PiloNape: Electrostatic Artificial Piloerection for Affecting Emotional Experiences

ANONYMOUS AUTHOR(S)

SUBMISSION ID: 9371*

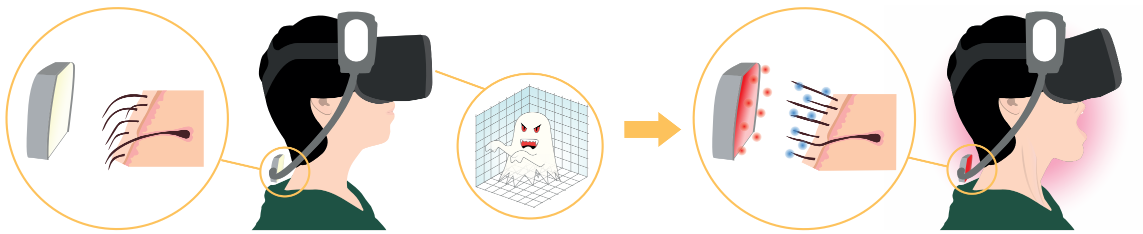

Fig. 1. The user is wearing a head-mounted display with an electrostatic generator attached, the generator is connected to an electrode above the nape. Left) The user is watching a scary clip. Right) The generator creates contactless piloerection on the hairs of the nape to increase the emotion of fear experienced by the user. The piloerection is caused with a positive charge on the electrode, that charges the hairs negatively through induction and attracts them.

Piloerection is a strong affective reaction that occurs in human beings. In this project, we induce artificial piloerection using contactless electrostatics to enhance the affective response of users when they are interacting with computer systems. Firstly, we design and compare various high-voltage generators in terms of the static charge, safety and frequency response with different electrodes as well as grounding strategies. Secondly, a psychophysics user study revealed which body parts are more sensitive to electrostatic piloerection and what adjectives are associated with them; the wrist and the nape were the most sensitive parts. Finally, we combine a generator with a head mounted display to add artificial piloerection to virtual experiences of fear. We hope that these findings allows designers to use contactless piloerection in affective experiences such as music, short movies, videogames or exhibitions.

CCS Concepts: • **Human-centered computing** → *User studies*; *Haptic devices.*

Additional Key Words and Phrases: piloerection, electrostatic, affective computing, emotion elicitation methods

ACM Reference Format:

Anonymous Author(s). 2018. PiloNape: Electrostatic Artificial Piloerection for Affecting Emotional Experiences . In . ACM, New York, NY, USA, 24 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

Human emotions define how we may feel or the decisions that we take. Emotions are experienced naturally in our everyday life. With the renewed interest in affective computing, accentuated by the virtual transition, finding ways in which computer systems can provoke more emotional reactions is of fundamental interest.

The James-Lange theory of emotion from 1894 [31] suggests that emotions are a result of bodily sensations; e.g. you become happier when you smile, your are sad because you cry, or you are afraid because you run. Other modern theories are in line with this idea, such as the two-factor theory of emotion [62].

Even artificially generated body sensations can trigger the emotions that are associated with the stimulus. For example, artificial tears dropped on the face can cause sadness [38, 75]; or modifying the hear beat affects decision making as if you were anxious or calm [72], [13].

Piloerection is the contraction of the muscles connected to the hair follicles below the skin, it causes the erection of the body hair. Darwin, in his book from 1872 [15] suggested that piloerection occurs in response to anger, fear, or excitement. Nowadays the physiological mechanisms of piloerection are well understood [10, 23]; however, which emotions are associated with piloerection remains unclear despite many studies on this subject [47], the agreement is that piloerection is associated with strong emotions (high levels of arousal).

In this project, artificial piloerection is caused to make experiences delivered by computers more emotional (Figure 1). Piloerection is an interesting trigger because: it is associated with strong emotions, does not leave traces in the user as releasing liquids may do, it can be induced in several body parts making it adaptable to desktop scenarios or head-mounted displays, it can be applied in a contactless way using electrostatics and the temporal actuation is in the order of seconds. Finally, we note that affective touch is connected with the C tactile afferents [44, 51], which are only present in hairy skin.

We show results for the intensity threshold of electrostatic piloerection for different body parts, with surprising large sensitivity for the wrist when compared with the traditional forearm. We explore piloerection in the nape, a sensitive area which is conveniently exposed when wearing head-mounted displays. Finally, we employ piloerection for affecting the emotional experience of fear.

In Section 2, we present the related work for piloerection, electrostatics and exploiting the James-Lange theory. In Section 3, we discuss the working principle of electrostatic piloerection, design high-voltage generators, electrodes and test their capabilities in fake hairy skin. In Section 4, we conduct a psychophysical study to determine their perception thresholds and associated adjectives of the stimuli. In Section 5, we show how artificial piloerection affects the physiological parameters and reported fear when watching scary clips. Finally, in section 6, we discuss limitations and future work for artificial piloerection.

2 RELATED WORK

2.1 Theories of Emotion

Emotions are a fundamental component of being human, they motivate our actions and add richness to the human experience. Traditionally, in human–computer interaction (HCI) users must discard their emotions to work efficiently and rationality with computers [7]. However, latest trends consider emotions of paramount importance in human-computer interactions and virtual scenarios [65].

In the 1990s the concept "Affective Computing" [54] studies how computational systems can recognize and react to human emotions, expressing them by means of an interface. Nowadays, affective computing is defined as a computing that relates to, arises from, or deliberately influences emotions [64].

To work with emotions, it is essential to know how they arise and manifest. Emotion theories can be classified into three main categories: neurological, physiological, and psychological [29]. Neurological theories, like Damasio's theory [42], have neural patterns representing changes in body and brain, these changes make up the emotion [8]. Physiological theories suggest that body responses are responsible for emotions, e.g., the James-Lange theory of emotion [30] asserts that emotions arise from physiological arousal; or the Cannon-Bard's theory [9] posits that physiological arousal and emotional experience occur simultaneously, although independently. Finally, Psychological theories argue that thoughts play an essential role in forming emotions: e.g, Roseman [59], Scherer [63] or OCC [52].

Emotions can be described as discrete entities or along continuous dimensions [25]. Discrete models propose a small set of discrete emotions. For example, Ekman [16], categorizes six basic emotions: happiness, anger, fear, sadness, surprise, and disgust. Another discrete model is proposed by Plutchik [56] with a wheel that includes: trust, surprise, joy, fear, disgust, sadness, anticipation and anger. On the other hand, the dimensional models represent emotions as combinations of multiple psychological dimensions. For example, Russell's circumplex [60] proposes: valence (a pleasure-displeasure continuum) and arousal (calmness to excitement). Later, Mehrabian and Russel [48] added Dominance to that model, dominance values range from being controlled to being in control.

2.2 Piloerection

The piloerection is an erection of the hairs of the skin caused by the contraction of the small muscles at the base of the hairs that are called arrectores pilorum. Piloerection occurs involuntarily, with a very small number people being able to control it voluntarily [26]; however, very little is known about the emotional correlations of this ability.

The involuntary piloerection has different functions in various species. It can be for temperature regulation [11] but also a response to an emotional stimuli. These stimuli generate a nerve discharge that affects the SNS (sympathetic nervous system) that creates the contraction of the arrectores pilorum muscles causing goosebumps. This emotional piloerection is not well-understood and raises many questions about the psychology of emotions [47].

Some studies suggest that piloerection occurs in response to any strong emotional reaction or high emotionality [2]. Piloerection has been linked with both positive and negative emotions. For example, Darwin in 1872 [15] suggested that piloerection occurs in response to anger, fear, or excitement. Yet, for a given emotion there are studies that connects it to piloerection with others stating that there is no association [47].

2.3 Affecting emotions through artificial body sensations

Affective computing also includes the induction of emotions. Emotion elicitation methods use external stimuli such as video, images, and sound, as well as recalling past events [58]. These methods can elicit certain emotions, but they have shortcomings such as low efficiency, high susceptibility to ambient interference, significant individual variance, and low ecological validity. Virtual reality can be seen as a more compelling elicitation method [36, 39, 58, 70, 74]. For example, a comparison between subjective and physiological measurements showed that VR triggers stronger emotions and higher heart rate than videos [77].

Several studies have explored emotional induction through artificial physiological stimuli. Following the physiological theory, if the stimuli are similar to real body sensations that we experienced with emotional states, the effect can be increased towards the original emotion.

For example, modifying the hear beat of the users affects decision making in a way that is similar to changes in the emotional status [72]. In [13], three general anxiety induction techniques were explored on a VE that reproduced a fire evacuation. Introducing a biofeedback heart beating sound effect produced much higher physiological arousal than visuals and sound. Similarly, playing a heartbeat sound to modify the user´s heartbeat can amplify fear while watching 3D films [71]. In [33] they combined a Head Mounted Display with mechanical and electrical muscle stimulation (EMS) actuators to make the experience more immersive.

Some authors tried to induce positive emotions although they are harder to elicit [75]. For example, a glass-style wearable that released water drops near the eyes in order to increase sadness or joy was only capable of increasing sadness, among both wearers and those observing them. Another example of inducing positive emotions is to use tickling to produce laughter and relieve stress [17]. An actuation mechanism, creating tickling sensations along the feet using a neodymium permanent magnet, and a brush which is mounted on the magnet could elicit a sense of fun and laughter.

2.4 Electrostatics in HCI

There are some uses of electrostatics in human-computer interaction. Electrostatic fields can be used to control the shape and trajectory of fog screens and bubbles respectively [61]. Metallized Mylar films cut with specific patterns can be actuated and expanded using electrostatic forces [19]. Regarding haptic feedback, electrostatic shocks can be artificially induced [50] and high-voltage arcs can also be perceived on the skin [68]. There is also the effect of feeling vibration when sliding the finger over a statically charged surface [3].

2.5 Artificial Piloerection

MagHair [5] applied ferromagnetic powder into the user hair for being able to move it with electromagnets in contact at the other side of the forearm. It was shown that linear patterns on the hair could be differentiated, this work was not aimed at measuring or provoking affective responses but at functional haptics. There has been excellent exploratory works in using electrostatic fields to create artificial piloerection in the forearm [20, 21], to measure if adding piloerection to an alarm sound produced a larger galvanic skin response due to an increase in the surprise.

However, we reckon that a deeper and wider exploration is needed to understand both the hardware components and the affective reaction of the users to artificial piloerection. Here, we explore different high-voltage generators and electrodes. More importantly, we studied the sensitivity of different body parts, and found that the nape is an unexplored area despite being exposed, compatible with HMD and sensitive for contact technologies [49].

3 ELECTROSTATIC PILOERECTION

3.1 Physical principle

A charged electrode generates an electrostatic field that can exert forces over other charged objects. As the Coulomb's law expresses $\mathbf{F} = \frac{q_1 q_2}{4\pi\varepsilon_0} \frac{\mathbf{r}_1 - \mathbf{r}_2}{|\mathbf{r}_1 - \mathbf{r}_2|^3}$ the force is attractive if the charges are of different polarity and of repulsion if they are the same. Hairs below an electrode can get charged if the user is connected to ground or because the charge is induced in the hairs. Charge by induction is a redistribution of the net charge on an object given the proximity of electrostatic fields; that is, although the total charge of the forearm is neutral, negative charges will migrate to the tip of the hairs when there is a positive electrode above them. When the external charge is removed, the negative charge of the hairs recombines with the positive charges and the total charge of the forearm returns to neutral (Figure 2).

3.2 Electrostatic generators

The oldest way of generating electrostatic charges was reported by Thales of Miletus back in 550 BC when rubbing fur on amber. This phenomenon is related to triboelectricity, which is the tendency of some materials to get or release electrons upon friction.

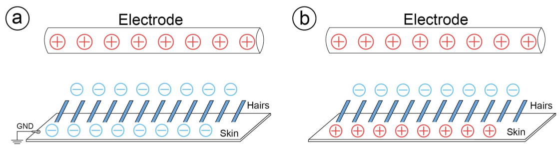

Fig. 2. Working principle of electrostatic piloerection. a) grounded. b) ungrounded with induction.

Van Der Graaft generators [22] exploit triboelectricity, having an insulating belt rolling over a rod made of aluminium (strong positive triboelectic coefficient) and a strong negative triboelectric material (e.g., teflon) on the other side. There are metallic combs at both sides to gather and release the electrons, a topload (usually a metallic sphere) can be added to accumulate charge.

Modern alternatives for generating high-voltage (HV) and in turn electrostatic fields include the flyback transformers [76], used in Catode Ray Tubes to accelerate the electrons into the screen. The principle is to use a high ratio transformer driven with a ZVS driver, a diode at the end usually rectifies AC into DC. Another way of obtaining high-voltage is the Cockcroft-Walton multiplier [18], a circuit composed of multiple stages of capacitors and diodes. Each stage doubles the input voltage and halves the current. These multipliers require an AC input and the output is DC.

Different High Voltage generators were created and compared with existing HV dc-dc converters. We created our own generators since the commercial ones do not reveal their full schematic, and some of them contain large capacitors that can store charge beyond safety levels. Also, we do not know the values of their limiting resistors. The generators that we built follow this design: a ZVS driver and a high-ratio transformer (both from the Walfront Boost Step-up), then a Cockcroft-Walton multiplier of different stages, a bleeder resistor between both sides of the multiplier ensures discharge of the capacitors and of the electrode, a limiting resistor control the maximum current that can be delivered outside of the circuit. The schematic can be seen in Figure 3. The whole high voltage multiplier was encapsulated in transparent epoxy.

Five generators were built:

- 6 and 1/2 stages: 6 capacitors (30KV, 0.1nF) in one side end 7 capacitors in the other side. It has 13 diodes (HV 20kV) placed to have positive charge at the V out. It has 1 GOhm bleeder resistor and a 1 GOhm limiting resistor.
- 9 stages: 9 capacitors (20KV) at each sides and 18 diodes. It has 500 MOhm bleeder and a 500 MOhm limiting resistor.
- 6 stage similar as before.
- 5 stage similar as before but 30kV capacitors.
- 5 stage similar as before.

Commercially available generators were tested:

- Cylindrical HV generator (advertised as 400 kV HC dcdc).
- FlyStick: toy Van der Graaft generator.
- High voltage generator (advertised at 5 kV).
- EMCO Cube F02 (rated at 4 kV for 12V input).

Some tests were performed with each of the generators powered at 3.3V and current limited at 2 A. The tests consisted on measuring the charge on a cardboard electrode using a contactless NEWTRY electrostatic charge measuring device (handheld 20kV). The generators can be seen in Figure 4 and their generated charge is plotted in Figure 5. The charge

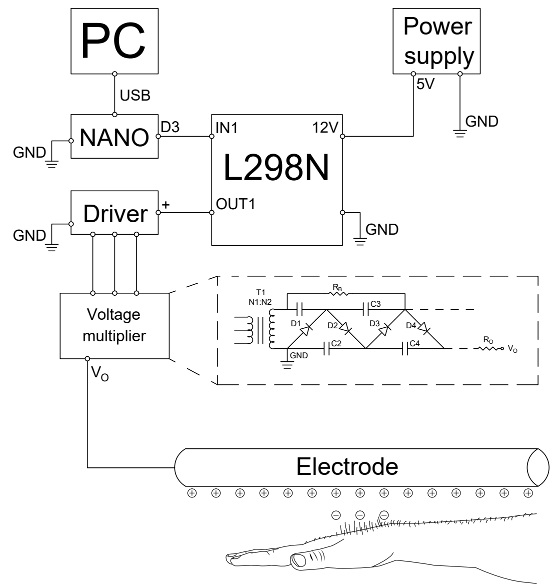

Fig. 3. Full schematic of a system capable of delivering controlled electrostatic charge into an electrode, to attract the hairs on an arm below it. The PC is connected to an Arduino Nano for sending the desired intensity (from 0 to 255), the Arduino generates a PWM signal that is amplified by a L298N that powers the multiplier that outputs high voltage into the electrode. Inside the multiplier there is a transformer (N1:N2 of 200) and multiple stages of a Cockcroft-Walton multiplier. R_b is the bleeder resistor and R_0 the limiting resistor.

can be controlled dynamically using different values for the duty cycle, the correspondence between duty cycle and charge for the 9-stage generator can be seen in Figure 6. The 9-stage generator will be used for the rest of the paper.

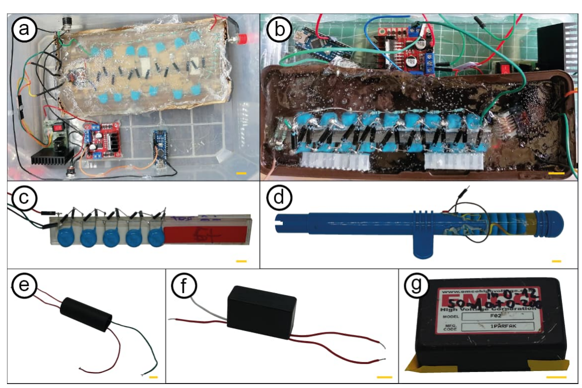

Fig. 4. Different generators tested. a) 6-stage potted and connected to the control circuit. b) 9-stages potted and with the control circuit. c) 5 stages. d) flystick. e) comercial HV generator advertised as 400 kV and 5 kV (f). g) EMCO cube model F02. Scale bars are 1 cm.

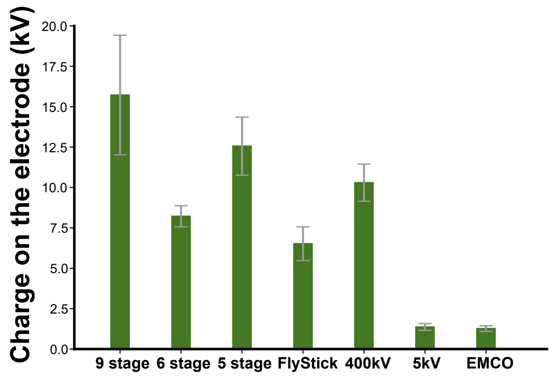

Fig. 5. Electrostatic charge generated on a 8 cm long 2 cm diameter, 1 mm thickness electrode made of cardboard. 5 measurements per device, error bars represent standard deviation.

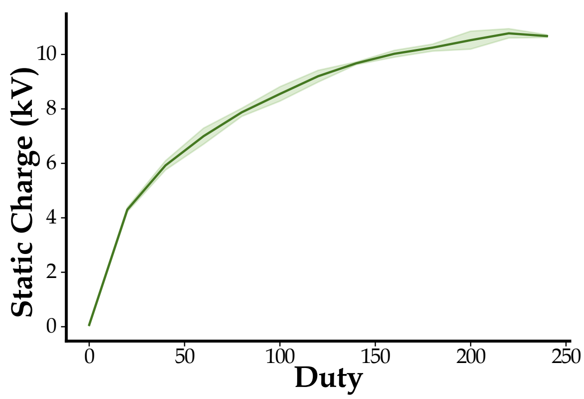

Fig. 6. Charge on the electrode as the duty cycle of the generator changed (from 0 to 255). 4 trials were conducted for values from 0 to 240, with steps of 20 on the duty cycle. Light colored area represents standard deviation.

3.2.1 Test hairy skin. Fake hairy skin replicas were created to safely test the different HV generators. The replicas were made of silicone polymer (PDMS) mixed with graphite to obtain similar conductivity to the human skin. Four different tests were made mixing different quantities of silicone and graphite. Two of the four samples were also mixed with isopropyl alcohol.

The sample that had the best conductivity (not too conductive nor too isolating compared to the human skin) had 2.25 vols of graphite per silicone. Two different hairy samples were made with these proportions. Hairs from a hair-dress practice mannequin were grafted before it dried, using a metallic grid to insert the hairs with an angle. After drying, the hairs were cut to the desired distance (Figure 7).

The time it takes to charge and discharge the electrode as well as the charged measured on the skin over time can be seen in Figure 8. The charging on both takes less than 100 ms and it reaches 9 kV in the electrode and 0.5 kV in the skin. Upon switching off in 1 s the electrode discharges to 1 kV and the skin discharges completely.

Fig. 7. Fake hairy skin made of silicon and graphite with fake hair grafted. Scale bar is 1 cm.

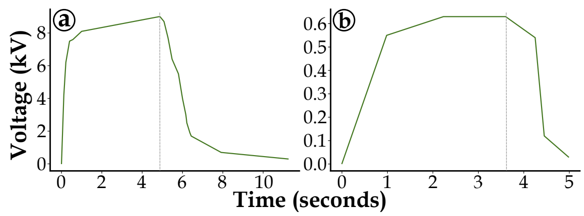

Fig. 8. Charge over time on the electrode (a) and on the skin (b). The generator was switched on at the beginning and switched off on the dashed vertical line.

3.3 Electrodes

We tested different shapes, sizes and materials for the electrode. We measured the charge on the electrode, on the fake skin and the residual charge in the skin after switching of the electrode. We also tested grounding the fake skin or leaving it ungrounded. The tested shapes were cylinders and flat electrodes. The materials: cardboard, plastic, cardboard with tinfoil inside, tinfoil and tinfoil with tape and a coat of nail polish. The electrodes can be seen in Figure 9.

Fig. 9. Different electrodes tested (left to right): plastic, cardboard, cardboard with tinfoil, plastic, cardboard, cardboard with tinfoil and plastic with tinfoil.

The chosen electrode was the cylinder made of cardboard. This electrode was the one inducing the largest hair movement and leaving the minimum residual charge. Flat electrodes with a conductive layer inside and a dielectric layer outside were used in an exploratory research for electrostatic piloerection [21] but cylindrical electrodes made of cardboard provided better results for us, similar electrodes were used in the FlyWand toy stick (Figure 4.d).

4 PSYCHOPHYSICAL STUDIES

The objective of this user study is to determine the perception threshold for different body parts that can be piloerected. In other words, what is the minimum intensity needed to make the stimuli perceptible by humans. Also, associated adjectives and emotions are listed by the participants when they received this stimulus.

4.1 Pilot Body Part

There are several body parts susceptible for piloerection: legs, pubis, arms, hands, nape, eyebrows or head. Piloerection is most often reported to be on the arms, nape, or legs [14]. We conducted a pilot study (N=6) to narrow down the number of suitable body parts. The legs and the pubis were discarded since they were not considered appropriate and the users are not used to wear devices on those areas; similarly eyebrows, eyelashes or beards were discarded for avoiding having electrodes in front of the face, yet they can be interesting areas for future studies. Therefore, we explored: nape, upper forearm, lower forearm, wrist, back of the hand and fingers (Figure 10). All on the back side, since the stimulus was not perceived on the fingertips or palm.

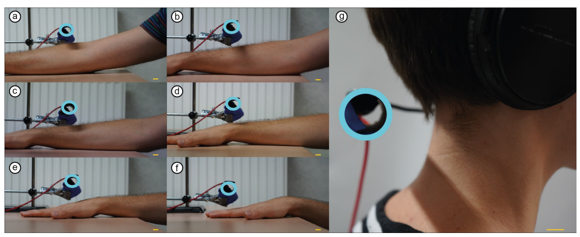

Fig. 10. Body parts on which piloerection was tested, the blue circle is the electrode. a) upper forearm, b) mid forearm, c) low forearm, d) wrist , e) backhand , f) fingers, g) nape. Separations was 3.5 cm. Scale bars are 1 cm.

Participants were sitting down wearing noise cancelling headphones and looking at a blank piece of board, the arm was resting on the table. The electrode was placed 3.5 cm above the target area, being held by a retort stand for the arm and with a flexible wire attached to the headphones for the nape. The different parts were excited at various electrostatic charges and the users were asked if they perceived the stimuli, a simple binary search was used to converge to a threshold in this pilot study.

The perception thresholds for the different body parts are shown in Figure 11. Surprisingly, the wrist was more sensitive than the forearm. Also, the nape was found to be sensitive and has not been explored in the literature. The forearm is the traditional area, which has been most widely study in the literature. Therefore, we selected: wrist, nape and forearm for the full study.

4.2 Time Dynamics Study

Another pilot study was conducted to check the delays on the perception for this stimulus. We recorded over time: the power going into the generator, the hairs movement and when the user reported feeling the stimulus. The data for four participants (2M, 2F) of varying hair on the forearm was captured. People with more hair could feel the stimuli during the whole activation, whereas people with less hair only felt the stimuli upon raising and falling of the hairs. All participants had a quick reaction time on rising edge: (0.235s SD=0.189s) from activation to hairs raising, and (0.298s SD=0.196s) from activation to perception; on falling edge there was some delay until the hairs fell (0.676s SD=1.405s), and (0.806s SD=1.376s) to perception.

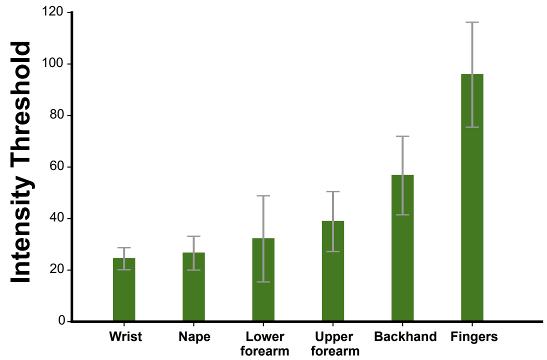

Fig. 11. Intensity Perception Threshold for different body parts from a pilot study. Error bars represent standard error from the 6 participants. Intensity ranged from 0 to 255.

In Figure 12 we show the aggregation of the participants for the time plots on device activation, hair movement and perceived stimulus. The short difference between perception and hair movement on rising edge (63ms), may indicate that the stimulus is captured by the skin before observable hair movement, since typical reaction times are between (150ms and 300ms) [34]. On falling edge, the difference was larger (130ms). Further investigation on this asymmetry could be interesting.

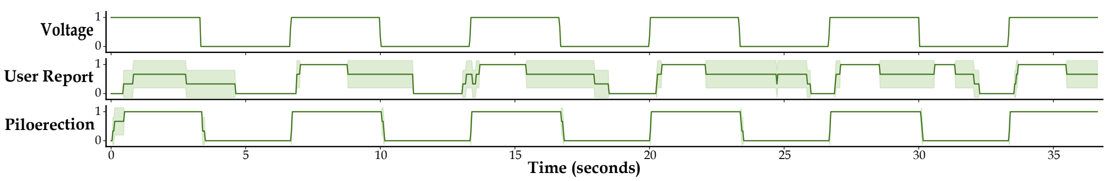

Fig. 12. Plots over time for the activation of the electrostatic field, the rising of the hairs and the perception of the user. The 4 users are aggregated showing the average as the solid line and the standard deviation as the light coloured area.

4.3 Perception Threshold Study

New participants (N=12; 7M, 5F) with age (31.7 SD=9.74) were recruited for the study. The three selected body parts from the pilot study are the nape, forearm and wrist. They were counterbalance in order. The users were sitting in front of the computer wearing noise cancelling headphones and reporting through a keyboard using the non-dominant hand, the dominant hand was the one stimulated. The experimental setup can be seen in Figure 13.

The perception threshold was estimated using a one-up/two-down adaptive staircase procedure with a two-alternative forced-choice paradigm [3]. Basically, two periods of time were indicated to the user and the stimulus was only present in one. As the user guessed correctly the period where the stimulus was applied, the intensity of the stimulus decreased, on failure there was a reversal and on two correct guesses, a positive reversal. We took the average of the last 3 reversals. The stimulus lasted 3 seconds and the up/down factors were (x1.26 for the coarse and x1.16 for the fine). An example of the measurements for a user can be seen in Figure 14.

The perception threshold staircase was performed for each of the body parts. Afterwards, the user filled in a questionnaire reporting freely adjectives, similar experiences and differences between body parts. Also, they reported with a Likert scale the association for each body part of the stimulus with 5 emotions and 8 adjectives common from tactile stimulus. The answers for the free adjectives were filled before showing the list of preselected adjectives. The whole procedure took an average of 35 minutes.

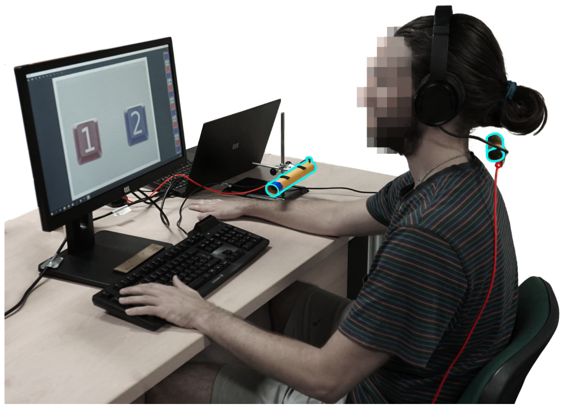

Fig. 13. Experimental setup for the user study of perception thresholds. There is an electrode above the forearm and above the nape (separation 3.5 cm). The user is in front of a computer to report the perception of the stimulus.

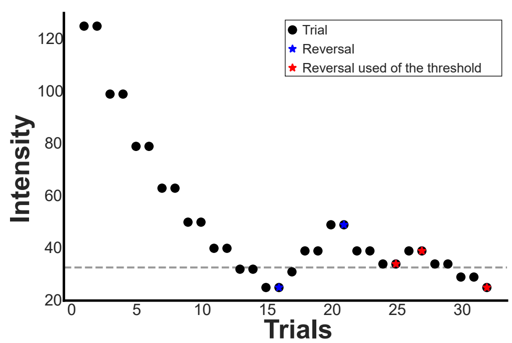

Fig. 14. Example of the staircase procedure from one of the participants to determine the perception threshold.

4.4 Results

4.4.1 Perception Threshold. The perception threshold averaged per user can be seen in Figure 15. The nape is still the most sensitive part but not significantly (ANOVA repeated measures: df=2, F=1.99, p=0.159) due to the large variance between users.

The hair amount was quantified by two evaluators from 1 (none) to 3 (abundant) for the nape, forearm and wrist. There was only disagreement in 3 instances of only 1 point. We found no correlation between the amount of hair and the sensitivity for nape (R=0.571, p=0.052), forearm (-0.539, p=0.071) or wrist (R=-0.471, p=0.122), the nape was close but with opposed sign (i.e., the less hair, the larger the sensitivity) to the expected one.

The correlations with age were (R=-0.288 p=0.36) for the nape, (R=0.663 p=0.02) for the wrist, and (R=0.515 p=0.09) for the forearm. Wrist sensitivity correlated with age meaning that the older the participants were, the less sensitivity they had in the wrist. We note that our sample pool is not large enough, neither varied in age to make these correlations meaningful. Attending to sex, males were significantly more hairy on the forearm (p=0.012) and wrist (p=0.017) than females. There was no difference on the sensitivity between genders (nape p=0.16, wrist p=0.41, forearm p=0.42).

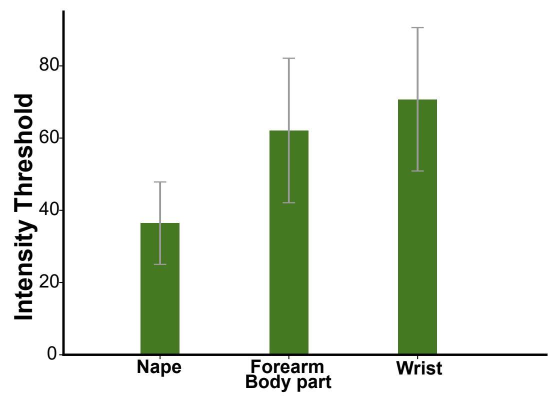

Fig. 15. Averaged perception thresholds (N=12 users) for different body parts. Scale bars represent standard error.

4.4.2 Free adjectives and descriptions. The free adjectives used to describe the general sensations were: tingling (7 times), tickling 7, pleasant 5, cold 2, beating 2, electric 2, bubbling 2, soft 2, subtle 1, light, vibrating, relaxing , unpleasant, diffuse , focused, strong, amusing, pinching and friendly.

When the participants were asked for similar experiences they answered: having goosebumps 3, approaching a CRT 2, caresses 2, wind 2, touching another hand 1, insects, webs, phantom feeling of phone notification, itchiness due to cold or heat, chill, awe from listening to music, wires that massage your head, electric shock and fear.

When asked about differences between body parts the participants answered: Nape feels more intimate and gradual, forearm more sudden, wrist more extended. Forearm was harder to feel over a continuous stimulus, on the nape it was weaker but I could feel it continuously. The nape was more on edge and delicate. Nape was more pleasant, almost erotic; wrist was neutral, forearm was amusing and gratifying; perhaps it is something cultural. I have not felt anything in the wrist, in the nape I felt tickling, in the forearm pinching/shock. In the nape I can feel my hair bristling, in the other areas I feel like cold air. Intensity was larger in the forearm x2. I can feel better the nape. As time pass I could perceived better the sensation. At high power I could feel at the sides, at low power I could feel at the centre. In the nape it felt like wind, at lower power felt like a swirl. In the forearm I felt my pulse, at lower power was like wind. In the wrist the sensations extended into the hand and the forearm.

4.4.3 Emotions and adjectives. The Likert results for the association with emotions can be seen in Figure 16. Wrist is the part that has the weakest associations (almost none with fear and sadness), perhaps because we are more used to be touched in that area under common social interactions. The nape had the strongest emotional associations. The emotions were associated with the stimulus in this order: surprise, excitement, happiness, fear, disgust and sadness. In general, the nape had stronger or similar associations than the forearm except for disgust. The general agreement that piloerection is associated with high arousal (Surprise and Exciting) vs low arousal (Sadness) holds in these reports. We note that this subjective self-reported feedback cannot be considered of significance and is more an overall exploration.

The association with pre-selected adjectives commonly used in tactile studies can be seen in Figure 17. The most common adjectives were comfortable, pleasant and tingling. It is interesting to note that positive or neutral adjectives appear more than negative ones, in the absence of other stimulus. Tingling and tickling were the most repeated freely picked adjectives. Again, we note that results from self-reported emotions or adjectives may not be conclusive.

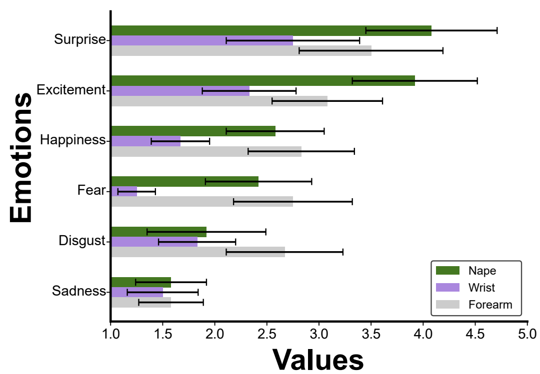

Fig. 16. Likert scale of the association with the stimulus and different emotions split by body parts. Being 1 no relation at all, and 7 totally related. Scale bars are standard error.

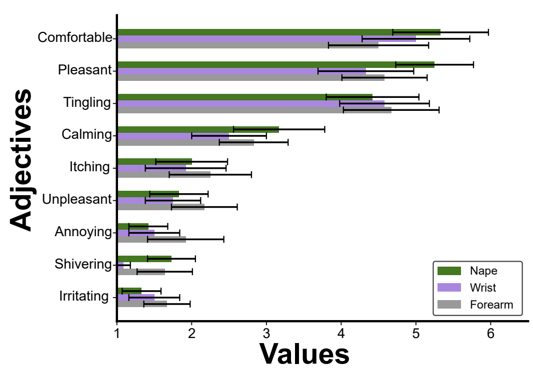

Fig. 17. Likert scale of the association with the stimulus and different adjectives split by body parts. Scale bars are standard error.

5 EXPERIENCE STUDY

In this study we measure the physiological responses of the users while they watched two 360° videos related to fear with and without PiloNape. Self-reported emotional perception and fear intensity were gathered with a Likert scale. This study is more organic and close to the final applications than the Psychophysical study (4). The piloerection was be applied in the nape, as concluded from the psycophysics study (4). We focused in one emotion, given that having multiple would require a between-subjects study to avoid cross-talk between the emotional states. Also, the lack of agreement on which emotions are connected to piloerection may indicate that a multi-emotion study is beyond the scope of a single paper.

5.1 Selecting the emotion

As discussed in the related work (2), the set of emotions that generate piloerection remains unclear in the scientific community, it is suggested that is an indication of peak moments [2, 15, 47]. Some experiments found associations with being moved [4], fear [28] or awe [57], yet there are other experiments that report no associations with those emotions [47].

For selecting an emotion, we discarded being moved since positive emotions are harder to elicit [75] and some studies point out that more chills occurred in response to negative valence [24], also, some results [46] suggest that piloerection is not reliably connected to awe, at least in a controlled environment. We selected fear because it is a strong emotion and piloerection in response to fear has only been recorded using self-reported measurements [47], thus we could make a contribution by adding physiological data. Also, in the previous section (16), we found that fear was the strongest negative association with piloerection in the nape.

5.2 Selecting the stimuli

Excerpts from films are used in several studies to induce emotions [35, 40, 43, 66]. In [40], a list of clips from mainstream movies is presented, whereas others use clips from research repositories [12, 27]. We tested the clips and we were not fully convinced since they lacked context and building up, they did not provoke strong reactions in the researchers. Furthermore, we wanted to conduct a study in an immersive scenario to avoid as much as possible the effects of the evaluation environment, virtual reality head mounted displays are a good option for this.

Following the line of Virtual Reality, we tested some videogames, such as Resident Evil 7 (for fear) and Journey (for awe), but the variability between participants trials would be very large. In addition, the ability of the participants with the controllers affects the results [57]. We decided to search for fear-related clips designed for VR or 360° environments. After watching a wide selection, we discarded clips that may contain dolls or clowns, since pediophobia and coulrophobia are wide-extended and would bias the responses. Finally, we chose two similar clips to alternate them in the user study: 'Conjuring 2'[55] and 'Portal'[69]. They are both related to ghosts and spirits, frames of the clips are shown in Figure 18.

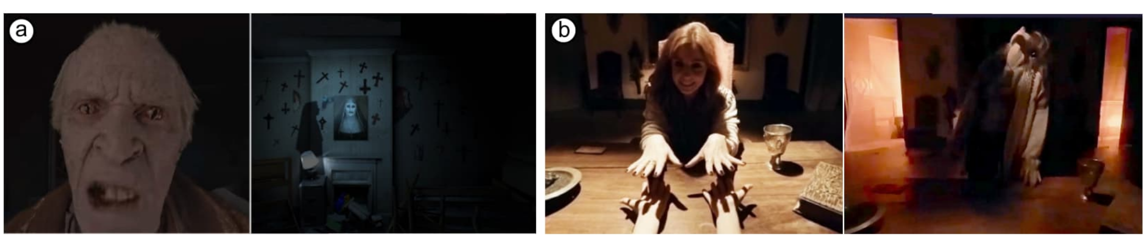

Fig. 18. Frames from the selected clips to induce fear. a) Conjuring, b) Portal.

We searched for clips related to relaxation and pleasantness to put them between the fear clips, so users could go back to a basal emotional state. We selected 'Aurora Borealis' [45] which had already been used by a previous research and combines relaxing visuals and music.

5.3 Measurements

We captured heart rate (HR) and galvanic skin response (GSR). Cardiovascular measures and skin conductance are indicators of physiological arousal and sympathetic activity (the higher the HR and GSR, the greater the anxiety) [32]. Exposure to fear increases arousal, which causes sweat secretion that can be measured by electrodermal activity. The GSR also shows changes when feeling an intense emotion. The increase of the heart rate is another reaction that occurs when piloerection appears. [47]. There are other works that suggest that the skin conductivity is one of the best measures for measuring the physiological effects of piloerection [53].

Biosignals were recorded using Neurobit Optima 4+ device [1], and heart rate with a finger pulsoximeter (Berry Electronics). The electrostatic piloerection did not affected the GSR and HR sensors since no changes in the signals were detected upon activation and deactivation.

For the subjective measurements we used the The Self-Assessment Manikin (SAM) [6]. SAM is a non-verbal pictorial assessment technique that measures the valence, arousal, and dominance associated with a person's reaction to a stimuli. SAM is widely used in VR applications [36, 39, 58, 70, 74]. Although some of them highlighted the need to correlate SAM with physiological measures [37, 41, 73].

5.4 Procedure

Twelve new participants (7M, 5F; age=33.33 SD=13.9) took part in the experience study. The participant sat down in front of a table, wearing the HMD (Meta Quest 2), noise cancelling headphones with the audio from the glasses, as well as the GSR electrodes on the non-dominant hand fingers and the heart rate sensor in the index finger of the dominant hand. A camera captured the forearm of the non-dominant hand to check for piloerection. The experimental setup can be seen in Figure 19.

The participant was informed about the experiment and signed the consent form. The sensors and the glasses were put on the user. Then, the user watched the first clip. After the first clip, they filled in a questionnaire. Afterwards, they watched a relaxing clip of the Aurora; then, the second fear clip. Finally, the last questionnaire was filled in.There were only two questionnaires, one per clip. The procedure took an average of 35 minutes. The clips for fear were counterbalanced in order and the application of PiloNape or not was also counterbalanced for each clip.

Two researchers decide 3 periods of the clips at which to apply PiloNape. Piloerection stimuli were applied 1 second before the moment when tension was starting to build up, and remained activated for approximately 20 seconds. This is approximately the duration of the natural occurring pilorection [4].

For the Conjuring clip, the timestamps are:

- 0:49 to 1:01: the man´s spirit appears for the first time.
- 1:48 to 2:00: the nun´s shadow appears, walks and goes out of the poster.
- 2:45 to 2:55: the last spirit appears.

For the Portal clip:

- 1:56 to 2:10: the cup starts moving and falls into the floor.
- 3:20 to 3:48: children scream and lights go on off while the pythoness gets possessed.
- 4:23 to 4:41: the chair moves and the pythoness appears suddenly.

Fig. 19. A user conducting the experience study. Wearing VR glasses (Quest 2) and noise cancelling headphones connected to them. The electrode (cyan) was above the nape at 3.5 cm. On the non-dominant hand, the galvanic skin response was measured with grounding on the ring and sensing on the index and heart fingers (red); a close-zoom camera with illumination recorded the forearm checking for piloerection (fuchsia). On the dominant hand, the heartrate was measured with a pulsoximeter (green).

5.5 Results

5.6 Physiological

5.6.1 Heart-rate and galvanic skin response. In Figure 20 we show the aggregated data over time for users watching the two clips with PiloNape and no PiloNape. Looking closely in the HR and GSR, there are changes during the scary moments. We note that scary moments 1 and 3 were more sudden jumpscares whereas moment 2 had more build-up; this was the case for both clips. In the more abrupt scary moments (1 and 3), applying piloerection increased the sudden raise on the hear-rate whereas the effect is less clear in the build-up moments (2). The plots for two specific users (not aggregated) can be seen in Figure 21, in the first user (a sensitive one) the effect of piloerection can be clearly seen whereas in the second user (a not reactive user) the effect is smaller.

The heart rate signals and galvanic skin response were preprocessed to extract features from the biosignals acquired over time. The data were normalized to fit in the range [0:1]. From the GSR signal, we extracted the tonic component, which describes slow changes and a faster-varying phasic component. The biosignals were summarized as the mean value and the entropy for each participant and experimental condition. The entropy is widely used in signal processing to quantify the complexity of the signals. The results are presented in Figure 22. The HR entropy, GSR entopy, GSR Tonic mean value, GSR Phasic mean and its entropy present higher data dispersion when applying PiloNape showing that participants experienced more varied physiological reactions through the experiment. GSR entropy shows much higher values for with applied PiloNape. Significant difference between the conditions was found for GSR mean (p=0.003) and for GSR entropy (p=0.015).

5.6.2 Piloerection. Real piloerection happening in the arm of the user was captured with a camera (see Figure 24). Three researchers looked at the videos to detect piloerection. The plots for the occurrence of piloerection per clip and condition are in figure 24. We note that artificial piloerection was applied in the nape and that the piloerection on the

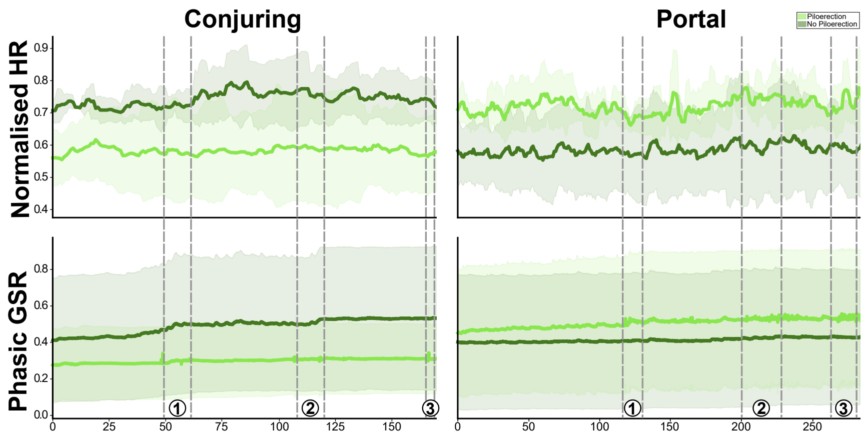

Fig. 20. Hear-rate (normalised) and Galvanic Skin response (Phasic) aggregated by users over time. The 3 scary moments are indicated between vertical dashed lines. The plot lines are the average and the coloured areas the standard deviation from the HR and GSR.

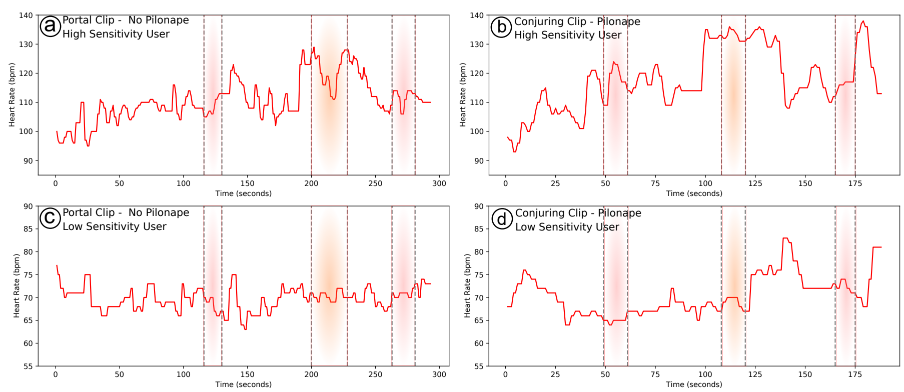

Fig. 21. Hear-rate over time for a sensitive user (a,b) and a non-sensitive user (c,d). (a) and (c) are for the clip Portal with no PiloNape, whereas (c) and (d) are for the clip Conjuring with PiloNape.

forearm was a purely physiological reaction of the user. In the Portal clip, no piloerection happened without applying PiloNape; however, all the 6 people that were watching Portal with artificial piloerection also got piloerection on the forearm. For the Conjuring clip, the effect was not so strong (2 vs 3), we have seen that 2 out of the 3 people that had not piloerection at all were in the group for Conjuring with PiloNape (and Portal no PiloNape).

5.7 Subjective

For each user and clip, the number of times that the users reported feeling shivers and goosebumps is shown in Figure 25. More users reported shivers and goosebumps when PiloNape was applied. It must be noted that this is self-reported data. Chi-square tests showed that users in general guessed correctly if they had piloerection (observed in the arm vs self-reported) (χ^2=4.11 p=0.043). When split by sex, men could distinguish (p=0.018) with some under-reports, but woman could not (p=0.598) equally under-reporting and over-reporting; although the size of the sample split by sex is not considered enough to support those findings.

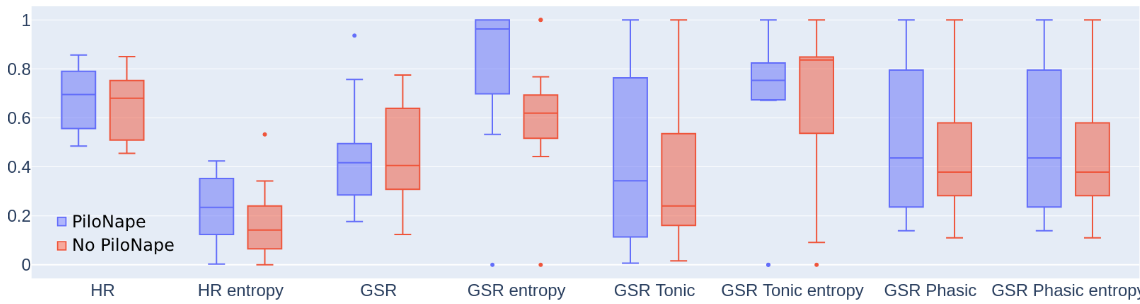

Fig. 22. Boxplot for the biosignals: heart-rate (HR), Galvanic Skin Response (GSR), GSR tonic component, GSR Phasic component. Calculated as mean and entropy for each condition.

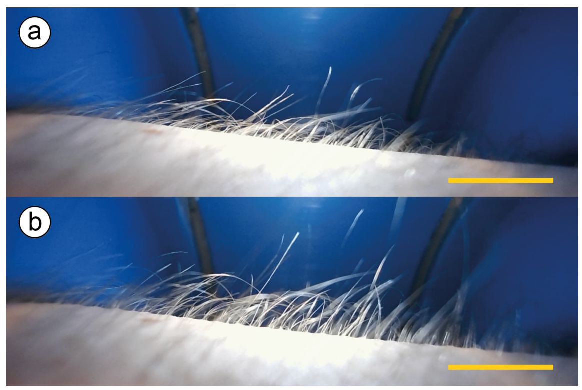

Fig. 23. Natural piloerection happening in the forearm. a) before piloerection. b) after piloerection. Scalebars are 1 cm.

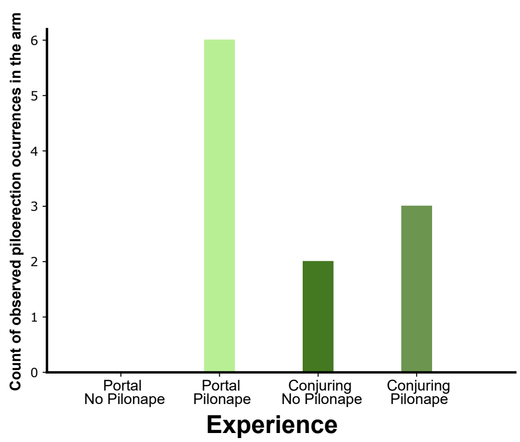

Fig. 24. Number of times that piloerection happened naturally on the forearm split by clip and conditions.

The results of subjective SAM questionnaires (valence, arousal and dominance) and the fear ratings are shown in Figure 26.

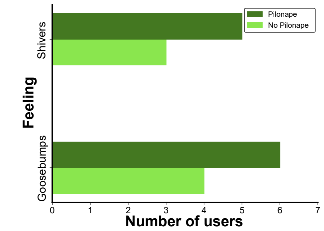

Fig. 25. Number of users split by conditions that reported shivers and goosebumps as they were watching the clips.

Valence goes from positive to negative (smiling to sad mannequin), there is a difference between the conditions (PiloNape, no PiloNape) but of opposed signs depending on the clip; for Portal the emotion become less with piloerection and for Conjuring the other way around. People in general had problems understanding valence. Arousal goes from calm to excited, this scale was easier to understand by the users and results indicate that applying PiloNape made the experience more exciting. Yet, differences do not seem significant; furthermore, this is self-reported data. Dominance seems to have no differences between conditions, most users reported that they did not understood this concept. The rating of fear was just slightly superior for the condition of PiloNape but not significantly.

There was a clear difference on those reported values depending on whether the users self-reported feeling piloerection (no piloerection <> piloerection): for valence (4 < 6.5 p=0.044) meaning that the experiences were more negative for people reporting piloerection; for arousal (4.6 > 2.3 p=0.024), for dominance (6.4 > 3.12 p=0.009) and for fear intensity (3.8 > 6.3 p=0.014).

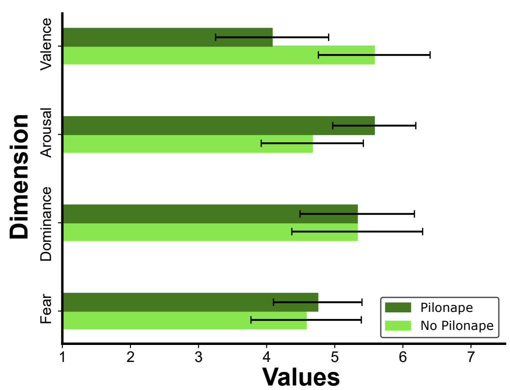

Fig. 26. Averaged results for the SAM questionnaire: Valence (positive to negative), Arousal (low to hight) and Dominance (low to high) and the ratings of fear (low to high). Error bars represent the standard error.

The adjectives selected for describing the experiences from a list of 6 were: Tense (6 times with PiloNape - 5 with no PiloNape), Alarmed (3-3), Fearful (2 - 1), Bored (0 - 2), Upset (0 - 1) and Frustrated (1 - 0). Showing qualitatively that more adjectives of high-arousal were selected for the PiloNape condition.

6 DISCUSSION

Significant effects were found when applying PiloNape on the real piloerection that appeared on the user arm, even when PiloNape was always applied on the nape. Attending to the hear-rate and galvanic skin reseponse, PiloNape had a significant effect on the GSR entropy. Yet, to understand better the effect of PiloNape on heart-rate, it was necessary to classify the scary moments into sudden jumpscares and build-up tension; PiloNape increased the former type whereas the effect on the latter was not clear.

Mechanical stimulation of the hairs could be an alternative to contactless electrostatics. However, when we were testing the sensations by tickling with brushes, it required significant accuracy for not touching the skin of the user or to do it with the correct pressure, especially for the nape. An automatic mechanical system capable of moving only the hairs would require distance sensors or computer vision to adapt to the different distances and body shapes. We also think that the contactless approach is and advantage in terms of hygiene in non head mounted setups, e.g., a box where the users can put their hands in. Also, the electrostatic was silent enough to not be perceived while the user was wearing headphones, even with no sound on them.

Long-terms studies of the reactions to the stimulus are important to check if this technique would be able to affect emotional experiences over the years. That is, that once that the wow effect is gone, is piloerection still an effective stimulus to modulate our emotions. We expect that the effect may not be as strong as the first time, yet as an involuntary response (in most cases) and an instinctive body reaction, we reckon that it will affect our emotions even if the users have experienced it several times. Yet, we think the artificial piloerection should used scarcely on interactive experiences to increase its effect, in a similar way as it happens to strident sound effects in scary movies.

Subjective self-reported data is useful and can help to identify patterns, yet we think it may be too fuzzy for dealing with emotions. That is why we captured physiological parameters as well as (i.e., HR and GSR). If a future study analyzes the effect of piloerection in other emotions (e.g., sadness, awe, anger), we would like to capture behavioral information. For that, more interactive experiences should be presented to the user, making the evaluations less structured and replicable. We imagine the user playing a horror game with zombies, a behavioral measurement would be the number of shots employed beyond what it is strictly necessary (shooting more would imply a high level of fear). Studies with decision-making over prolonged organic activities would be an interesting method to explore.

We focused on fear in the experience study (5). We planned to test sadness and awe but on preliminary tests, we noticed that all the clips, songs, or apps tested for awe were not eliciting those sensations. We found a strong clip for sadness (Up from Pixar) that left several researchers emotionally affected for hours even when they have already watched it. Therefore a larger user study with between-subjects (separated by emotion) or across different weeks is needed for multi-emotional testing. Also, we reckon that connecting piloerection with emotions may be a hard task for a paper since dozens of articles contradict each other in the connection to a specific emotion [47]. Perhaps, paying attention to behavioral changes is a solution.

A study with designers and content creators could analyze the type of piloerection stimuli that they use for accompanying different clips or exhibitions. When we were creating the timestamps for applying piloerection in the 2 clips, we were tempted to apply dynamic intensity patterns. For example, making the intensity follow the music or having an increasing frequency of blinking stimuli to build up tension. However, naturally occurring piloerection does not have those complex patterns but in future work we would like to create piloerection patterns that go beyond the naturally occurring ones and see if they elicit different emotions or adjectives in the users.

Spatially varying patterns can be created with more electrodes. Again, it is not a naturally occurring response, but complex time and spatial patterns could be interesting to test. For example, stroking of the forearm or stimulating different sides of the nape to indicate incoming obstacles on that direction. This would require two-point discrimination studies to determine how much spatial resolution can be perceived by humans (and if it is the same as the contact skin resolution).

We focused on the nape area because it was previously unexplored, it is very accessible when wearing head-mounted displays and had good sensitivity amongst all the participants. It also had stronger associations with emotions and adjectives than other parts. Nonetheless, we think that other parts of the face are interesting and could be piloerected when wearing a head-mounted display such as the eyebrows, eyelashes, or beard.

Electrostatic piloerection may seem niche or too exotic, and although the system can be integrated in a compact way with head-mounted displays, it is hard to imagine all the VR systems shipped with this integration. Yet, we think it could be a compelling addition for more controlled environments that want to deliver an immersive or special experience like in cinemas, dining experiences, or museums.

Having sensors attached to the fingers or the mere presence of the evaluator could have affected the emotions that the users experienced. We separated the evaluator from the user with a folding screen and the VR headset isolated the user from the environment. Yet, the contact sensors could be replaced by physiological contactless measurements of heart rate, oxygen saturation (transmission infrared), pupil dilation, facial expression or body movement and pose.

Reduced sensitivity with age has been reported for contactless tactile technologies such as focused ultrasound [67]. In our study, we did not target specifically a wide range of age groups, yet we saw a negative correlation between age and sensitivity on the wrist as well as the forearm. Interestingly, the nape sensitivity was not correlated with age. A targeted study on the sensitivity of the nape at different ages may report that the area remains more sensitive than other areas to tactile stimuli. This is important since the perception of tactile stimuli from different technologies decreases with age; the elder population may benefit tremendously from more affective virtual and remote experiences.

We set the distance of the electrode at 3.5 cm from the skin because it seemed a reasonable contactless distance and allowed PiloNape to target the area without cross-talking other areas. Yet, we experience the feeling of piloerection even when the electrode was 10 cm away, depending on the charge and size of the electrode, but we can imagine a large electrode on top of a box that can create sensations when you have your hand (and wrist) inside the box performing gestures. In this work, we focused on charging the electrode, but also the user can be charged making their hair and clothes move slightly pressing or rubbing the skin. This is another alternative that requires not electrodes but should be accompanied by a close-loop system that removes the charge from the body to avoid unpleasant shocks when touching real-world objects afterward. The generator and charge monitor can be integrated into a compact device at the top of the strap of the VR headset.

Studying how PiloNape affects highly sensitive people (HSP) may provide more insights in the connection between certain emotions and piloerection. HSP have an extreme reaction to both sensorial and psychological stimuli. They experience a higher autonomic arousal and their physiological responses are higher than for non-HSP. HSP are particularly perceptive to subtle changes in their environment. Similarly, people with voluntary control of piloerection can be of particular interest to study.

The modulation of the user's emotions should be handled under strict ethics considerations if this was deployed into a commercial system. Touch, and piloerection specifically, can provoke a more innate and emotional response than images or sound, or at least we are more used to control the reactions from the last two stimuli. Consequently, specific permissions and more refined information about what the stimulus could provoke should be provided to the user when interacting with a system using piloerection.

7 CONCLUSION

We have designed a device capable of generating an electrostatic field that causes artificial piloerection. It acts on the hairy area of the skin which is connected to affective touch. Different parts of the body were tested in terms of sensitivity to piloerection and a psycophysic study was performed in the 3 most promising areas: nape, wrist and forearm. The effect that artificial piloerection has on the physiological reactions of the user and its perceived emotions was tested while visualising two 360 videos related to fear. Piloerection is a contactless approach for haptics that could be used by designers of movies, videogames or museum experiences to enhance the affective reactions of the users.

REFERENCES

[1] 2022. Neurobit. http://www.neurobit.com.pl/.

[2] Scott Bannister and Tuomas Eerola. 2018. Suppressing the chills: Effects of musical manipulation on the chills response. *Frontiers in Psychology* 9 (2018), 2046.

[3] Olivier Bau, Ivan Poupyrev, Ali Israr, and Chris Harrison. 2010. TeslaTouch: electrovibration for touch surfaces. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*. 283–292.

[4] Mathias Benedek and Christian Kaernbach. 2011. Physiological correlates and emotional specificity of human piloerection. *Biological psychology* 86, 3 (2011), 320–329.

[5] Roger Boldu, Mevan Wijewardena, Haimo Zhang, and Suranga Nanayakkara. 2020. MAGHair: A Wearable System to Create Unique Tactile Feedback by Stimulating Only the Body Hair. In *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services*. 1–10.

[6] Lang PJ. Bradley MM. 1994. Measuring emotion: the Self-Assessment Manikin and the Semantic Differential. *J Behav Ther Exp Psychiatry* 25, 1 (1994), :49–5.

[7] Scott Brave and Clifford Nass. 2002. Emotion in Human–Computer Interaction. *The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies and Emerging Applications* (01 2002). https://doi.org/10.1201/b10368-6

[8] Svend Brinkmann. 2006. Damasio on mind and emotions: A conceptual critique. *Nordic Psychology* 58, 4 (2006), 366–380. https://doi.org/10.1027/1901-2276.54.4.366

[9] Walter B. Cannon. 1927. The James-Lange Theory of Emotions: A Critical Examination and an Alternative Theory. *The American Journal of Psychology* 39, 1/ (1927), 106–124. https://doi.org/10

[10] George Chaplin, Nina G Jablonski, Robert W Sussman, and Elizabeth A Kelley. 2014. The role of piloerection in primate thermoregulation. *Folia primatologica* 85, 1 (2014), 1–17.

[11] George Chaplin, Nina G Jablonski, Robert W Sussman, and Elizabeth A Kelley. 2014. The role of piloerection in primate thermoregulation. *Folia primatologica* 85, 1 (2014), 1–17.

[12] HongYi Chen, Kai Ling Chin, and Chrystalle BY Tan. 2021. Selection and validation of emotional videos: Dataset of professional and amateur videos that elicit basic emotions. *Data in Brief* 34 (2021), 106662.

[13] Luca Chittaro. 2014. Anxiety Induction in Virtual Environments: An Experimental Comparison of Three General Techniques. *Interact. Comput.* 26 (2014), 528–539.

[14] Daniel G Craig. 2005. An exploratory study of physiological changes during "chills" induced by music. *Musicae scientiae* 9, 2 (2005), 273–287.

[15] Charles Darwin and Phillip Prodger. 1998. *The expression of the emotions in man and animals*. Oxford University Press, USA.

[16] Paul Ekman. 1993. Facial expression and emotion. *The American psychologist* 48 4 (1993), 384–92.

[17] Don Samitha Elvitigala, Roger Boldu, Suranga Nanayakkara, and Denys JC Matthies. 2022. TickleFoot: Design, Development and Evaluation of a Novel Foot-Tickling Mechanism That Can Evoke Laughter. *ACM Transactions on Computer-Human Interaction* 29, 3 (2022), 1–23.

[18] Edgar Everhart and Paul Lorrain. 1953. The Cockcroft-Walton voltage multiplying circuit. *Review of Scientific Instruments* 24, 3 (1953), 221–226.

[19] Cathy Mengying Fang, Jianzhe Gu, Lining Yao, and Chris Harrison. 2022. ElectriPop: Low-Cost, Shape-Changing Displays Using Electrostatically Inflated Mylar Sheets. In *CHI Conference on Human Factors in Computing Systems*. 1–15.

[20] Shogo Fukushima and Hiroyuki Kajimoto. 2012. Chilly chair: facilitating an emotional feeling with artificial piloerection. In *ACM SIGGRAPH 2012 Emerging Technologies*. 1–1.

[21] Shogo Fukushima and Hiroyuki Kajimoto. 2012. Facilitating a surprised feeling by artificial control of piloerection on the forearm. In *Proceedings of the 3rd Augmented Human International Conference*. 1–4.

[22] F Anthony Furfari. 2005. A history of the Van de Graaff generator. *IEEE Industry Applications Magazine* 11, 1 (2005), 10–14.

[23] Patrick Glatte, Sylvia J Buchmann, Mido Max Hijazi, Ben Min-Woo Illigens, and Timo Siepmann. 2019. Architecture of the cutaneous autonomic nervous system. *Frontiers in neurology* 10 (2019), 970.

[24] Oliver Grewe, Björn Katzur, Reinhard Kopiez, and Eckart Altenmüller. 2011. Chills in different sensory domains: Frisson elicited by acoustical, visual, tactile and gustatory stimuli. *Psychology of Music* 39, 2 (2011), 220–239.

[25] Eddie Harmon-Jones, Cindy Harmon-Jones, and Elizabeth Summerell. 2017. On the Importance of Both Dimensional and Discrete Models of Emotion. *Behavioral Sciences* 7 (2017).

[26] James AJ Heathers, Kirill Fayn, Paul J Silvia, Niko Tiliopoulos, and Matthew S Goodwin. 2018. The voluntary control of piloerection. *PeerJ* 6 (2018), e5292.

[27] Johannes Hewig, Dirk Hagemann, Jan Seifert, Mario Gollwitzer, Ewald Naumann, and Dieter Bartussek. 2005. A revised film set for the induction of basic emotions. *Cognition and emotion* 19, 7 (2005), 1095.

[28] David Huron. 2008. *Sweet anticipation: Music and the psychology of expectation.* MIT press.

[29] Shikha Jain and Krishna Asawa. 2019. Modeling of Emotion Elicitation Conditions for a Cognitive-Emotive Architecture. *Cogn. Syst. Res.* 55, C (jun 2019), 60–76. https://doi.org/10.1016/j.cogsys.2018.12.012

[30] William James. 1884. What is an emotion? *Mind* os-IX, 34 (04 1884), 188–205. https://doi.org/10.1093/mind/os-IX.34.188 arXiv:https://academic.oup.com/mind/article-pdf/os-IX/34/188/9278514/os-IX_34_188.pdf

[31] William James. 1894. Discussion: The physical basis of emotion. *Psychological review* 1, 5 (1894), 516.

[32] Elina E Ketonen, Visajaani Salonen, Kirsti Lonka, and Katariina Salmela-Aro. 2022. Can you feel the excitement? Physiological correlates of students' self-reported emotions. *British Journal of Educational Psychology* (2022), e12534.

[33] Michinari Kono, Takashi Miyaki, and Jun Rekimoto. 2018. In-pulse: inducing fear and pain in virtual experiences. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*. 1–5.

[34] Robert J Kosinski. 2008. A literature review on reaction time. *Clemson University* 10, 1 (2008), 337–344.

[35] Paul Lemmens, Floris Crompvoets, Dirk Brokken, Jack Van Den Eerenbeemd, and Gert-Jan de Vries. 2009. A body-conforming tactile jacket to enrich movie viewing. In *World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, 7–12.

[36] Benjamin Li, Jeremy Bailenson, Adam Pines, Walter Greenleaf, and Leanne Williams. 2017. A Public Database of Immersive VR Videos with Corresponding Ratings of Arousal, Valence, and Correlations between Head Movements and Self Report Measures. *Frontiers in Psychology* 8 (12 2017). https://doi.org/10.3389/fpsyg.2017.02116

[37] Ming Li, Junjun Pan, Yang Gao, Yang Shen, Fang Luo, Ju Dai, Aimin Hao, and Hong Qin. 2022. Neurophysiological and Subjective Analysis of VR Emotion Induction Paradigm. *IEEE Transactions on Visualization and Computer Graphics* (2022), 1–11. https://doi.org/10.1109/TVCG.2022.3203099

[38] Yu Liang, Kazuma Shimokawa, Shigeo Yoshida, and Eriko Sugimori. 2020. What "Tears" Remind Us of: An Investigation of Embodied Cognition and Schizotypal Personality Trait Using Pencil and Teardrop Glasses. *Frontiers in Psychology* 10 (2020), 2826.

[39] Dan Liao, Lin Shu, Guodong Liang, Yingxuan Li, Yue Zhang, Wenzhuo Zhang, and Xiangming Xu. 2020. Design and Evaluation of Affective Virtual Reality System Based on Multimodal Physiological Signals and Self-Assessment Manikin. *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology* 4, 3 (2020), 216–224. https://doi.org/10.1109/JERM.2019.2948767

[40] Antonio Maffei and Alessandro Angrilli. 2019. E-MOVIE-Experimental MOVies for Induction of Emotions in neuroscience: An innovative film database with normative data and sex differences. *Plos one* 14, 10 (2019), e0223124.

[41] Martin Magdin, Zoltán Balogh, Jaroslav Reichel, Jan Francisti, Štefan Koprda, and Molnár György. 2021. Automatic Detection and Classification of Emotional States in Virtual Reality and Standard Environments (LCD): Comparing Valence and Arousal of Induced Emotions. *Virtual Real.* 25, 4 (dec 2021), 1029–1041. https://doi.org/10.1007/s10055-021-00506-5

[42] Elwin Marg. 1995. DESCARTES'ERROR: emotion, reason, and the human brain. *Optometry and Vision Science* 72, 11 (1995), 847–848.

[43] Naveen Masood and Humera Farooq. 2019. Investigating EEG patterns for dual-stimuli induced human fear emotional state. *Sensors* 19, 3 (2019), 522.

[44] Francis McGlone, Ake B Vallbo, Hakan Olausson, Line Loken, and Johan Wessberg. 2007. Discriminative touch and emotional touch. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale* 61, 3 (2007), 173.

[45] Jonathon McPhetres. 2019. Oh, the things you don't know: awe promotes awareness of knowledge gaps and science interest. *Cognition and Emotion* 33, 8 (2019), 1599–1615.

[46] Jonathon McPhetres and Andrew Shtulman. 2021. Piloerection is not a reliable physiological correlate of awe. *International Journal of Psychophysiology* 159 (2021), 88–93.

[47] Jonathon McPhetres and Janis H Zickfeld. 2022. The physiological study of emotional piloerection: A systematic review and guide for future research. *International Journal of Psychophysiology* 179 (2022), 6–20.

[48] Albert Mehrabian and James A. Russell. 1974. An approach to environmental psychology.

[49] Enrico Mosca. 2017. *Assessment of the neck as a haptic surface for displaying vibrations for emotional responses.* Master's thesis.

[50] Adiyan Mujibiya. 2015. Corona: Interactivity of body electrostatics in mobile scenarios using wearable high-voltage static charger. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*. 435–444.

[51] Håkan Olausson, Y Lamarre, H Backlund, C Morin, BG Wallin, G Starck, S Ekholm, I Strigo, K Worsley, ÅB Vallbo, et al. 2002. Unmyelinated tactile afferents signal touch and project to insular cortex. *Nature neuroscience* 5, 9 (2002), 900–904.

[52] Andrew Ortony, Gerald Clore, and Allan Collins. 1988. *The Cognitive Structure of Emotion*. Vol. 18. https://doi.org/10.2307/2074241

[53] Claire Pelo, Michal Goldstein, Dana Bevilacqua, Michael McPhee, Ellie Abrams, and Pablo Ripollés. 2021. CHILLER: a Computer Human Interface for the Live Labeling of Emotional Responses. (2021).

[54] Rosalind W. Picard. 1997. Affective Computing.

[55] Warnet Bros. Pictures. 2016. *The Conjuring 2 - Experience Enfield VR 360 [HD]*. https://www.youtube.com/watch?v=A6aRkhlqWuE&ab_channel=WarnerBros.Pictures

[56] Robert Plutchik. 1997. The measurement of emotions. *Acta Neuropsychiatrica* 9 (1997), 58 – 60.

[57] Denise T. Quesnel and Bernhard E. Riecke. 2018. Are You Awed Yet? How Virtual Reality Gives Us Awe and Goose Bumps. *Frontiers in Psychology* 9 (2018).

[58] Radiah Rivu, Ruoyu Jiang, Ville Mäkelä, Mariam Hassib, and Florian Alt. 2021. Emotion Elicitation Techniques in Virtual Reality. In *Human-Computer Interaction – INTERACT 2021: 18th IFIP TC 13 International Conference, Bari, Italy, August 30 – September 3, 2021, Proceedings, Part I* (Bari, Italy). Springer-Verlag, Berlin, Heidelberg, 93–114. https://doi.org/10.1007/978-3-030-85623-6_8

[59] Ira J Roseman, Martin S Spindel, and Paul E Jose. 1990. Appraisals of emotion-eliciting events: Testing a theory of discrete emotions. *Journal of personality and social psychology* 59, 5 (1990), 899.

[60] James A. Russell. 1980. A circumplex model of affect. *Journal of Personality and Social Psychology* 39 (1980), 1161–1178.

[61] Deepak Ranjan Sahoo, Diego Martinez Plasencia, and Sriram Subramanian. 2015. Control of non-solid diffusers by electrostatic charging. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 11–14.

[62] Stanley Schachter and Jerome Singer. 1962. Cognitive, social, and physiological determinants of emotional state. *Psychological review* 69, 5 (1962), 379.

[63] Klaus R Scherer. 1984. Emotion as a multicomponent process: a model and some cross-cultural data. *Review of personality & social psychology* (1984).

[64] Björn W. Schuller, Rosalind Picard, Elisabeth André, Jonathan Gratch, and Jianhua Tao. 2021. Intelligent Signal Processing for Affective Computing [From the Guest Editors]. *IEEE Signal Processing Magazine* 38, 6 (2021), 9–11. https://doi.org/10.1109/MSP.2021.3096415

[65] Yoones A Sekhavat, Milad Jafari Sisi, and Samad Roohi. 2021. Affective interaction: Using emotions as a user interface in games. *Multimedia Tools and Applications* 80, 4 (2021), 5225–5253.

[66] Ewa Siedlecka and Thomas F Denson. 2019. Experimental methods for inducing basic emotions: A qualitative review. *Emotion Review* 11, 1 (2019), 87–97.

[67] Yatharth Singhal, Haokun Wang, Hyunjae Gil, and Jin Ryong Kim. 2021. Mid-Air Thermo-Tactile Feedback using Ultrasound Haptic Display. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. 1–11.

[68] Daniel Spelmezan, Deepak Ranjan Sahoo, and Sriram Subramanian. 2016. Sparkle: Towards haptic hover-feedback with electric arcs. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 55–57.

[69] Futura VR Studio and The Dream VR. 2018. *Portal*. https://www.with.in/watch/portal

[70] Feng Tian, Xiaofei Hou, and Minlei Hua. 2020. Emotional Response Increments Induced by Equivalent Enhancement of Different Valence Films. 213–218. https://doi.org/10.1109/ICECTT50890.2020.00055

[71] Ryoko Ueoka and Kouya Ishigaki. 2015. Development of the horror emotion amplification system by means of biofeedback method. In *International Conference on Human Interface and the Management of Information*. Springer, 657–665.

[72] Stuart Valins. 1966. Cognitive effects of false heart-rate feedback. *Journal of personality and social psychology* 4, 4 (1966), 400.

[73] Jan-Niklas Voigt-Antons, Robert Spang, Tanja Kojić, Luis Meier, Maurizio Vergari, and Sebastian Möller. 2021. Don't Worry be Happy - Using virtual environments to induce emotional states measured by subjective scales and heart rate parameters. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. 679–686. https://doi.org/10.1109/VR50410.2021.00094

[74] Tianhua Xie, Mingliang Cao, and Zhigeng Pan. 2020. Applying Self-Assessment Manikin (SAM) to Evaluate the Affective Arousal Effects of VR Games. In *Proceedings of the 2020 3rd International Conference on Image and Graphics Processing* (Singapore, Singapore) *(ICIGP 2020)*. Association for Computing Machinery, New York, NY, USA, 134–138. https://doi.org/10.1145/3383812.3383844

[75] Shigeo Yoshida, Takuji Narumi, Tomohiro Tanikawa, Hideaki Kuzuoka, and Michitaka Hirose. 2021. Teardrop Glasses: Pseudo Tears Induce Sadness in You and Those Around You. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–12.

[76] Xiangjun Zhang, Hankui Liu, and Dianguo Xu. 2003. Analysis and design of the flyback transformer. In *IECON'03. 29th Annual Conference of the IEEE Industrial Electronics Society (IEEE Cat. No. 03CH37468)*, Vol. 1. IEEE, 715–719.

[77] Yuankun Zhu and Arindam Dey. 2022. Comparing Physiological and Emotional Effects of Happy and Sad Virtual Environments Experienced in Video and Virtual Reality. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* (2022), 848–849.