimaker (first prototypes) and Formlabs Form 2 using Grey Resin and White Resin.

Finally, in order to have a polished final result we send the design to Shapeways for printing. We explored the use of different materials such as white strong and flexible materials, polished gold steel and polished nickel steel (Figure 38).
Figure 39. 3D Model of the stationary device. It consists of three different layers. The top layer (A) covers the electronics and press fits the piezoelectrics. The second layer (B) has 6 different screw mechanisms that will hold the containers. The user can easily unscrew each to change the liquid. (C) Closing part of the case. It press fits the containers with the second layer so as not to spill any liquid. Designs by Judith Amores and Lucia Liu.
4.5. Final Design

Figure 40. Final design of the necklace prototype. The first two pictures show a minimalist design that could potentially be used by men. In the bottom, a small decorative gold/bronze-style accessory that is most likely to be worn by women. Photos by Judith Amores.
One of our goals was to make the necklace as small and lightweight as possible so as to be comfortable enough to be worn on the neck all day and potentially all night, so that ideally the back part of the necklace would be flexible and neck-adaptable. Initially we wanted to create a piece of jewelry targeted to women, and finally we decided to create a version for men as well (Figure 40).

The necklace is approximately located 7 inches from the nose (enough to reach the nose and not be too noticeable by the user). This size was chosen so as to fit over the head (30”, see Figure 41).

The scents we use in the prototype are mostly of 3 different types. One is natural essential oil commonly used in Aromatherapy (like lavender, peppermint, eucalyptus, etc.), the second type are regular fragrances or perfumes. We also used diluted oils from Nature's Garden supplies [67]. These oils include a variety of unique scents like “fresh cut grass”, “baby clean fragrance oil” (Top notes: granny smith apples, lemon zests, mint. Mid notes: baby powder. Base notes: wildflowers, butterfly violets, honeysuckle), “Christmas memories fragrance oil” (Top notes: orange peel, cranberry. Mid notes: cinnamon, clove. Base notes: evergreen pinecones). And those are only some of them, they have a variety of hundreds different scents (we tried around 20).

And third, we did some experiments with pheromone scents. We used sprays from Raw Chemistry Lab [68] and odor-less gels from Love Scent [69]. The sprays and oils use a "patented blend of human pheromones including Androstadienone, Androstenol, Androstenone and Androsterone".
Aside from pheromones, we could potentially use hormones like Oxytocin. A recent paper shows that a single dose of Oxytocin nasal spray decreases impulsive behavior in overweight and obese men [70]. Oxytocin is currently approved in Europe but not in the United States other than for clinical trials. During the period of this thesis we visited the authors of this paper at Massachusetts General Hospital to talk about the possibility of using the necklace for hormones like Oxytocin and test it with patients. We talked with Dr. Franziska Plessow, Instructor in Medicine at MGH and Elizabeth A. Lawson, MD, MMSc a clinician in the Neuroendocrine Clinical Center and a member of the Neuroendocrine Unity at the Massachusetts General Hospital and an Assistant Professor of Medicine at Harvard Medical School. She is also a clinical researcher and Director of the interdisciplinary Oxytocin Research Program. In the future we plan to use the liquid form of the Oxytocin nasal spray (made by Novartis, a synthetic version of the hormone oxytocin) and employ it in the Essence necklace.

Figure 42. Scents used in the wearable and stationary device. Photos by Judith Amores.
Chapter 5
APPLICATIONS

Unlike the sight, hearing or touch, the sense of smell is often easy to forget, people do no tend to pay attention of their use and its impact in their daily life. The lack of compelling applications that could benefit from olfactory displays is one of the many constraints why scent has been underdeveloped in HCI. Moreover, most of the systems require burdensome and not portable devices that hinder designing systems for everyday life.

In the following sections we describe a set of applications that use scent in everyday life situations and that have not been explored in HCI (sleep and memory, learning and cognitive performance). We also describe more common use cases like communication or wellbeing. Essence can be used in a variety of applications most of them related to memory performance, health and personal relationships.

5.1. Sleep and Memory

Sleep has been identified as a state that optimizes the consolidation of memories [71][72]. Studies show that newly encoded memories are reactivated during sleep. Neuroscientists conducted laboratory studies that cued new memories in humans during sleep by presenting an odor that had been presented as context during a prior learning episode, and showed that reactivation indeed causes memory consolidation during sleep [73][74]. Participants learned the positions of card-pairs in a visual-spatial task while the scent of roses was released via a nasal mask. One night after learning, the same scent was presented again while they were in slow wave sleep. The
same process was done with an odorless scent (both for learning and during the night). After the night with scent, users remembered significantly more of the learned card-pairs compared to the night without olfactory stimulation [73].

Recent findings suggest that novel associations can be learned during sleep and can alter later waking behavior. Researchers found that a single night of olfactory aversive conditioning during sleep, significantly reduced cigarette-smoking behavior in the wakefulness state and persisted for several days [75].

Such functional studies continue to remain in the realms of research laboratories. The main aim of this project was to design and fabricate a technology that people could use in their daily life, for example, while they are sleeping at home. For this purpose, over the period of this thesis we studied what would be the best way to do so. Most of the current sleep monitoring apps and devices rely purely on accelerometer data, therefore, only differentiating between REM and non-REM stages. These systems are usually noisy and not very accurate, since they rely on the premise that during REM our bodies are paralyzed. On the other hand, professional medical studies use a multi-parametric test (Polysomnography) that monitors many body functions including brain (EEG), eye movements (EOG), muscle activity or skeletal muscle activation (EMG), heart rhythm (ECG) and respiratory airflow (pulse oximetry). These systems require the user to stay at the hospital and be connected to a minimum of 22 wire attachments. Moreover, these channels vary in every sleeping lab and may be adapted to meet the doctor’s request.

With Essence, we created a system that can be used by any person in their daily life without the need for medical assistance. We monitor real-time brain activity and do sleep score to identify when the user gets in the right stage of the sleep cycle (Figure 43).
Figure 1. Human Sleep Stages

Awake - low voltage - random, fast

Drowsy - 8 to 12 cps - alpha waves

Stage 1 - 3 to 7 cps - theta waves

Stage 2 - 12 to 14 cps - sleep spindles and K complexes

Delta Sleep - 1/2 to 2 cps - delta waves >75 μV

REM Sleep - low voltage - random, fast with sawtooth waves

Figure 43. Characteristic electroencephalogram (EEG) patterns of human sleep stages. Photo by Sleep Disorders; Sleep Foundation.
Sleep scoring is commonly used in the medical field. A "Sleep Scorer" or "Sleep Technologist" provides comprehensive evaluation about sleep, including scoring and interpretation of Polysomnographic results, including EEG data. We aim to detect the deep sleep also known as Slow Wave Sleep (SWS), which is a state where memories get consolidated. In this stage, brain activity transitions to delta waves which are the lowest in frequency and highest in amplitude. Most studies suggest that the optimal learning point occurs when memories are processed in SWS and then REM sleep [76][77]. When the user enters the SWS sleep stage, the Essence system releases the fragrances using the necklace or the stationary device (Figure 44) (see Evaluation section for more details).

![Measure and record brain activity while sleeping using EEG](image)

When Slow Wave Sleep is detected, subtle bursts of scent will be triggered.

*Figure 44. People in their homes could use the system to improve sleep quality, reduce nightmares or even control the quality of their dreams. Design by Judith Amores.*
5.2. Learning and Cognitive Performance

Since ancient time, humans have tried to understand what memory is, how it works and why it goes wrong. It is an important part of what makes us truly human, and yet it is one of the most elusive and misunderstood of human attributes. In 1885, psychologist Hermann Ebbinghaus, known for his discovery of the forgetting curve [78] and the spacing effect [79] published a simple way to calculate the rate of forgetting after a study session. The forgetting curve demonstrates how memory declines over time and that more practice, results in higher test scores and slower rate of forgetting.

However, in the 1900s, Philip Boswood Ballard showed a study [80] that contradicted Ebbinghaus theory. He demonstrated that instead of declining, memory improves after few days of a study session. He made his students study a verse of poetry over time. The students were not expecting to be retested and yet their ability to remember the poetry verse improved by an average of 10 percent the following day. Ballard tested them once more, again unannounced, days later. He ran hundreds of tests to students and proved that memory improved in the first few days without any further study, and only began to decrease around the fourth day. "J.T. improved from 15 to 21 lines in three days", "Imagined I saw the lines in front of me", "as I began to write it I could picture it on the paper before me." Some students improved from three to eleven lines in seven days, others nine lines on the first test and then 13.

Both Ballard and Ebbinghaus theories were correct since memory does not have just one tendency over time. Ebbinghaus studied the memorization of nonsense syllables; by contrast, Ballard studied poetry. In the case of nonsense syllables or abstract concepts, memory recall decreases right after every study session whereas poetry or imagery-related concepts improve and start declining after four days approximately. Erdelyi et al. [81] compared the results of a group that studied sixty words versus a group that studied sketches of the same words. The group that studied with words and no
sketches, improved from 27 to 30 in the first ten hours and no more. The group that studied with sketches improved from 27 to 32 ten hours later, a day later 34 and by four days 38 and no more.

So apparently, the more stimuli we add to the learning experience, the more recall rate improves. There are other studies that show that studying with music in the background is better than in silence, and that the recall rate is much better if we reproduce the same song while taking the exam [82]. The whole environment is strongly connected with the learning process, lights, ambience, etc. That might be one of the reasons why many students like to work in coffee places. You can clearly see a peak time when finals are coming; Starbucks and coffee places are full of students. There is this culture or tendency to associate drinking coffee with working or studying. Do caffeine scent and the aroma of brewed coffee subliminally help people focus? There is the clear fact of drinking the coffee, however people stay in these places for hours –without the need to drink more than one cup.

It has been proved that peppermint scent promotes a general arousal of attention, and people stay focused on their task and increased their concentration [23][24]. Essence can release these scents while people are studying and then helping them retrieve the learned facts by releasing those scents again. In Chapter 6 – Evaluation, we conducted a user study that uses Essence and peppermint fragrance for a real-life context situation while participants were performing a cognitive task of memorization (See Chapter 6 for more details and results).
5.3. Wellbeing

There are a variety of application scenarios related to health purposes ranging from using Essence as a personal, wearable device for cold and flu treatment, allergies, asthma or other respiratory problems to beauty treatments like face moisturizer for dry skin.

In the same way, we could potentially release the scent of lavender or vanilla to reduce stress levels or pain for diseases like cancer (the positive effects of scent for pain and anxiety management have been previously discussed in the "Hidden Power of Scent" section).

On the other hand, more common use cases could potentially help a person concentrate or focus, like when meditating or doing yoga. In the following section we describe a proof-of-concept we built that integrates Essence with ambient lights and releases subtle bursts of scent triggered by brain signals and micro facial gestures such as blinks or jaw clenches. We non-invasively monitor real-time brain activity data using EEG and reflect this information using scent and subtle changes in the ambient light of the environment.
5.4. Physiological and Light Integration

Essence can be remotely controlled through a custom-made smartphone app that interfaces with an EEG sensor and ambient lights [83] (Figure 45). The system can automatically trigger subtle bursts of scent and vary the intensity and frequency depending on the given inputs. In this section we discuss the supporting software that connects the ambient lights and the EEG sensor. We also discuss the use of subliminal cues like light color and intensity as well as varying the scent for different kinds of behavior changes. For example, we experiment with the use of peppermint scent and cool white light (4000K) or artificial daylight (6500K) for enhancing task performance.

The system consists of three main parts (see below diagram):

(A) Scent release system
(B) Brain activity sensing
(C) Controllable ambient light

All three components interface with a custom-made Android application. In the following sections we describe each part of the system. (Figure 45)
Figure 45. (A) Muse EEG headband triggers the Essence Necklace (B) and the color and intensity of the Philips Hue light (C). Design by Judith Amores.
Brain Activity

In order to detect brain activity we used the MUSE Headband. The device is slim and flexible making it comfortable for use with the Essence necklace.

Both the necklace and the stationary device interface with an Android app that controls the rest of the system (EEG brain signals and lighting conditions). In the case of EEG we use the MUSE Headband API to detect parameters such as mellow, concentration, blink and jaw clenches.

The data extracted from the BCI is data available from the Muse Research Tools using MuselO [84] and Android developer SDK LibMuse 5.8.0 [85]. The data is streamed from the headband and control from the client software. We used high level values from the Muse API. Depending on these parameters, the light (Philips Hue) will change its saturation and color temperature to calm, alert or focus the user (in concert with the scent). By sensing brainwaves using a series of EEG sensors, the level of activity is fed back to the user via subtle light changes and burst of scent.

These brainwaves can be categorized accordingly to their frequency: Gamma brainwaves (100-38 Hz), Beta (38-15 Hz), Alpha (14-8Hz), Theta (7-4Hz) and Delta (3-0.5Hz).

Our aim is to detect when the user is emitting Gamma brainwaves. Gamma values are usually seen in states of peak performance, high focus and concentration. These values increase when the user is focused and directs his/her attention with intensity, thinks about something in particular, reads or tries to solve a problem that involves concentration. We mapped the values from 0 to 1 and synchronized them with the color and intensity of the light. When the user is distracted, the lighting conditions are similar to a household incandescent light bulb (around 2000K) (Figure 46). If the user is focused (higher brainwave frequency - gamma values), the lights while become cooler white lights (around 4000K) for enhancing task performance or meditation.
The system adapts the external lighting conditions of the room accordingly to the brainwave frequencies; the higher the frequency (more focus), the higher the Kelvin color temperature (cooler light) (Figure 46).

![Chromaticity scale diagram (close up of the CIE 1960 UCS)](https://example.com/chromaticity-scale-diagram.png)

*Figure 46. Chromaticity scale diagram (close up of the CIE 1960 UCS). Photo by Wikipedia.*

Color influences perceptions that are not obvious and can enhance the effectiveness of the placebo effect. It is widely used in marketing and branding. For example, a study by psychologist Andrew J. Elliot [86] found that women dressed in red were significantly perceived as more attractive than if they were dressed in any other color. On the other hand, color lighting conditions also have an impact in our mood [87][88]. The intensity of light has an impact on the intensity of our emotions. The more intense is the lighting, the greater a person's emotions [89]. Recent research [90] has examined the effects of lighting on student learning and concluded that students under 6000K lighting conditions lead to a higher percentage in oral reading fluency performance (36%) than did with natural lighting (17%). This explains why lighting conditions with 2700K are subjectively more relaxing than higher color temperatures (4000K). Higher luminance (5500K) stimulates the alerting system more efficiently than with warm colors (3000K).
5.4. Communication

Smells unconsciously connect people, but can smells be an interface to connect remote people? If so, is it better than connecting audio and video? Is a combination of senses optimal?

We could combine ShowMe [8] (Figure 47) or other augmented or virtual reality systems for remote connectivity [91] with Essence to create a more complete sensorial experience for telepresence. Adding the sense of smell in immersive environments may better connect remote people and trigger a stronger emotional reaction between remote users (potentially using pheromones or even the scent of that person).

Figure 47. ShowMe is a remote collaboration system for reaching into the environment of a remote user using Mixed Reality. The remote expert can provide guidance through the use of hand gestures that are reproduced in real-time in the local user's field of view as superimposed 3D hands. The remote expert is also able to operate Internet connected devices in the novice' environment and bring about physical changes in that environment. Project by Xavier Benavides and Judith Amores.

Beyond immersive systems we could also use Essence as a subtle way of communication amongst remote users. As mentioned in the System Description section, Essence is capable of using date, location and time information. A remote user could remotely control the necklace and release the scent at a certain location or time of the day as a means of subliminal messaging and notifications as if "I am thinking of you" or "I am worried". For example, if the user goes to the doctor and stress levels go beyond a certain threshold, the remote wearer could sense the "scent of fear", increasing empathy between them. The remote person could then trigger a nice scent to
calm the stressed person down, or the system itself could automatically release a burst of scent when the doctor's location is detected.

Essence could potentially be combined with the Tagme system [12] and be triggered every time we use certain object (Figure 48). People often have an emotional attachment to the objects around them. For instance, an object may remind us of the person who gave it to us. If we collected the object at a meaningful time in our life, the use of the object might bring back special memories. TagMe can be used to augment such objects so that every time the user touches it, a special action is taken, such as releasing a burst of scent from the Essence necklace that is associated with that memory.

Figure 48. Tagme is an RFID-tag reading bracelet that can recognize the particular object or surface the user is touching. The user can make their interactions with everyday objects result into acts of communication, creating simple and customizable rules (send a tweet, SMS or a Facebook message every time they touch a certain RFID-tagged object). Project by Xavier Benavides and Judith Amores.

Beyond long-distance communication, it would be interesting to use Essence to connect people within the same environment. First encounters and interactions with another person strongly affect a person's perception. Although we are not completely aware, while we are having a social interaction we experience the entire environment around us, meaning that we use all five senses. Current commercial technologies are mostly vision based and are targeted to connect people at a distance. With the rise of social media, the question that we may think about is if today's interpersonal relationships are better with these new ways of interaction. This problem was one of the
motivations to create “Social Textiles” [11] (Figure 49).
What we choose to wear is public to the world and we are aware of it. In contrast, what we post online about ourselves reaches thousands of people and generates social consequences, but it doesn’t feel that way. Could you imagine if human beings had a pheromone status like in Facebook? “Friendship Pheromones”, people could respond with "yes", "no", "busy" and ask again later by using scent.

Figure 49. Social Textiles embodies who you are and dynamically reflects your shared interests with people nearby. It enables you to gain access to communities of people in the physical world and enables social ice-breaking interactions through wearable social messaging on an e-textile T-shirt. Photo by Social Textiles team.
5.5. Encoding, Storing and Retrieving Memories

The original idea of Essence was to design and fabricate a system that could allow people to encode, store and recall memories. The system consisted on a wearable device (Figure 50) and a stationary device (Figure 51).

Each scented bottle contains unique chemically produced scents that the user has never experienced before. By sniffing the scent, the user will associate for the first time that unique odor with the events and emotions that are being experienced. The system could at the same time capture a picture, time and location to better associate that memory. Moreover, it could track the user's respiration levels to make sure they took a deep breath while sniffing the odor.

Figure 50. The scented bottles could contain unique odors that will be associated with the memory that the user wants to capture. The user could record the memory by sniffing and taking a deep breath of the desired scent (that could be detected by the wearable device). Photo by Judith Amores.
The stationary device or "Memory Bank" (Figure 51), could serve as a storage and recall of the memories the user had captured beforehand (using the wearable device). The "Memory Bank" could contain a variety of scents that could be controlled by the user or by the system. Therefore, it could serve as an output device to recall each memory. The scents are unique chemically produced scents that the user has never experienced before. Every time the user would like to recall a memory, he or she would trigger it through a smartphone application that is connected with the Memory Bank. Finally, the system could also be able to automatically recall the memories by itself, leading to possible applications such scent release while sleeping.

Figure 51. The "Memory Bank" releases scents automatically or through a smartphone application whenever the user wants to recall certain memory. Each scented bottle has a unique identifier that is linked with the memory recorded by the wearable (including a picture, the time and location as well as respiration levels). Photo by Judith Amores.
Chapter 6

EVALUATION

In order to evaluate the system, two sets of preliminary user studies were carried out. These studies were meant to collect both qualitative and quantitative data from users and evaluate the necklace and stationary system in a real-life context. Through these studies we analyzed users' interaction with the necklace as well as evaluated the power of scents to influence mood and cognitive performance (memory consolidation) during wakefulness and sleep state.

6.1. Sleep Experiments

The following tests were conducted under the supervision of Moran Cerf, and with the help of Ronen Zilberman and Andres Campero. These experiments do not show statistically significant data, however the main aim was to study and understand real-time sleeping data using an EEG headband and to see whether we could create a system for use by people in their homes. We chose to use EEG since based on the literature, it is the most reliable measurement we could get from only one device. The electrodes would provide readout of the brain activity that can be "scored" into different stages of sleep (N1, N2, N3, REM and wakefulness).

8 volunteers used the EEG headband while they were sleeping at their homes and 4 of them were monitored in real time under supervision. The first experiments were done on ourselves, gathering most of the data from self-reported experiences. In order to track brain activity we used the research version of the MUSE headband (Figure 52). This version of the headband is not yet a commercial device and was lent to us for research purposes. It has 3 reference sensors, and 4 electrodes for brain activity measurements.
Figure 52. MUSE research headband. Photo by Judith Amores.

Although the headband is not meant to be used while sleeping, the research version is flexible and thin, making it comfortable to sleep with.

Using the initial data collected we better understood the different sleep stages and trained ourselves to do sleep scoring. For this thesis we learned how to sleep score using brain activity data, applying professionally accepted guidelines to differentiate each one of the sleep stages.

Once trained, we tested the stationary Essence system in combination with the EEG headband. We tested the system in an extreme case: an Iraq combat Veteran. His name is Nicolas Aaron Mezzanatto [92] and he openly accepted to appear as a non-anonymous subject in this thesis. He is a Hollywood Director and directed and co-wrote action-thriller films like SEAL Patrol and Verdict, and served as first assistant director for the film “The Speak”. His service to the US army has inspired many of his films and scripts. He was an infantryman with the 101st Airborne 1-502nd Infantry in the “Triangle of Death” from 2005 to 2006, when he had to go back home disabled by a Traumatic Brain Injury and Post Traumatic Stress Disorder (PTSD). PTSD is a mental disorder that can be developed after a traumatizing event such as warfare, sexual assault or other life threatening memories. There is no current solution to cure the symptoms and these memories can last for years or lifelong. “We really don’t know why people respond so differently to traumatic experiences” - says Gregory J. Quirk, PhD, who investigates the neuroscience of fear. “Sleep is key for learning, and people with PTSD show reduced or disrupted sleep.
Recent data show that extinction of conditioned fear occurs more effectively in the morning versus the evening, suggesting that there may be optimal times of the day for exposure therapy.

Our hope for the study was to see if we could positively affect Nicolas' traumatic memories while he was in slow wave sleep using scents. Contrary to the cigarette study [75], this time instead of associating a bad scent with a good memory (smoking cigarettes), we wanted to associate a traumatic memory with a good scent. To do so, we first had to analyze how to trigger those traumatic memories while he was sleeping. Nicolas shared with us a series of disturbing images and sounds that arouse him and makes him stressed and violent. The sounds included a variety of perturbing pain screeches, bombs, machine gun shoots, kids crying, etc. Our goal was to use these sounds every sleeping cycle when he was in slow wave sleep (exactly at the moment when memories are consolidated). At that moment, the memory would be "open", and right after that we would subliminally release a pleasurable scent to "close" or "overwrite" the traumatic memory.

**Procedure**

*Scent Selection*

Before we conducted the study, we had an intense interview with the subject and asked about the disturbing experiences he had while he was in Iraq. We videotaped the whole conversation and recorded the sound as well. The stories he shared were traumatizing and terrifying real stories based on real events and experiences.

The entire study took 3 days and nights. In order to choose the pleasurable scents that would be used during sleep time, Nicolas was given a series of pleasurable standard scents. After each sniff we made him rank the presented scent from 1 (very unpleasant) to 10 (very pleasant) and how strong from 1 (very light) to 10 as (very strong). In between scents, he was given coffee beans to "clean" his nose and 25 seconds of break. In order to ensure the
data was consistent, we made 8 randomized repetitions for 10 different scents (lavender, roses, lemon, cinnamon, vanilla, ylang ylang, peppermint, honey, and some special fragrance oils from Nature’s Garden supplies [68] that combined notes like strawberry, mint, banana, etc.)

Finally, we analyzed and chose the top 4 most pleasurable and strong scents. In the case of Nicolas, the top scents were to be lemon, mulberry, vanilla and a fragrance combination that contained as top notes: strawberry, coconut, cherry, mid notes: banana, melon, peach, apple, pear and base Notes: French vanilla, mint, clove. Interestingly, common pleasurable scents like roses didn’t seem to appeal to him much, whereas more exotic and citric fragrances like mulberry or lemon were top ranked. As expected vanilla was amongst the top rated scents as well. Vanilla is universally perceived as "pleasant", probably cause childhood memories are pleasant, sweet treats and rewards, ice-cream holidays, etc.

**Sound Selection**

Once we had identified the top 4 most pleasurable scents for our subject, we proceeded to find out about the top 4 most stressful sounds. In order to see whether the selection of sounds he gave us really aroused him, we collected the following physiological data:

1. Heart rate, respiration and posture. We used the BioPatch sensor, a small and comfortable patch that attaches to traditional disposable ECG electrodes.

2. Electro dermal activity (EDA) using Empatica E4 wristbands (one for each wrist).

Amongst the sounds he gave to us, we also added other neutral sounds to compare the data. For each one of the sounds Nicolas had to rank how aroused/sleepy and pleasurable/displeasurable he felt on a scale from 0 to 10.
We had a list of 21 sounds, although we finally used 12 and made 8 randomized repetitions for all the sounds (total of 96 points).

**How does the sound make you feel?**

![Diagram](image)

*Figure 53. The diagram we used is based on the famous Russell’s circumplex model of affect [95], and Plutchik’s [96] primary emotions plotted on Valence-Arousal dimensions.*

**Experiment**

Once the top 4 pleasurable scents and 8 most stressful sounds (upper left quadrant in figure 53) were selected, we proceeded to start the tests while he was sleeping. During the night, aside from wearing the sensors mentioned above, he was also wearing an EEG headband so we could monitor real-time brain activity and do sleep scoring. The participant was sleeping in an adjacent room and fell asleep approximately one hour after putting on the sensors.
Once we were sure he was sleep, we located the Essence stationary prototype on the bedside table (the participant did not know at any moment that we were going to play sounds and scents nor what the premise of the whole experiment was). Once he was in slow wave sleep (Figure 54), we started playing each sound and following it with a pleasurable scent. In order to test to what extent only the sounds (without an associated scent) would affect Nicolas perceptions, we also used odor-less scent (water vapor).

In total we did 6 rounds of 4 sound-smell and 4 sound-no smell (in total 6x8 data points). The next day, Nicolas took the same test with the same sounds again. These sounds consisted of the same 12 sounds from the first day in three different conditions:

1. 4 sounds that were presented the night before with associated pleasurable scents during deep sleep (SWS).
2. 4 sounds presented with placebo odor (odor-less scent) during deep sleep (SWS).
3. 4 sounds that were not used at all during the night.

The results (Figure 55) show that the experiment had a positive effect on Nicolas' perceptions of the sounds.
The levels of arousal decreased and pleasantness increased considering the aversion and traumatic responses he had before (from 2.06 to 3.5).

![Graph showing comparison between day 1 and day 2](image)

*Figure 55. Comparison between day 1 and day 2 (after being exposed to odor and sound during deep sleep).*

Although the results (Figure 56, Figure 57) show that there was an overall improvement in his mood and perception of the sounds whether the scents had been used or not during the night (possibly because of the placebo effect and hope for the researchers), there is a significant difference between condition (I) – sound and scents during SWS and the rest of conditions with unscented vapor (II) and not presented at all (III). This leads us to think that associating traumatic sounds and pleasurable scents during sleeping time seemed to have a larger positive effect than the other conditions.
Odor and sound during SWS

Sound but no odor during SWS

No sound and no odor during SWS

Although we cannot establish robust conclusions yet, it is promising and leads to thinking about possible applications for the use of Essence as an alternative or complementary treatment for traumatic stress disorders, phobias or other related mental disorders. Further research is needed.

Figure 56. Differences between Day 1 and Day 2 in each of the 3 different conditions.

Figure 57. Differences in pleasantness levels between day 1 and day 2.
6.2. Just in Time Context Study

In order to evaluate the Essence system, we conducted a user study to test if users could use the necklace in a real-life context situation while performing a cognitive task of memorization. Specifically we wanted to test the robustness of the system and better understand the satisfaction, ease of use and fatigue of the users while wearing the necklace.

Our goal was to show whether a mobile olfactory system like Essence could be used successfully in a mobile situation. We were primarily interested in user responses about the feel of the necklace and the intensity and frequency of the scent to identify opportunities for improvement. We were also seeking to gather potential use cases and possible far-vision ideas from our test users.

Additionally, this study also examined to what extent atmospherics affect people's mood and cognitive performance. More specifically, to what extent do scent and lighting, affect peoples' mood and cognitive performance. This study was planned in collaboration with Asaph Azaria and Nan Zhao from the Responsive Environments group at the MIT Media Lab and made use of the "Mediated Atmosphere" (Figure 58), a modular workspace that can digitally transform its ambiance, via video projection, spatial sound and controllable lighting.

![Image of Mediated Atmosphere setup](Image by Asaph Azaria and Nan Zhao.)
Procedure

We recruited a total of 14 participants, with a mean age of 27. Out of the 14, 4 participants used the necklace. Users were asked to memorize a set of Hindi vocabulary words while wearing the wearable in different places on campus. There were 20 different Hindi-English cards for each location (Figure 59). The 3 locations were:

Figure 60. Silverman Deck, MIT Building E-14, 6th floor. Day 1. The users are wearing the Essence necklace while memorizing the Hindi/English words and filling out the surveys about their experience. Photos by Judith Amores.

Figure 61. Rotch Library, Architecture and Planning MIT. Day 3. Photos by Judith Amores.
Participants were asked to fill out a questionnaire about their experiences while being in each location. After filling the questionnaire, they had 15 minutes to memorize the Hindi words and their translations in English. Finally, after leaving the location, they were asked to fill out a post-experience questionnaire. The questionnaires included questions about how did the environment made them feel in regards to the audio-visual experience and olfactory experience. Some of the questions related to the olfactory experiences were: how aware they were of the scent, ranking of the intensity of the scents that they smelled, how pleasant they found the scents. Finally, those who were given the necklace were also asked about ease of use, satisfaction and comfort of the "scented necklace". They also filled out qualitative data about how aware they were of the necklace, to what extent the scent helped them relax/focus/be more immersed, if the scent distracted them from the memory task, etc.

The next day, the same participants took another survey and a test about the Hindi words learned in the Mediated Atmosphere room (Figure 63).
Figure 63. Mediated Atmosphere simulating the Silverman Deck and Rotch Library. Users are wearing the Essence necklace while taking the test and filling out surveys (Day 2, 4, 6). Photos by Judith Amores.

We also collected data that included heart rate, posture, respiration, electrodermal activity and video recorded their facial expressions (Figure 64). At the end of the study they filled out a final survey. Additionally, we recorded an interview asking about the overall experience, possible improvements and feedback.
The study took approximately 6 days that consisted of:

- **Day 1**: Real environment experience: Silverman Deck (Scent of Tea Tree) (Figure 60). Survey about the experience and post-survey.

- **Day 2**: Artificial environment experience: Silverman Deck (Scent of Tea Tree). Survey about the experience and post-survey. (Figure 61)

- **Day 3**: Real environment experience: Rotch Library (Scent of Peppermint) (Figure 62). Survey about the experience and post-survey.

- **Day 4**: Artificial environment experience: Rotch Library (Scent of Peppermint). Survey about the experience and post-survey. (Figure 63)

- **Day 5**: Real environment experience: Physics Department (Scent of Roses) (Figure 62). Survey about the experience and post-survey.

- **Day 6**: Artificial environment experience: Physics Department
(Scent of Roses). Survey about the experience and post-survey.
(Figure 63)
Final survey and recorded interview.

Results

We used a computer-based survey and in-person interview to gain an understanding of the participants' perception of the system. Evaluating the results from this study, hearing the feedback from people and seeing the interactions with the system, allowed us to evaluate the Essence necklace in a real-time awake situation, outside the lab, in a live context. It gave us an overview of how the necklace was working, what the failures and limitations were, as well as possibilities to improve the overall system.

The participants that wore the essence prototype were men, with a mean of 29 years old. Although necklaces are frequently used by women, we also wanted to test in what extend men could use the system. The participants reported not using accessories or necklaces in their daily life (a drawback that might bias against the study). However, participants ranked very positively the experience of wearing the Essence necklace. Figure 64 shows results reported through questionnaires regarding ease of use (mean = 4.464, std = 0.744), satisfaction (mean = 3.964, std = 0.961), and overall comfort (mean = 4.035, std = 0.961). The results suggest that users generally found easy and effortless to use the necklace while doing a task.
Figure 65. The chart shows user feedback where 5 = very effortless, very satisfying and very comfortable, suggesting that users found the system easy to use and were satisfied overall with the experience of wearing the necklace.

When asked to rank how aware they were of the necklace, most of the users mentioned that they were not aware (mean of 2, were 1 is "not at all", and 5 is "very much"). However, although the mean was 2, one of the participants (P12) ranked negatively the necklace and mentioned he was aware of it all time because the scent was too strong for him, specially the Peppermint (mean of 3.4). Another interesting thing happened with P11, he ranked awareness in all situations "1" – as if he was not aware of the necklace, however in Day 2 - Silverman Desk Artificial environment, he ranked the necklace as "5" – very aware, because the scent was "too strong" for him. Interestingly, the type of scent and intensity were exactly the same in Day 1, but then he ranked as "1" – not aware of the necklace. That day, in the report he wrote, "I am almost not aware of the necklace. However, I could smell the scent much less at the beginning. Seems like I need some time to get used to the smell. Maybe it's because I was biking right before doing the study."

In general, during the study and while interviewing people, we realized how different people's perceptions are in regard to smell. While for one person the scent was not strong enough, for the other it was too much. While some of them loved the Peppermint scent, others did not like it at all. The preferences even vary from day to day within the same person. That definitely points out that the best option is to create a device that can be controlled by the user depending on their preferences (like augmenting/decreasing intensity and frequency of the scent). As mentioned previously in this thesis, the current
prototype releases a burst of scent every 20 seconds (1 second per burst). We asked users if they would increase or decrease the intensity or timing of every burst of scent. The results were completely different for each person. For example, P10 would increase the intensity of scent in all conditions, whereas for P12 the scents were too strong so he wanted to decrease them.

In the same condition (Artificial environment – Silverman Desk), P12 ranked as “decrease intensity during this session. Too strong!”, while the rest of participants mentioned “just about right” or “increase”.

In the final survey, participants were asked if they would wear the essence necklace in their daily life and in what kind cases they would use it for. Some of the comments we received were “I would use it in my office when working, when trying to concentrate, when trying to relax, when meditating” or “when there is other bad smell around”.

Participant P12 mentioned he would not use it in a daily life situation since he does not like accessories. When asked in what kinds of cases he would like to use it for, he wrote “Maybe if I knew I was going into an environment with an inherently bad smell”- Another participant mentioned “I would wear it more if it was more portable and less visible. I usually don’t wear necklaces, so it would be nice if I could somehow hide it.” Some participants responded they would use the necklace for meditation sessions and concentration.

Some of the possible improvements people mentioned were the ability to control intensity, and make the back part of the necklace smaller, more compact and less noticeable “I wouldn’t wear it just not to have people keep asking me what it is”. Some other comments were “it would be nice to avoid shooting the scent directly to the nose, it can become overwhelming at some point.”

When asked to describe the experience of wearing the necklace in the different environments, participants mentioned:
"Effortless, it was nice to feel the good smell from time to time", "Most of the time I completely forgot it was there, except for some moments when the scent suddenly became more noticeable, either stronger or just different. However even when it was noticeable it was pleasant, it never became an inconvenience." "The scents were pleasant and relaxing and otherwise I hardly noticed it was there." "It was very seamless, and enhanced the environment nicely." "The necklace wasn't too invasive. I did feel some weight of the device in the back of my neck, but quickly forgot about it. I noticed that when I was leaning forward the scent would not directly reach my nose, so even though I could still smell it, I was consciously aware of it being active."

An interesting phenomenon happened when comparing the post-experience surveys between people who used the scented necklace and the rest of people who had a regular experience (without scent). We asked how clear their memory of the sounds and sights was that they heard and seen. They also had to specify as many things as they could recall about the sounds in the environment.

Figure 66 and 67 shows the results reported about how clear their memory of the sights and sounds were. In color blue, the participants who used the necklace, and in grey is the rest of people who did not. Exp. I and Exp. II are related with the audio memory and Exp. III and Exp. IV with the visual memory.

As expected and previously demonstrated by psychology research, reminiscence is strong for imagery (Exp. III, Exp. IV) than for sounds (Exp.I, Exp. II). In the case of scent, the difference between the words recalled by users in Exp. III and Exp III are astounding (Figure 67). We can clearly see a meaningful difference in the number of words they wrote about their memories. This trend is the same in the case of the self-report data about how clear their memory of the sights was.
How clear your memory of the sounds you have heard?

Not at all     Very much
No scent      Exp. I
Using scent   Exp. II

1  1.5  2  2.5  3  3.5  4  4.5  5

How clear your memory of the sights you have seen?

Not at all     Very much
No scent      Exp. III
Using scent   Exp. IV

1  1.5  2  2.5  3  3.5  4  4.5  5

Figure 66. In blue, the participants that used the necklace. In grey the rest of the people that did not. Exp I (mean = 4, std = 1.30), Exp. II (mean = 4, std = 1.021), Exp. III (mean = 4, std = 0.810), Exp. IV (mean = 4, std = 0.893).

# of words described

Exp. I      Exp. III      Exp. II      Exp. IV
8           12           22           53

Figure 67. Words recalled by the users in the four different conditions mentioned above. Exp. I No scent, audio memory. Exp. II. Scent, audio memory. Exp. III. No scent, visual memory. Exp. IV. Scent, visual memory.

The people that did not have the scented necklace (total of 24 responses) wrote a total of 1808 words related with the scene they were in (533 related with the sound and 1275 related with the sight). The rest of the people (total of 44 responses) wrote 842 words (371 related with the sound, and 525 related with the sight).
These results might be biased because the people who used scent described more accurately their memories and paid more attention when answering the questions, so they wrote more words. Another reason might be that the people who wore the necklace were better at remembering things in general. In the study we tested both what they remembered about the scenario (visually and auditory) and also the different Hindi words they studied. From the small number of samples the distribution of scores are not normally distributed, therefore we cannot conclude any confidence interval to show if users who used the necklace had better memory in general or it was an effect of the scent. However, still the difference of words (Figure 67) is very significant and that definitely encourages us to conduct more studies in this area. It is interesting to see the difference as well amongst people in the same condition (using scent), namely how much audio versus visual memories they remembered. As mentioned previously in this thesis, the olfactory bulb has direct connections to the two brain areas that control emotions and memories: the Amygdala and Hippocampus. The Hippocampus plays a crucial role in spatial navigation of the environment and processing information about spatial locations. Visual memory (also called iconic memories) retains visual colors and shapes. The combination of both spatial and visual memory is the result of Exp. III and Exp. IV. Audio memories (also called "Echoic memories") unlike visual memories are stored for slightly shorter periods of time (as we can see in Exp.I and Exp.II).

Finally, all participants (including the once that did not use the necklace) were asked a series of questions that looked into far-vision ideas like "If you had a technology that could capture any scent, which scent would you capture?" or "If you had a technology that could recreate any experience, which experiences would you use it for?" The results were quite binary, either they would recreate nature or past memories:

*Recreating scenic views of nature so I could feel like I was looking at some panoramic view of a mountain or forest or sunset* *Some smell of nature: the
smell of sea, the smell of a forest, the smell of spring...

"Scent of humans that I like. Have you seen the movie titled Perfume?" "The scent of early springtime. Or male pheromones." "I would recreate pleasant memories or important moments in my life; trips, friends, milestones, etc. I would love to relive the experience of "first impressions". The first time I was in a city or country, first time I met somebody special, first time I tried something new."; "Good memory with friends, cozy afternoon in a cafe.", "The presence of the ones we lost" "Childhood memory".
CONCLUSION

Studying smells is hard, prototyping with them is harder, and understanding the potential for smell to be used in Human Computer Interaction is the hardest task of all. Scent is the most pervasive sense, it is subliminal, and unlike signals that can be seen or heard, odors remain in the environment for extended periods of time. They can be transmitted in total darkness and around obstacles; they are invisible and hard to control. Unlike colors, there is no vocabulary for scents. We have to express our smell experience by means of metaphors "it smells like...". Similar to emotions, scents are abstract, and there is no certain accurate way of expressing our most deep feelings and sensations with few words. They affect us below the level of consciousness, and are therefore hard to test in human subjects. Preliminary studies like the one we did with the PTSD subject, allow us to understand how scent affects the unconscious and leads to intriguing opportunities to use scent in the field of HCI.

Currently people go to sleep and do not really take advantage of all the time spent in bed. Systems like Essence use sleep to affect the unconscious and positively affect people’s mood. In the future we could potentially use Essence to modify people’s dreams, trigger hidden memories to combat phobias, improve people’s sleep quality and even rehearse learned contents while dreaming.

In future work we would like to explore these research areas more deeply. The result could be personal, wearable devices that will promote health and wellbeing in very different ways than today’s fitness and sleep trackers. We would like to deploy several Essence wearable and stationary devices to investigate people’s sleep in every day life as well as other possibilities to unconsciously affect people’s moods and behaviors through scent. A system like Essence could serve as a wearable device to change people’s mood or behavior without them thinking about it consciously (it would be more an
example of "Pavlovian conditioning" [97] rather than what we understand as usual "learning"). After a while, hopefully, these behaviors would become habits and the person would not need the device any more.

With the evolution of wearable computing, computerized fashion, textiles and jewelry will become more integrated in and on our bodies. They will keep track of our physiological responses, behavior and social interactions while keeping us "well-dressed" and improving our well-being.

We believe that in the next 10 years wearable technology and other gadgets will increasingly leverage the sense of smell as another interface modality. Our hope is that in the future we will be able to integrate smell as an interface element in everyday personal devices to improve people's mood and wellbeing, facilitate learning and improve people's ability to connect at a distance.

When coupled with Virtual Reality or Mixed Reality, the addition of smell will significantly enhance the sense of immersion. In the next few years we will start to see how scent is slowly being integrated in these systems using off-the-shelf fragrances to augment digital experiences. Odor-less scents like pheromones or hormones will be used to remotely intersect users' realities and perceptions. We may induce pleasure, or may put subjects into a state of high suggestibility. The user will have complete control over the secreted chemical signals that will trigger stronger social response between subjects.

On the sensing part, there will be a point were we will be able to overcome the limitations and challenges of electric noses and will reach sensing capabilities similar to the human olfactory system. Using machine learning we will be able to predict and mimic the mechanisms that react to VOC in our noses and will be able to deconstruct and recreate these compounds on our own free will as if they were sounds or images. Understanding how human sensory perception works, we will be able to reflect accurately to the user the modified sensations and even augment these perceptions.
As a future vision, we believe we will be able to sense and recreate people's scent and create customized perfumes defined by our own body odors. Current deodorants mask or kill bacteria, but what if we could transform these body odors to create unique personal fragrances? Body odor is the result of bacteria living on our skin that break down secretions of sweat into odorous compounds. Using synthetic biology we could create a deodorant that transforms the bacteria stink into a nice fragrance. Since deodorants and antiperspirants don't actually stop the sweating process we will have a long-lasting unique perfume – our own unique scent.

We are starting to see dating apps like "Smell Dating" [98], that let you choose the person you will like by smelling a series of t-shirts previously worn by these people (similarly to the "sweaty T-shirt experiment" by Wedekind [44]). If we reach the point where we can sense and recreate people's smells, we could potentially see dating apps like Tinder [99] integrating the scent of people.

Another interesting speculative fiction is the possibility to use scent as an interspecies communication, a "unified language". As previously mentioned in this thesis, chemical signals communicate human emotions [4][5][6]. We secrete different odors depending on the emotional state that we are in, such as the "smell of fear" or "aggression". It has also been shown that diseases or tumors release certain scents. We could potentially use this as a form of non-verbal communication with other species that do not use the same form of language as we do. Dogs already do this, and you have probably heard that when we are scared, dogs can sense it. However, when humans try to understand dogs' or other animals' emotions, we only rely on their body language and certain sounds. The same happens with newborns, they understand their mother's chemosignals but we do not understand theirs. We consciously rely on their body language and specific sounds like a cry or laugh. Sensing their chemosignals would be a meaningful advance in understanding their physical and emotional state. We could potentially know whether they are in pain, if they are hungry, feel lonely, have fear, etc.
In the next few years we will see an exponential improvement in cancer detection by understanding how VOC are released by cancerous tumors. As it has been described in this thesis, we are currently doing so with dogs, but there will be a point that these dogs will be replaced with electric noses that will be able to accurately diagnose cancer or other diseases based on smell.

Our long-term vision is that olfactory devices would serve both as displays and sensing technologies. We believe that wearable systems like Essence will sense VOC emitted by the user and the environment [100][101]. This will open new opportunities for sensing emotions and physiological information such as relax, happiness, stress, anxiety or detect diseases in early stage such as cancer or psychiatric disorders.

Finally, we will be able to recreate these scents by will. Coupled with physiological signals and smart environments, we will be able to influence human behavior by means of subliminal stimuli [83]. In future work we would like to incorporate previous author’s work on BCI and Virtual Reality [102] to improve the sense of immersion and mindfulness. Our hope is that in the future, users will be able to use this kind of systems to facilitate memory consolidation for learning purposes, enhance mood and wellbeing or even improve people’s experience while communicating at a distance.
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