Towards Affective Chronometry: Exploring Smart Materials and Actuators for Real-time Representations of Changes in Arousal

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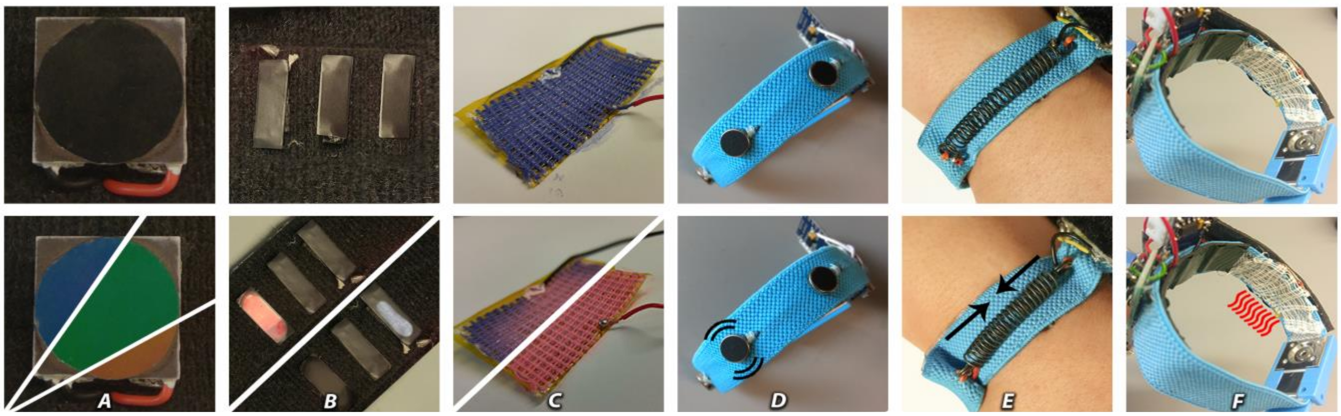

Figure 1: Smart materials and actuators-based prototypes A) flashing display B) three-colored display C) single-colored display D) vibrating band E) squeezing band F) heating band. Top row shows prototypes' default states and bottom row shows actuated states.

ABSTRACT
Increasing HCI work on affective interfaces aimed to capture and communicate users' emotions in order to support self-understanding. While most such interfaces employ traditional screen-based displays, more novel approaches have started to investigate smart materials and actuators-based prototypes. In this paper, we describe our exploration of smart materials and actuators leveraging their temporal qualities as well as common metaphors for real-time representation of changes in arousal through visual and haptic modalities. This exploration provided rationale for the design and implementation of six novel wrist-worn prototypes evaluated with 12 users who wore them over 2 days. Our findings describe how people use them in daily life, and how their material-driven qualities such as responsiveness, duration, rhythm, inertia, aliveness and range shape people's emotion identification, attribution, and regulation. Our findings led to four design implications including support for affective chronometry for both raise and decay time of emotional response, design for slowness, and for expressiveness.

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INTRODUCTION
Emotions play an important role in our everyday lives. They have a strong influence on how we perceive, interpret and interact with the environment around us [53]. Despite the adaptive value of emotions for signaling events of significance, emotional awareness and regulation, i.e., knowing our emotions, and how we can control them, are complex skills that many people find difficult to acquire. HCI work has focused on technologies for affective feedback in both clinical [46,62,74,85] and non-clinical settings [26,30,41,48,92]. Such work aims to support increased self-awareness by providing interactive feedback mirroring physiological signals. Previous work on affective designs has focused on time-series graphs [33,103,108] and abstract visualizations [22,26,41,78,99,102] of biosignals on traditional mobile and desktop interfaces.

Moving away from traditional displays, an emerging body of work has explored alternative ways to support feedback on affective data through different materials such as paper [100], ambient light [77], clothing [34,35], shape-changing surfaces [101] and haptic actuators [8,47]. We agree with Dourish and Mazmanian [19] on the importance of materiality of digital data in shaping people's interpretations. Unlike the predominant focus on screen-based light emitting affective displays, we explored alternative materials in raw form such as thermochromic ones, heating elements, shape memory alloys, and vibrotactile actuators. Although both arousal and valence are important dimensions of affect [64], most wearable biosensors capture arousal [22,35,47,56,67,88] because of sensor's increased wearability and less invasive nature. This paper aims to explore the feasibility of smart materials and actuators to represent real-time arousal in everyday contexts through metaphors such as *arousal is red, arousal is (haptic) intensity, arousal is heat*, and how they shape people's subjective interpretations of their emotions. For this, we focus on the following research questions:

- What are the specific material-driven qualities of smart materials and actuators to represent real-time changes in arousal leveraging existing metaphors of arousal?
- How these qualities shape people's understanding of their emotions in daily lives?

To address these research questions, we employed a research through design exploration of smart materials and actuators, which underpinned the design rationale for our prototypes (Figure l). We report the design and evaluation of six prototypes harnessing the value of metaphorical representations of arousal captured through biosensors. We were interested in exploring how these prototypes may support people to develop a richer understanding of their emotional responses unfolding in time, through rise, peak and decay time – parameters captured under the concept of *affective chronometry* [12].

Affective chronometry refers to the temporal dynamics involved in emotional responses and much research has shown its relationship with wellbeing and affective health [11]. Our research shifts the focus away from lab-based measurements of emotional responses, to how people using our prototypes in their daily lives may become more aware of their emotions and of their temporal unfolding. This paper's contributions include a rich vocabulary to talk about smart materials and actuators as well as their properties as resource for design in HCI, and design guidelines for representing arousal through such materials.

RELATED WORK

Our work inspires from related research on affective interfaces and material exploration in HCI.

Affective Interfaces

Over the last decade, there has been a growing HCI interest in designing technologies that provide affective feedback. These include biofeedback systems for well-being [22,47], self-awareness, reflection [50,78], and emotion regulation [8,51], as well as mindfulness practices [10,85]. For instance, AffectAura [50] is a timeline-based interactive interface that represents affect through bubbles, allowing users to reflect on everyday emotional experiences. Valence is captured through speech and facial expressions, and represented by bubble's color, i.e. pink for positive emotions and blue for negative ones, while arousal is conveyed through the bubble's shape, with the "burst" representing the activated state. Although AffectAura allows people to reflect on their past affective states, it is a desktop-based interface with limited wearability. Other systems provide affective feedback away from the desktop, through mobile interfaces. For example, Affective Diary [78] translates bodily experiences into colorful and abstract body shapes indicating levels of arousal supporting participants to reflect on their past experiences. Affective Health system identified several experiential qualities of designs [22,67] such as update in real-time, ambiguous and open for interpretation.

Most previous work has explored traditional screen-based interfaces like smartphones, whose materiality has seldom been brought into question. However, leveraging the aesthetic and experiential qualities of materials [37], an emerging research direction has started to explore alternative technologies as a medium to convey arousal data. For example, through ambient lighting that changes from blue to purple to red communicating real-time changes in arousal [77], or clothing-based displays [14] representing arousal in social settings [34]. Ripple, a color-changing shirt with thermochromic patterns invites interpretation of changes in arousal. While it encourages reflection on emotional experiences, its increased ambiguity promoted questions over the display's authority [35]. Although most of such interfaces provide visual feedback, there is also a growing interest in multimodal feedback for representing and regulating affect particularly through haptics [51]. For instance, Yavuz and colleagues explored communicating biosignals over long distance with Skin Deep, a collar and bracelet set which transmits heartbeat through vibration patterns and blinking light [87].

Synestouch combines vibrotactile stimuli on the wrist with auditory feedback and found the latter to be more expressive in conveying emotions [56]. In addition, vibrotactile feedback simulating heartbeats has also been employed to regulate anxiety [8,83]. Other work explored thermal stimuli to represent [97] and augment emotions [1,84], while thermal feedback has also been combined with vibrotactile and visual feedback to increase the range of emotional states to be communicated [96]. Furthermore, affective interfaces have been also discussed in relation to expressive interfaces [79], which tend to focus on emotions through multimodalities [96].

To conclude, most work on affective representations has identified both traditional time-series graph-based representations [33,103,108], as well as abstract visualizations on screen-based devices [22,26,41,78,99,102] and actuators [8,38,47,97,101]. They provide a limited understanding on how arousal-based representations through different materials and actuators might play a role in emotional awareness and understanding.

Material Exploration in HCI

From Schön's framing of design as a conversation with materials [73], to the emergence of physical computing and "material move" within HCI [19], the exploration of the digital as material for interaction has received increased attention [81,91], with the aim to uncover how its qualities become critical within the design process. A number of frameworks have addressed the notion of 'materiality'. For example, Wiberg [95] advanced a methodology for material-centered design research which emphasizes exploration by working back and forth between materials and texture, details and wholeness. Jung and Solterman [37], called for material research that focuses on both aesthetic and experiential qualities of using and making sense of materials. Giaccardi and Karana [27] proposed a material experience framework consisting of four experiential levels: *sensorial*, *interpretive*, *affective* and *performative* integrating materials and people. In a similar approach, Doring [18] introduced a material profile integrating both qualitative and quantitative aspects of material interaction, which allow for the construction of material's meanings and emotions evoked through interaction.

While most of these approaches advance theoretical frameworks, there has been a less empirical exploration of specific material qualities. Noticeable exceptions include the systematic exploration of shape-changing materials and their properties [59], the identified design challenges around hardware's affordances, software's properties, and sensors' material properties [81] or how such properties can be leveraged for the design of embodied experiences [82]. We follow a similar approach focusing on less explored digital materials in HCI, namely smart materials and actuators.

DESIGN EXPLORATION OF SMART MATERIALS AND ACTUATORS FOR REPRESENTING AROUSAL

We employed a research through design material exploration [82] consisting of a playful and tinkering approach [57] to discover novel material properties. Due to its suitability to support imaginative exploration of novel designs, and potential emphasis on the body [42], research through design has been employed in both e-textiles [14] and wearable artifacts [71,89].

The aim of our approach is to create low-cost, simple prototypes to support engagement with, and understanding of real-time changes in arousal. For this, we explored both the biosensors for capturing arousal, as well as smart materials and actuators for representing arousal. In particular, we worked with different thermochromic materials to fabricate three prototypes i.e. *flashing, three-colored and single-colored displays*, and three haptic actuators to fabricate *vibrating, squeezing and heating bands*. We used galvanic skin response sensor to calculate real-time changes in arousal and represented it through the prototypes. The prototypes are wearable on the wrist and are always on sight: can be seen or felt in real-time.

Capturing Arousal

Galvanic skin response (GSR), has been consistently linked to emotional arousal [3,45,67]. GSR measures the electrical conductivity of the skin resulting from sympathetic nervous system activity. It maps physiologically arousing events to rapid increase and gradual decay of GSR signal. GSR sensors consist of two electrodes worn on the fingers, palm, or wrist [86]. We explored two commercial GSR sensors: BITalino [104], and Grove [105] and chose the latter as it was easier to wear on the wrist [108]. For signal processing, we used a moving average algorithm [106] to filter out the noise and calculated GSR peaks from 5 seconds worth of data, with a sampling frequency of 20 samples/second. As a result, each prototype takes 5 seconds to actuate. With the caveat of this small delay, we argue that prototypes can be seen as representing real-time (rather than historic) data, and that the delay may pose interesting interpretation challenges.

Representing Arousal

We explored thermochromic materials and haptic actuators for visual and haptic representations, respectively. Through material exploration, we identified key properties, often unrecognized within traditional screen-based interfaces. In practice, both the development of the prototypes and the exploration of materials and actuators unfold together however, it was the qualities of the materials and actuators that inspired the construction of the prototypes. Therefore, in this section we first describe these temporal qualities of actuation and de-actuation which have shaped the representation of arousal (Table 1), whereas the following section details the development of six prototypes.

	Flashing Display	Three-colored Display	Single-colored Display	Vibrating Band	Squeezing Band	Heating Band
Responsiveness	Instant	Slow	Moderate	Instant	Instant	Moderate
Duration (s)	3	15	4	Varies with skin conduct.	2.2	5
Rhythm/ Inertia (s)	15	120	300	0	300	300
Aliveness	Variable	Variable	Variable	Variable	Const.	Const.
Range	Single	Three	Single	Single	Single	Single

Table 1. Summary of temporal qualities of smart materials and actuators-based prototypes for communicating arousal.

Responsiveness refers to the speed of prototype's actuation to signal increase in arousal, i.e., instant or slow while *duration* is the interval of time during which the actuation is maintained, i.e., flash or continuous. *Rhythm* indicates the frequency of actuation within each unit of time, i.e., frequent or rare, which depends on prototype's *inertia*: the time a prototype will take to de-actuate and recover to its default state. By *Aliveness*, we mean the actuation's property to change in its temporal unfolding every time it actuates, i.e., the sense of aliveness in the actuation (thermochromic materials can change colors from blue to red based on skin conductance or ambient temperature, while vibration varies with skin conductance). Finally, *range* corresponds to levels of inputs a prototype supports at any given time, i.e., single or multiple levels of arousal captured within 5-second window. We now describe in detail the explored thermochromic materials and haptic actuators-based prototypes and their temporal qualities to communicate real-time arousal.

Thermochromic Materials

Thermochromic materials are non-emissive materials such as paints, pigments, and sheets, which change color when heated up. Specific colors are actuated by specific temperature ranges. The responsiveness and inertia of the heating layer directly shape the change of colors in thermochromic materials. The aesthetic qualities of thermochromic materials are supported at both heating and color level [37]. The heating layer underneath the thermochromic material consists of high resistance materials such as gold leaf [38], conductive threads [14,39], or wires [75,88]. Thermochromic materials require an additional insulation layer to protect the skin from the heat. We used thermochromic materials actuated within the range of 25°C - 40°C, making it safe to use near body. We also selected them because of their aliveness, i.e., gradual appearance of color, increased expressiveness as some of them can allow for multiple representations of arousal (range), and tendency to be slow. The readings for responsiveness and inertia of thermochromic materials (Table 1) were taken at 21°C in lab settings.

Colors are often associated with emotions [90] and our choice of colors is based on existing work on colors and arousal: bright red containing more energy represents high arousal; dark blue containing less energy represents low arousal [31,80,94]. Therefore, we used red to represent high arousal, blue to represent low arousal state, and yellow (positioned mid-way between red and blue) to represent medium arousal. We now describe briefly each of the visual prototypes.

Flashing Display

Flashing display uses a thermochromic liquid crystal (TLC) sheet to represent changes from low to high arousal. TLC sheets are available in a variety of actuation temperatures ranging from -30°C to above 100°C and have been used for different applications [65]. We used a 30-35°C TLC sheet with adhesive backing, which changes three colors i.e. red, green and blue when the temperature falls within its actuation range. Our aim was to support three different colors for different arousal levels but found TLC sheet to be sensitive to small temperature changes, which poses difficulties for controlling the colors. Increase in captured arousal actuates a Peltier module for 3 seconds, which instantly changes the sheet's color from black to blue, creating a high-resolution flashing effect. As the generated heat dissipates, the color dissipates from blue to green, and then to red and finally to black again, within 15 seconds, creating a slow, gradual representation of fading arousal.

Three-Colored Display

Three-colored display uses conductive fabric as a resistive heating element, with red, yellow and blue color palettes to represent high, medium, and low arousal states, respectively. This prototype is the only one that can display multiple representations of arousal (range). The top layer consists of a 31°C rub and reveal thermochromic film, which unveils the middle-layered color palettes when the fabric heats up. The colors take 15 seconds to fully display and 2 minutes to decay.

Single-Colored Display

Single-colored display uses thermochromic paint, with bluish-purple and reddish-pink representing low and high arousal, respectively. For the heating layer, we used polyester filament and micro metal conductive fiber heating pad [107]. The color change from bluish-purple to reddish-pink is actuated at 28°C, which takes about 4 seconds at 1.1A current. The reverse color change to full bluish-purple happens after 5 minutes.

Haptic Actuators

We also wanted to compare these visual, color-based representations of arousal, with tactile ones which are hidden and immediate, and leverage other metaphors of arousal as being tapped, held or warm [69]. Such metaphors draw from embodied emotion theories according to which bodily feelings including those mediated by touch, posture or movement, are not only key elements of emotional experience but also influence affective perception of people, objects or events [23]. In HCI, haptic interfaces have been used mostly for affective communication [6,32,76] and less for emotional awareness and understanding. Below, we describe the fabrication of vibration, squeezing and heating bands that indicate sensations of tap, held, and warmth respectively.

Vibrating Band

Vibrating Band is a haptic simulator, which provides instant vibrotactile feedback upon changes in arousal, in the form of subtle vibrations experienced as tap on the wrist. Prior research have explored wrist-worn vibration patterns [5] and their lack of expressivity hindered affect differentiation [56]. Vibrotactile perception is supported by vibrations' frequency, amplitude, and acceleration. Existing research shows that people perceived frequency and amplitude of vibrations, rather than acceleration [58]. Hence, we leveraged the former two properties to design for vibrations which vary in intensity (aliveness). The band hosts three mini vibrating motor disks controlled by pulse width modulation (pwn) pins. To provide subtle feedback on arousal, we used only one vibration disk and kept the intensity of vibrations constant; however, the rhythm of vibrations reflected the changes in arousal. This prototype is arguably the most embodied one in terms of duration and rhythm, as these qualities respond in real-time to the skin conductance, rather than being predetermined like for other prototypes. In other words, the maintenance of arousal peak, and the frequency of feedback is solely determined by the level of arousal.

Squeezing Band

Squeezing band is a shape memory alloy which provides squeezing sensation upon arousal. These smart materials recover their initial shape after deformation, and are also actuated by heat [28,47,52]. We used Nitinol tension spring of 2cm length and 6.5mm diameter which when deformed, returns to its original length at about 45°C to 50°C. We trained the spring to change its shape to mark both increase in arousal, and to recover its initial shape to mark decrease in arousal. We hooked the spring onto a stretch band and added an insulation tape for heat protection during actuation state. Increase in arousal is communicated by actuating the spring for 2.2 seconds at 1.2A current, which is experienced as a gentle hold of the wrist. When the current is removed, the spring's high inertia lets it slowly return to its low temperature state. To avoid accumulation of heat overtime, we only actuate the spring after 5 minutes.

Heating Band

Heating Band uses heat to represent changes in arousal. Similar to single-colored display, we used polyester filament and micro metal conductive fiber heating pad. This module sits under the stretch band and produces heating sensation on the wrist experienced as warmth. Existing research shows that 2°C changes in temperature are sufficient for creating distinguishable thermal stimuli [66,98]. Increasing arousal builds up the heat slowly to total 3°C increase with respect to the hand temperature, within 5 seconds. In order to protect from heat accumulation, we provided a 5 min cool off period between two consecutive actuations.

EVALUATING PROTOTYPES IN THE WILD

Prototypes were controlled by 5V Arduino Nano connected to GSR sensor. Additionally, Arduino was also used to drive the vibration disks and fabric strips in the three-colored display. The rest of the prototypes were powered by 3.7V, 750mAh Lithium Polymer battery along with a switch module while Arduino Nano and GSR sensor were powered by four 3V CR2032 Lithium coin cells. All the visual prototypes along with electronics were hosted on a Velcro band, while for haptics, we used stretch bands allowing the prototypes to be easily worn and taken off the wrist at any time.

User Study

To explore how prototypes may shape people's understanding of their emotions in everyday life, we recruited 12 students (7 males and 5 females, age ranged 20-35) with no prior experience of emotion-tracking devices. Prototypes were randomly assigned to participants, ensuring that each prototype was used exactly by two participants. The study consisted of two parts. In the first part, participants were invited to the lab where they were familiarized with the prototype they were going to use, i.e., its inner working, how to wear and take off, turn on/off, and change batteries. Given people's limited knowledge of body physiology [55], in a 20 minutes session we introduced participants to the concepts of electrodermal activity (EDA) and skin conductance response [2], and what are the other factors that may influence skin conductance, i.e. emotional arousal, physical activity, or attention in cognitively demanding tasks [13]. The session only contained generic information about these concepts and no information about the particular GSR sensor. Participants were also encouraged to ask questions. In the end, a leaflet capturing the session's information was also handed out to participants so that they could read it during the study if needed.

The second part of the study involved participants using the prototypes for 2 days of their daily life. Our focus on increased wearability and real-time changes in arousal meant trading off our prototypes' ability to log the captured arousal and its representations. In order to ensure that participants remember the prototypes' actuation for the post-study interview, we asked them to complete a brief online diary entry as close in time as possible after an actuation occurred: what they were doing, how they were feeling, and how they interpreted the prototypes' visual or haptic response.

At the end of the second day of the study, we completed a semi-structured interview, which included reviewing diaries to recall specific moments of prototype's actuation and its interpretation. We also asked about situations where they experienced an actuation but could not make sense, and questions related to privacy of bodily data. Interviews took in average 50 minutes, were audio recorded and transcribed. We used a hybrid approach [21] for data analysis and thematically coded participants' interpretations and experiences. Participants were rewarded £15.

FINDINGS

This section discusses findings regarding the understanding of prototypes' actuations; emotion reflexivity, identification attribution, regulation; as well as affective chronometry.

Understanding Prototypes' Actuations

Overall, participants used each prototype for 8-16 hours of their daily lives. In total, participants reported over 60 events of prototypes' actuation ranging between 4 to 8 actuation events per prototype. These events included diverse activities such as having conversations, playing games, working, shopping, cooking, walking, eating, saying goodbye to a friend, watching movies, getting scared, laughing, having phone or video calls, playing with pets, or relaxing at home.

Findings indicate participants' active engagement with the prototypes, and in making sense of their actuations, both expected and unexpected. In either case, the actuations prompted them to try understand the cause of actuation, often through a reflection-in-action process [73]: "*every time [the prototype] responded, it made me question, I always assumed there was some reason, I tried to work out what that was*" [P12], or *"whenever the device triggered the heat, I started analyzing my thoughts and what I was thinking at that specific moment"* [P10].

Outcomes also indicate that most actuations were perceived as signaling co-occurring emotional experiences, and as a result, most participants started paying attention to their in-the-moment emotional response: *"I came home from work, I was very tired […] I played some music, opened a beer and after some time, I felt the heat [from Heating Band]. It was unexpected [and] I started quickly thinking: really, my mood changed that fast?"* [P10].

Through such reflection-in-action most participants also developed the *experiential understanding* that actuations are triggered by factors other than emotional responses. This is an important outcome, as although this information has been delivered during the lab session, it had to be directly experienced in order to shift people's emphasis from one to one mapping of actuation to emotion [4]. For instance, P1 used the vibrating band mentioned: "*sometimes it's easy to map the response to my emotions but sometimes it's quite difficult [and] I don't think it maps to emotion"*. Through experimentation, he later realized that other factors such as physical activity could also trigger the actuation. *"[The band] also vibrates to associated physical activities"* [P1]. Another important outcome is the insight that prototypes' actuation can only gain meaning through reflection on one's emotional responses. P6 who used the single-colored display mentioned: *"because my feelings could be hidden […] this technology could help me to unpack those feelings [but] I have to combine both my feelings and [prototype's actuation] to reflect on"*.

Context of Use, Privacy, and Ethics

Overall, participants' experiences with the prototypes were positive, particularly with regard to actuations triggered by emotional experiences: "*it's nice to have something like this, that is aware of your emotions"* [P1], and several participants expressed desire of using them for longer time [P6, P7, P9, P12], and extend their functionalities as mood tracking devices: *"I want to use it to record my emotions, how I am doing overall, and what I need to improve"* [P10].

Interestingly, only two participants expressed privacy concerns. P7 wore the three-colored prototype noted: *"I don't want my colleagues or boss to see my mood […] I really like the squeeze feature, because you don't have to see it, only you know, when you have to stop or change something"* [P7]. P11, a privacy researcher, was especially concerned about the privacy of his bodily data and mentioned that he would have never used it if it was a commercial device.

An important outcome relates to the observation that actuations triggered by strong negative emotions could become problematic, as "*it can be used as a trigger and might push you down the negative path*" [P2]. Although she did not mention any specific instances when this occurred, and no other participant mentioned such situations, this outcome is important, emphasizing the ethical sensitivity required for designing affective interfaces for more vulnerable user groups.

Emotions: Reflexivity, Identification, Attribution and Regulation

Findings suggest that the understanding of the prototype's actuations was intertwined with participants' efforts to make sense of their emotional responses. We now describe these efforts to understand emotional responses triggering the actuations, which include reflexivity, emotion identification, emotion attribution and regulation.

Reflexivity

An important aspect of the wrist-worn arousal representations is that the actuation made participants pay attention to the self in the present. This process of acting back upon oneself is captured by the concept of reflexivity [63], and has also been discussed in *make me think* relationship model [25]. P4, for example, who used the squeezing band mentioned: "*when the device squeezes, it makes me think about what I was doing at the time*". Similarly, P6 felt present in the moment, every time her display flashed: *"when I see the feedback, I feel present, I start to reflect what I was doing before and try to think how I am feeling at that moment"*. As reported by participants wearing the heating band, heat supported better awareness of the emotional event because of its more embodied nature compared to visual feedback, which in turn may support stronger encoding of its memory. P10, who used the heating band, added: *"when the device triggers, you will remember the events because there is a physical stimulus. It's pretty intense; you would really feel it"*.

Emotion Identification

A striking finding is that the arousal-based feedback supported participants to start identifying emotional responses that they failed to do before wearing the prototypes: "*it made me more aware of my feelings and made me think what feelings I have. but if I didn't have the device, I wouldn't be probably as aware as I am when wearing it. It did give me a way to think of my own emotion; made me aware of my own emotions"* [P3]. Thus, a valuable outcome is prototypes' ability to support people's awareness of their emotions by prompting their identification.

Prior research called for multiple dimensions to express affect [93], and we now discuss how visual and haptic modalities supported emotion identification. Through its expressiveness, the three-colored display was particularly useful in supporting the increased understanding of one's emotions from discrete emotions, to positive or negative ones (valence), and finally as high, medium, or low intensity ones (arousal).

While discrete positive or negative emotions were reported by users of all other prototypes, the understanding that the prototypes communicate arousal was achieved only by participants wearing the three-colored display. For example, P9's initial encounters with the colors in the three-colored display made her associate blue with negative valence: "*when my boyfriend scared me suddenly to see if there is any color change and then it turned blue*". However, repeated interactions with the prototype challenged this initial understanding: "*when I was talking with my mom, it turned blue [but] I don't think that at that time I was sad or scary"* [P9]. This constancy of the representations allowed the realization that valence may be less relevant, as both positive and negative emotions are mapped to the same color, i.e., blue. Later, she successfully linked the colors to the intensity of emotions as: "*I think red is stronger emotions, and blue is very normal thing"*. Similarly, P7, who also used the three-colored display, mapped the colors to arousal after several interactions, "*my feeling is that the blue is first level, yellow is second level, and red is the highest"*. These outcome suggest that colors affected participants' interpretation of arousal, confirming findings on the role of colors on people's affect and cognition [20].

For the other prototypes, the awareness of the mapping of colors to arousal was limited, albeit many participants described their emotions both as discrete but also in terms of emotional valence. For instance, heating band was valued for providing feedback on both positive and negative emotions: "*the heat was always the same, it made me reflect on my emotions; then, I could tell whether it was positive or negative"* [P3]. The actuation of squeezing band was also linked to positive and negative valence: "*it responds to fear and it responds to joy as well"* [P4]. Similarly, the instant response time and less inertia of both flashing display and vibrating band acted as signals for both positive and negative emotions. This indicates that the less expressive interfaces, lacking explicit representations of arousal levels, prompted the understanding that the device does not discriminate emotional valence, but failed to recognise that is actuated by high emotional responses.

Emotion Attribution

In this section we describe the process through which participants identified the source of the emotional response reflected in the actuation. Such process is called *emotion attribution* [61] and has been advanced by the two-factor theory of emotion. The latter states that experienced emotional response motivates people to search for cues for labelling that emotion [72].

Findings indicate that emotion attribution was quick and easier in the case of intense emotional responses, particularly positive ones such as (falling in) love. P1, for example attributed the vibrations on his wrist to strong positive feelings for a friend he fancies: "*after she get off the bus, I said goodbye through the window […] a few seconds later [it] started vibrating. I think I was more happy than usual at that time"*. For P12, the color change in the flashing display represented love for her dog: *"it went quite green when I was playing with my dog […] I am crazy about my dog, so maybe it's because I love her so much"*.

People also attributed the actuations to intense negative feelings of anger or anxiety. When P10 felt angry, he could immediately link it to the heat response: *"my father called me, and we had an argument, and [heating band] went off again; this time I knew it is negative emotion, obviously, it immediately recognised that my emotions changed"*. The heating band's actuation was also mentioned by P10 in relation to anxiety: "*I was cooking, and [the band] started to give me heat. I started thinking, why my mood changed and realized that I was worried about my application for a language test. It was negative emotions; it made me trace specifically and remember the thoughts that crossed my mind and actually triggered an emotion"*.

Another important finding is that besides most of the instances of in-the-moment emotion attribution mentioned above, a few participants mentioned connecting memories of similar actuations/emotional responses, which in turn facilitates more problematic emotion attribution. These occurred when participants could not immediately identify an emotion, but later experiences helped them reflect on prior experiences and understand them. For example, P11 linked the current emotion to a previous similar one for which he couldn't initially identify the cause of color change: "*at one point, [I noticed] a change in color; then I realized that earlier, when I could not figure out why the color changed, that I was frustrated at that time as well*".

Emotion Regulation

Although the prototypes have not been purposely designed to support emotion regulation, i.e., ability to module one's emotional responses, a surprising finding was that a few participants appropriated them for regulating intense negative feelings: "*I was discussing dislike of my supervisor's comments and the device gave me heat. I knew it was telling me that, hey! You have negative emotions! But it didn't stop me from being angry, so I just kept talking"* [P3]. Later, thinking about this, made him reflect on his experience: "*it gave me time to reflect whether I should be angry or not that angry, and then I learned that I chose being angry. Because, I kept going instead of stop and relax"*.

The slowly unfolding appearance of yellow color in three-colored display helped P7 manage her emotions: "*I argued with a friend and yellow started to appear and I saw it getting bigger and bigger, so I thought, maybe I shouldn't talk that way; I should be polite and keep my mood more gentle, not that strong"*. Later, she offered an apology to her friend and wanted to use the prototype during family time: "*the yellow thing really helped me to relax and keep myself calm and have some conversation. that would be helpful if you are talking to someone you really want to argue with [such as] my husband. It's kind of having some* *voice [telling] it's too much or just say it in a different way"*. Other participants also saw prototypes' potential for regulation of negative affect in everyday life: *"I guess when I am feeling really frustrated, I will definitely use it to monitor my emotions to know when to stop*" [P8], and "*in situations which are highly stressful, perhaps [it can offer] an early alarm for self-diagnosis"* [P4].

Awareness of Affective Chronometry

A key finding is that despite being used for only two days, all prototypes supported participants' paying attention and developing increased awareness of how their emotional responses unfold in time, i.e., raise and decay, albeit they did so in different ways.

Raise Time of Emotional Response

Findings indicate that prototypes with binary, rather than continuous gradual actuation, provided more intense stimuli, closer to the moment when physiological arousal increased. As a result, such prototypes facilitated increased awareness of the *moments of increased arousal*. Interestingly, the same prototypes made participants more aware of delays in device's actuation (calculation of GSR peaks within 5-second intervals). This finding was consistent across both haptic and visual modalities. For example, the fast and salient nature of vibrating band allowed P2 to identify the delay between prototype's actuation and the moment of her increase in arousal: "*it goes from nothing to everything with my arousal, but the device has a lag"*. Similarly, P12, who was using the flashing display with fast color changes also noticed a delay in the feedback: "*it would change color a little bit after I would expect it to"* and attributed the delay to her skin's limited responsiveness rather than to the prototype.

As these quotes indicate, people make conjunctions with respect to such idiosyncrasies between their emotional experience and prototypes' actuations. More specifically, prototypes with instant feedback provided the strongest support for the raise time of emotional response. These findings indicate that such brief delays before the feedback can make people explore the reasons for these delays [9]. Findings also suggest that compared to visual feedback, the haptic one better supported the perception of, and awareness of emotional arousal. The physical sensation of haptic stimulus and its more embodied, *felt-life* quality [49] promoted participants to pay more attention to the prototypes' feedback and subsequently their arousal.

Existing research on thermal stimulation shows that people are able to detect even one degree change in temperature [98]. The gradual increase in temperature during the heat feedback was particularly expressive: *"it's quite an intense stimulus, you feel it; it makes you pay attention immediately"* [P10]. Compared to heat feedback, participants experienced vibrations as less noticeable, especially if the prototype vibrated over a longer time interval: "*when it's too long, I lose track of it; for me, the trigger is when it starts vibrating"* [P2]. They also experienced the squeeze feedback as more subtle: "*it's subtle and one may miss it"* [P4].

In contrast to haptic feedback's ability to increase participants' awareness of moments of high arousal, the visual feedback in the form of slow changing colors was less effective. P8 commented on the displays' inability to differentiate his new feelings after it changed to reddish-pink: "*when I got more excited, it could not go any more pink, it requires long time to make a simple change*". This quote highlights the need for expressiveness of colors to represent emotions [93] i.e. representing more than one level of arousal (achieved with the three-colored display).

Decay Time of Emotional Response

The longevity and continuity (prototypes' ability to detect significant increases in arousal) was perceived differently for haptic and visual feedback. While all prototypes successfully communicated the increase of arousal, the expressive communication of maintaining high level of arousal, or decreasing arousal was more challenging.

Vibrating band was different from the other prototypes as it provided feedback not only when the captured arousal exceeded the threshold for high, but it also continued to provide such feedback until the level of arousal dropped below this threshold. The rationale for this choice was due to the binary aspect of vibration, and its limited ability to convey de-actuation or lowering of arousal. Hence, we wanted to explore if the latter can be communicated by providing no more vibrations. Findings suggest that this mapping worked to some extent, as participants could relate the duration of vibrations to the duration of their high arousal: "*it was a roller coaster that went up and down*" [P2]. Although it worked, this prolonged feedback become problematic as people experienced habituation followed by ignoring it. Nevertheless, this points out the fact that the time of raise matters more than the time that the emotional response lasts. For example, P1, who was getting multiple vibrations while he was talking to his friend, expressed the desire to slow it down to a fix, small duration for each recognized moment of high arousal: "*it was giving me multiple vibrations for one activity. It would be nice to have it vibrate in certain time, if my arousal is high for an activity"*. These findings indicate increased challenges of haptic binary feedback for communicating the lowering of arousal. The other two haptic prototypes providing squeeze and heat feedback did not attract participants' attention to their communication of decrease in arousal. This could be because of the gradual dissipation of heat (5 minutes) and the gradual de-actuation of squeezing band (5 minutes).

Unlike haptic prototypes, where the communication of decreasing arousal was either ignored or unnoticed, the slowness and volatility of thermochromic materials increased ambiguity in visual displays [14,34,88], which challenged participants to engage in sense making. Two visual prototypes provided visual representations of slow, gradual, reverse change of color from red, yellow, and blue

(2 minutes), and from reddish-pink to bluish-purple (5 minutes). The challenge here was that the communication of the prototype's recovery status could not be provided. This in turn, increased the ambiguity of these visual displays. For example, P7, who was using the three-colored display commented about the colors being slow: *"I feel it's too slow"*, which in turn, prompted her to question the persistence of the intense emotions shown on the display: *"I just don't know for how long it lasts or if I have strong feelings"*. P8 also associated the presence of pink color with more intense emotions: "*it goes from purple to pink quickly and goes back very slowly. I am not sure if that's about my emotions or about the device"*. These quotes indicate how the persistence of colors was seen as an indicator of prolonged emotions which in turn led them to question their emotional awareness. However, through repeated interactions and even experimentations, participants felt comfortable critiquing their prototype and came to better understand that the slowness of visual representations may relate to the slowness of the prototypes: *"once I took it off, I thought the color would go away very soon, but it didn't"* [P9]. This made P9 realize that, it's not her who is "*so emotional*", but that the prototype is slow. This is in turn, increased her awareness of the duration of emotional experience: "*after, I tried it so many times, I feel like my feelings go away, but the colors don't […] It can't make me believe that every time my emotions are all still there"*.

DISCUSSION

We engaged participants in an exploration of 6 arousal-based prototypes, designed and built with smart materials and actuators. An important finding is prototypes' impact on participants' relationship with their emotions, mediated through an ongoing experimentation and sense-making process. All prototypes sensitized participants' towards the self, present moment, emotional responses, while engaging in emotion identification, attribution and even regulation [44]. Findings suggest that participants were more successful in their emotion identification when they managed to integrate physiological arousal with cognitive labeling, providing support for the two-factor theory of emotion [72].

Participants also become motivated to understand the temporal unfolding of their emotional responses, albeit each prototype supported this in different ways. These are important outcomes, given the ambiguity and temporal qualities of our prototypes such as responsiveness, duration, rhythm, inertia, aliveness and range. We argue that precisely such qualities become leveraged in the interaction through moments of pause [9], which engaged participants in deeper reflection. We do not claim that our prototypes captured affective chronometry, but that through their temporal qualities, they sensitized and motivated people towards it.

We argue for the importance of these material-driven qualities of smart materials and actuators. Indeed, the prototypes we developed to showcase these qualities offer a less explored approach to developing arousal-based interfaces. By working through, and with the affordances and constraints of these materials, we developed innovative interfaces emphasizing slowness and aliveness and multisensory inputs which would have been more difficult to imagine if we were to use traditional screen-based interfaces. It was precisely these interactions through temporal qualities of materials that shaped how people engaged in emotional awareness, making sense, and even self-regulation. We argue that a better understanding of these less explored materials and their qualities could open up new design opportunities for representing arousal, and more broadly, designing expressive interactions to better support sense of self and meaning making.

Our findings also suggested increased ethical sensitivity, particularly with regard to communicating strong negative affect. We found a few instances where some of the participants interpreted such actuation as potentially harmful as it brings to awareness negative emotions. Existing work on HCI and affective health [68] has already started to highlight such ethical concerns, together with some good practices for addressing them. While participants in our study belonged to non-clinical population and such risks would be low, the awareness of on-going negative emotions can lead to increased negative experiences [40,47]. Such experiences can be mitigated by designing interfaces that do not attempt to diagnose mental health [7,22], encourage open critique of representations [35]; invite reflection [36], or encourage participants' screening [17,67]. Our prototypes were not designed for clinical population, but merely as probes to understand how people experience and understand them.

We now discuss our contributions by reflecting on research questions. With respect to the first research question on qualities of smart materials and actuators, we explored different thermochromic materials and haptic actuators and highlighted their key properties for real-time representations of changes in arousal: *flashing, three-colored, single-colored displays and vibrating, squeezing, heating bands*. To address the second research question on how these qualities shape people's understanding of their daily emotions, we detailed how material-driven design qualities of such materials and actuators can support users make sense of their emotional responses: *reflexivity, emotion identification, attribution and regulation*, as well as their raise and decay.

We chose wrist as a location for our prototypes to increase their wearability for daily lives. Future work could explore other body locations where the identified qualities might be differently experienced, or even the combination of personal and public displays [15,16,43]. Going forward, we call for designers of affective technologies to continue exploring other materials, actuators on different bodily locations, and possible with alternative biosensors. We have presented different material qualities, their affordances and how they foster different reflections which designers can consider when deciding which such modalities. Future work will focus on building a DIY toolkit with modularized components [70] of different actuators that can be plugged and played with biosensors. Such kit may be used for co-designing with therapists to better tailor it to the needs of people living with affective disorders such as depression [60,68]. We now discuss four design implications of our findings including support for affective chronometry for both raise and decay time of emotional response, design for slowness, and for expressiveness.

Supporting Affective Chronometry: immediate, heat-based feedback for awareness of raise time

Findings indicate the prototyped arousal-based interfaces supported an increased understanding of the temporal dynamics of emotional responses. In turn, this laid the ground for participants' further engagement with the prototype in order to understand and make sense of representations. Two key chronometry properties supported by our prototypes were the raise time and the decay time of emotional responses. However, the distinct material qualities underpinning each prototype played different roles in supporting the communication and understanding of the raise time and decay time. Thus, findings indicate that the moment of arousal is best supported by smart materials and actuators which are instant and constant, i.e., flash of constant intensity that appears and disappears quickly, or a burst of heat that appears and disappears quickly; and preferably haptic rather than visual. Findings also indicate that slowness matters, particularly the delay between the moment of arousal and the actuation of the device. With respect to the two modalities, the physical sensation of haptic feedback and its more embodied, felt-life quality was particularly valuable in increasing the awareness of the raise time of one's emotional response.

Supporting Affective Chronometry: gradual, slow thermochromic feedback for awareness of decay time

Study outcomes show that unlike the raise time of emotional response, communicating about and increasing awareness of the decay time is more challenging. Such findings bring to light the importance of the material qualities relating to deactuation, which have been less recognized in HCI work. Awareness of the lingering emotions is however critical for emotional wellbeing and affective health [11,49]. Our findings indicate that the material quality of aliveness which shows continual gradual slow change is particularly useful to communicate about and prompt participants' awareness of the decay time of their emotional response. With respect to modalities, haptic feedback is less valuable, as dissipating heat can easily be ignored. Thus, the embodied felt-like quality of heat which serves well to support awareness of the raise time is less effective for the decay time. In contrast, the less embodied quality of the visual feedback can continue to hold attention even if its signals gradual decay.

Design for Slowness: delays and ambiguity prompt engagement and reflection

Our prototypes had a built-in delay of 5 seconds, which rather than being perceived as hindrances, served a valuable role: increased awareness of the raise time in prototypes with instant responsiveness. Findings also indicate that delays are also important in prompting awareness of the decay time; be them due to the aliveness quality communicated on the interface or the inertia quality of the prototype which could not be communicated on the representations. The latter in particular contributed to the ambiguity in visual prototypes [35], prompting further explorations and effort to understand about the decay time of one's emotional response. Prior research on slow technology also argues that slowness of appearance and presence encourages people to think and reflect on it [29,54]. This is an important finding as previous work on affective representations indicated that although ambiguity invites active interpretation [24,67], it also poses considerable challenges [35] when the mapping is difficult to understand. Ours findings suggest that ambiguity and especially temporal ambiguity of our representations has been particularly beneficial for motivating users to pause [8] and engage in the exploration of their affective chronometry, an aspect which has not been much reported in HCI. Such critical questioning could in turn empower users [22,78].

Design for Expressiveness: increased emotional awareness

The three-colored display supported multiple levels of arousal. Findings indicate that expressiveness of three-colored display proved to be effective in conveying different levels of arousal. Existing research calls for multiple dimensions to express affect [93]. The lack of emotional expressivity of remaining prototypes along arousal axis hindered participants understanding of their levels of arousal. Our findings indicate that complexity of affective states require various levels to express and understand it.

CONCLUSION

We employed a research through design exploration of smart materials and actuators and unpack their material properties both as affordances and constraints for design. This understanding underpinned the design rationale for six visual and haptic prototypes for representing changes in arousal. We report on interviews with 12 participants who wore the prototypes for 2 days. Our findings highlight the value of visual and haptic representations of arousal in daily life and how specific material-driven qualities of these prototypes such as responsiveness, duration, rhythm, inertia, aliveness and range shape people's emotion identification, attribution, and even regulation. Our findings led to four design implications including support for affective chronometry for both raise and decay time of emotional response, design for slowness, and for expressiveness.

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REFERENCES

[1] Moses Akazue, Martin Halvey, Lynne Baillie, and Stephen Brewster. 2016. The Effect of Thermal Stimuli on the Emotional Perception of Images. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, 4401–4412. https://doi.org/10.1145/2858036.2858307

[2] Wolfram Boucsein. 2012. *Electrodermal Activity*. Springer US, Boston, MA.

[3] Margaret M Bradley and Peter J Lang. 2000. Measuring emotion: Behavior, feeling, and physiology. In *Series in affective science. Cognitive neuroscience of emotion*. Oxford University Press, 242–276.

[4] John T Cacioppo and Louis G Tassinary. 1990. Inferring psychological significance from physiological signals. *American Psychologist* 45, 1: 16–28.

[5] Jessica R Cauchard, Janette L Cheng, Thomas Pietrzak, and James A Landay. 2016. ActiVibe: Design and Evaluation of Vibrations for Progress Monitoring. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, 3261–3271. https://doi.org/10.1145/2858036.2858046

[6] Angela Chang, Sile O'Modhrain, Rob Jacob, Eric Gunther, and Hiroshi Ishii. 2002. ComTouch: design of a vibrotactile communication device. In *Proceedings of the conference on Designing interactive systems processes, practices, methods, and techniques - DIS '02*, 312–320. https://doi.org/10.1145/778712.778755

[7] Munmun De Choudhury, Sanket S. Sharma, Tomaz Logar, Wouter Eekhout, and René Clausen Nielsen. 2017. Gender and Cross-Cultural Differences in Social Media Disclosures of Mental Illness. In *Proceedings of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing - CSCW '17*, 353–369. https://doi.org/10.1145/2998181.2998220

[8] Jean Costa, Alexander T Adams, Malte F Jung, François Guimbetière, and Tanzeem Choudhury. 2016. EmotionCheck: leveraging bodily signals and false feedback to regulate our emotions. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing - UbiComp '16*, 758–769. https://doi.org/10.1145/2971648.2971752

[9] Anna L Cox, Sandy J.J. Gould, Marta E Cecchinato, Ioanna Iacovides, and Ian Renfree. 2016. Design Frictions for Mindful Interactions: The Case for Microboundaries. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 1389–1397. https://doi.org/10.1145/2851581.2892410

[10] Claudia Daudén Roquet and Corina Sas. 2018. Evaluating Mindfulness Meditation Apps. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. https://doi.org/10.1145/3170427.3188616

[11] Richard J Davidson. 2015. Comment: Affective Chronometry Has Come of Age. *Emotion Review* 7, 4: 368–370.

[12] Richard J Davidson and Shelly Benjamim Irwin. 1999. The functional neuroanatomy of emotion and affective style. *Trends in cognitive sciences* 3, 1: 11–21.

[13] Michael E Dawson, Anne M Schell, Diane L Filion, and Gary G. Berntson. 2007. The Electrodermal System. In *Handbook of Psychophysiology*, John T. Cacioppo, Louis G. Tassinary and Gary Berntson (eds.). Cambridge University Press, Cambridge, 159–181.

[14] Laura Devendorf, Kimiko Ryokai, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-Wei Gong, M. Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. "I don't Want to Wear a Screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, 6028–6039. https://doi.org/10.1145/2858036.2858192

[15] Alan Dix and Corina Sas. Mobile Personal Devices meet Situated Public Displays: Synergies and Opportunities. *International Journal of Ubiquitous Computing (IJUC)* 1, 1: 11–28.

[16] Alan Dix and Corina Sas. 2008. *Public displays and private devices: A design space analysis*. New York, New York, USA. Retrieved from https://alandix.com/academic/papers/Dix-Sas-PDPD-2008/

[17] Gavin Doherty, David Coyle, and John Sharry. 2012. Engagement with online mental health interventions: an exploratory clinical study of a treatment for depression. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*, 1421–1430. https://doi.org/10.1145/2207676.2208602

[18] Tanja Döring. 2016. The Interaction Material Profile: Understanding and Inspiring How Physical Materials Shape Interaction. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 2446–2453. https://doi.org/10.1145/2851581.2892516

[19] Paul Dourish and Melissa Mazmanian. 2013. Media as Material: Information Representations as Material Foundations for Organizational Practice. In *How Matter Matters: Objects, Artifacts, and Materiality in Organization Studies*, Paul R. Carlile, Davide Nicolini, Ann Langley and Haridimos Tsoukas (eds.). Oxford University Press, 92–118.

[20] Andrew J Elliot and Markus A Maier. 2014. Color psychology: effects of perceiving color on psychological functioning in humans. *Annual Review of Psychology* 65, 1: 95–120.

[21] Jennifer Fereday and Eimear Muir-Cochrane. 2006. Demonstrating Rigor Using Thematic Analysis: A Hybrid Approach of Inductive and Deductive Coding and Theme Development. *International Journal of Qualitative Methods* 5, 1: 80–92.

[22] Pedro Ferreira, Pedro Sanches, Kristina Höök, and Tove Jaensson. 2008. License to chill!: how to empower users to cope with stress. In *Proceedings of the 5th Nordic conference on Human-computer interaction building bridges - NordiCHI '08*, 123. https://doi.org/10.1145/1463160.1463174

[23] Thomas Fuchs and Sabine C Koch. 2014. Embodied affectivity: on moving and being moved. *Frontiers in Psychology* 5: 508.

[24] William W Gaver, Jacob Beaver, and Steve Benford. 2003. Ambiguity as a resource for design. In *Proceedings of the conference on Human factors in computing systems - CHI '03*, 233–240. https://doi.org/10.1145/642611.642653

[25] Maliheh Ghajargar, Mikael Wiberg, and Erik Stolterman. 2018. Designing IoT Systems that Support Reflective Thinking: A Relational Approach. *International Journal of Design* 12, 1: 21–35.

[26] Asma Ghandeharioun and Rosalind Picard. 2017. BrightBeat: Effortlessly Influencing Breathing for Cultivating Calmness and Focus. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '17*, 1624–1631. https://doi.org/10.1145/3027063.3053164

[27] Elisa Giaccardi and Elvin Karana. 2015. Foundations of Materials Experience: An Approach for HCI. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, 2447–2456. https://doi.org/10.1145/2702123.2702337

[28] Aakar Gupta, Antony Albert Raj Irudayaraj, and Ravin Balakrishnan. 2017. HapticClench: Investigating Squeeze Sensations using Memory Alloys. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology - UIST '17*, 109–117. https://doi.org/10.1145/3126594.3126598

[29] Lars Hallnäs and Johan Redström. 2001. Slow Technology – Designing for Reflection. *Personal and Ubiquitous Computing* 5, 3: 201–212. https://doi.org/10.1007/PL00000019

[30] Yu Hao, James Budd, Melody Moore Jackson, Mukul Sati, and Sandeep Soni. 2014. A visual feedback design based on a brain-computer interface to assist users regulate their emotional state. In *Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems - CHI EA '14*, 2491–2496. https://doi.org/10.1145/2559206.2581132

[31] Clyde L Hardin and Luisa Maffi. 1997. *Color Categories in Thought and Language*. Cambridge University Press.

[32] Matthew J Hertenstein, Rachel Holmes, Margaret McCullough, and Dacher Keltner. 2009. The communication of emotion via touch. *Emotion* 9, 4: 566–573.

[33] Victoria Hollis, Artie Konrad, Aaron Springer, Matthew Antoun, Christopher Antoun, Rob Martin, and Steve Whittaker. 2017. What Does All This Data Mean for My Future Mood? Actionable Analytics and Targeted Reflection for Emotional Well-Being. *Human–Computer Interaction* 32, 5–6: 208–267. https://doi.org/10.1080/07370024.2016.1277724

[34] Noura Howell, Laura Devendorf, Rundong Kevin Tian, Tomás Vega Galvez, Nan-Wei Gong, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. Biosignals as Social Cues: Ambiguity and Emotional Interpretation in Social Displays of Skin Conductance. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems - DIS '16*, 865–870. https://doi.org/10.1145/2901790.2901850

[35] Noura Howell, Laura Devendorf, Tomás Alfonso Vega Gálvez, Rundong Tian, and Kimiko Ryokai. 2018. Tensions of Data-Driven Reflection: A Case Study of Real-Time Emotional Biosensing. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, 1–13. https://doi.org/10.1145/3173574.3174005

[36] Ellen Isaacs, Artie Konrad, Alan Walendowski, Thomas Lennig, Victoria Hollis, and Steve Whittaker. 2013. Echoes from the past: how technology mediated reflection improves well-being. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*, 1071–1080. https://doi.org/10.1145/2470654.2466137

[37] Heekyoung Jung and Erik Stolterman. 2012. Digital form and materiality: propositions for a new approach to interaction design research. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction Making Sense Through Design - NordiCHI '12*, 645. https://doi.org/10.1145/2399016.2399115

[38] Hsin-Liu Cindy Kao, Christian Holz, Asta Roseway, Andres Calvo, and Chris Schmandt. 2016. DuoSkin: rapidly prototyping on-skin user interfaces using skin-friendly materials. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers - ISWC '16*, 16–23. https://doi.org/10.1145/2971763.2971777

[39] Hsin-Liu Cindy Kao, Manisha Mohan, Chris Schmandt, Joseph A Paradiso, and Katia Vega. 2016. ChromoSkin: Towards Interactive Cosmetics Using Thermochromic Pigments. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 3703–3706. https://doi.org/10.1145/2851581.2890270

[40] Christina Kelley, Bongshin Lee, and Lauren Wilcox. 2017. Self-tracking for Mental Wellness: Understanding Expert Perspectives and Student Experiences. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17*, 629–641. https://doi.org/10.1145/3025453.3025750

[41] George (Poonkhin) Khut. 2016. Designing Biofeedback Artworks for Relaxation. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 3859–3862. https://doi.org/10.1145/2851581.2891089

[42] Ilpo Koskinen, John Zimmerman, Thomas Binder, Johan Redstrom, and Stephan Wensveen. 2011. *Design research through practice: From the lab, field, and showroom*. Elsevier.

[43] Christian Kray, Keith Cheverst, Dan Fitton, Corina Sas, John Patterson, Mark Rouncefield, and Christoph Stahl. 2006. Sharing control of dispersed situated displays between nand residential users. In *Proceedings of the 8th conference on Human-computer interaction with mobile devices and services - MobileHCI '06*, 61–68. https://doi.org/10.1145/1152215.1152229

[44] Richard D Lane and Gary E Schwartz. 1987. Levels of emotional awareness: a cognitive-developmental theory and its application to psychopathology [published erratum appears in Am J Psychiatry 1987 Apr;144(4):542]. *American Journal of Psychiatry* 144, 4: 133–143.

[45] Peter J Lang, Margaret M Bradley, and Bruce N Cuthbert. 1998. Emotion, motivation, and anxiety: brain mechanisms and psychophysiology. *Biological psychiatry* 44, 12: 1248–63.

[46] Adam Lobel, Marientina Gotsis, Erin Reynolds, Michael Annetta, Rutger C.M.E. Engels, and Isabela Granic. 2016. Designing and Utilizing Biofeedback Games for Emotion Regulation. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 1945–1951. https://doi.org/10.1145/2851581.2892521

[47] Diana MacLean, Asta Roseway, and Mary Czerwinski. 2013. MoodWings: a wearable biofeedback device for real-time stress intervention. In *Proceedings of the 6th International Conference on PErvasive Technologies Related to Assistive Environments - PETRA '13*. https://doi.org/10.1145/2504335.2504406

[48] Mark Matthews, Jaime Snyder, Lindsay Reynolds, Jacqueline T Chien, Adam Shih, Jonathan W Lee, and Geri Gay. 2015. Real-Time Representation Versus Response Elicitation in Biosensor Data. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, 605–608. https://doi.org/10.1145/2702123.2702485

[49] John McCarthy and Peter Wright. 2005. Putting 'felt-life' at the centre of human–computer interaction (HCI). *Cognition, Technology & Work* 7, 4: 262–271.

[50] Daniel McDuff, Amy Karlson, Ashish Kapoor, Asta Roseway, and Mary Czerwinski. 2012. AffectAura: an intelligent system for emotional memory. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*, 849. https://doi.org/10.1145/2207676.2208525

[51] Pardis Miri, Andero Uusberg, Heather Culbertson, Robert Flory, Helen Uusberg, James J Gross, Keith Marzullo, and Katherine Isbister. 2018. Emotion Regulation in the Wild: Introducing WEHAB System Architecture. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. https://doi.org/10.1145/3170427.3188495

[52] Jaronie Mohd Jani, Martin Leary, Aleksandar Subic, and Mark A Gibson. 2014. A review of shape memory alloy research, applications and opportunities. *Materials & Design (1980-2015)* 56: 1078–1113.

[53] Keith Oatley, Dacher Keltner, and Jennifer M Jenkins. 1996. *Understanding Emotions*. Blackwell Publishing.

[54] William Odom, Richard Banks, Abigail Durrant, David Kirk, and James Pierce. 2012. Slow technology: critical reflection and future directions. In *Proceedings of the Designing Interactive Systems Conference on - DIS '12*, 816–817. https://doi.org/10.1145/2317956.2318088

[55] Mika Pantzar and Minna Ruckenstein. 2015. The heart of everyday analytics: emotional, material and practical extensions in self-tracking market. *Consumption Markets & Culture* 18, 1: 92–109.

[56] Pablo Paredes, Ryuka Ko, Arezu Aghaseyedjavadi, John Chuang, John Canny, and Linda Babler. 2015. Synestouch: Haptic + audio affective design for wearable devices. In *2015 International Conference on Affective Computing and Intelligent Interaction (ACII)*, 595–601. https://doi.org/10.1109/ACII.2015.7344630

[57] Stefano Parisi, Valentina Rognoli, and Marieke Sonneveld. 2017. Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education. *The Design Journal* 20, sup1: S1167–S1184.

[58] Helena Pongrac. 2007. Vibrotactile perception: examining the coding of vibrations and the just noticeable difference under various conditions. *Multimedia Systems* 13, 4: 297–307.

[59] Isabel P. S. Qamar, Rainer Groh, David Holman, and Anne Roudaut. 2018. HCI meets Material Science: A Literature Review of Morphing Materials for the Design of Shape-Changing Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, 23. https://doi.org/10.1145/3173574.3173948

[60] Chengcheng Qu, Corina Sas, and Gavin Doherty. 2019. Exploring and Designing for Memory Impairments in Depression. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*. https://doi.org/10.1145/3290605.3300740

[61] Rainer Reisenzein. 1983. The Schachter theory of emotion: Two decades later. *Psychological Bulletin* 94, 2: 239–264.

[62] Marieke van Rooij, Adam Lobel, Owen Harris, Niki Smit, and Isabela Granic. 2016. DEEP: A Biofeedback Virtual Reality Game for Children At-risk for Anxiety. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 1989–1997. https://doi.org/10.1145/2851581.2892452

[63] Morris Rosenberg. 1990. Reflexivity and Emotions. *Social Psychology Quarterly* 53, 1: 3.

[64] James A Russell. 1980. A circumplex model of affect. *Journal of Personality and Social Psychology* 39, 6: 1161–1178.

[65] Ian Sage. 2011. Thermochromic liquid crystals. *Liquid crystals* 38, 11–12: 1551–1561.

[66] Katri Salminen, Veikko Surakka, Jukka Raisamo, Jani Lylykangas, Johannes Pystynen, Roope Raisamo, Kalle Mäkelä, and Teemu Ahmaniemi. 2011. Emotional responses to thermal stimuli. In *Proceedings of the 13th international conference on multimodal interfaces - ICMI '11*, 193–196. https://doi.org/10.1145/2070481.2070513

[67] Pedro Sanches, Kristina Höök, Elsa Vaara, Claus Weymann, Markus Bylund, Pedro Ferreira, Nathalie Peira, and Marie Sjölinder. 2010. Mind the body!: designing a mobile stress management application encouraging personal reflection. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems - DIS '10*, 47. https://doi.org/10.1145/1858171.1858182

[68] Pedro Sanches, Axel Janson, Pavel Karpashevich, Camille Nadal, Chengcheng Qu, Claudia Dauden Roquet, Muhammad Umair, Charles Windlin, Gavin Doherty, Kristina Hook, and others. 2019. HCI and Affective Health: Taking stock of a decade of studies and charting future research directions. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*. https://doi.org/10.1145/3290605.3300475

[69] Karin Sandström. 2006. When motion becomes emotion: A study of emotion metaphors derived from motion verbs. Retrieved from http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1027700&dswid=-7486

[70] Corina Sas and Carman Neustaedter. 2017. Exploring DIY Practices of Complex Home Technologies. *ACM Transactions on Computer-Human Interaction (TOCHI) - Special Issue EUD for IoT* 24, 2.

[71] Corina Sas, Muhammad Umair, and Muhammad Hamza Latif. 2018. *Designing for Self-Regulation from both Pragmatic and Critical Design Lenses*. Retrieved from

http://eprints.lancs.ac.uk/125125/4/Designing_for_Self_Regulation.pdf

[72] Stanley Schachter and Jerome Singer. 1962. Cognitive, social, and physiological determinants of emotional state. *Psychological Review* 69, 5: 379–399.

[73] Donald A Schön. 2017. *The Reflective Practitioner: How Professionals Think in Action*. Routledge.

[74] Eunbi Seol, Chul-Hyun Cho, Seungmoon Choi, Dooyoung Jung, Seulki Min, Sungho Seo, Seoyeon Jung, Youngil Lee, Jaedong Lee, Gerard Kim, Chungyean Cho, and Seungmoo Lee. 2017. "Drop the beat": virtual reality based mindfulness and cognitive behavioral therapy for panic disorder --- a pilot study. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology - VRST '17*, 1–3. https://doi.org/10.1145/3139131.3141199

[75] Adam C Siegel, Scott T Phillips, Benjamin J Wiley, and George M Whitesides. 2009. Thin, lightweight, foldable thermochromic displays on paper. *Lab on a Chip* 9, 19: 2775–81.

[76] Jocelyn Smith and Karon MacLean. 2007. Communicating emotion through a haptic link: Design space and methodology. *International Journal of Human-Computer Studies* 65, 4: 376–387.

[77] Jaime Snyder, Mark Matthews, Jacqueline Chien, Pamara F Chang, Emily Sun, Saeed Abdullah, and Geri Gay. 2015. MoodLight: Exploring Personal and Social Implications of Ambient Display of Biosensor Data. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing - CSCW '15*, 143–153. https://doi.org/10.1145/2675133.2675191

[78] Anna Ståhl, Kristina Höök, Martin Svensson, Alex S Taylor, and Marco Combetto. 2009. Experiencing the Affective Diary. *Personal and Ubiquitous Computing* 13, 5: 365–378.

[79] Anna Ståhl, Petra Sundström, and Kristina Höök. 2005. A foundation for emotional expressivity. In *Proceedings of the 2005 conference on Designing for User eXperience - DUX '05*.

[80] Petra Sundström, Anna Ståhl, and Kristina Höök. 2007. In situ informants exploring an emotional mobile messaging system in their everyday practice. *International Journal of Human-Computer Studies* 65, 4: 388–403.

[81] Petra Sundström, Alex Taylor, Katja Grufberg, Niklas Wirström, Jordi Solsona Belenguer, and Marcus Lundén. 2011. Inspirational bits: towards a shared understanding of the digital material. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, 1561–1570. https://doi.org/10.1145/1978942.1979170

[82] Petra Sundström, Elsa Vaara, Jordi Solsona, Niklas Wirström, Marcus Lundén, Jarmo Laaksolhati, Annika Waern, and Kristina Höök. 2011. Experiential artifacts as a design method for somaesthetic service development. In *Proceedings of the 2011 ACM symposium on The role of design in UbiComp research & practice - RDURP '11*, 33–36. https://doi.org/10.1145/2030031.2030041

[83] Ruben T. Azevedo, Nell Bennett, Andreas Bilicki, Jack Hooper, Fotini Markopoulou, and Manos Tsakiris. 2017. The calming effect of a new wearable device during the anticipation of public speech. *Scientific Reports* 7, 1: 2285.

[84] Jordan Tewell, Jon Bird, and George R Buchanan. 2017. The Heat is On: A Temperature Display for Conveying Affective Feedback. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17*, 1756–1767. https://doi.org/10.1145/3025453.3025844

[85] Anja Thieme, Jayne Wallace, Paula Johnson, John McCarthy, Siân Lindley, Peter Wright, Patrick Olivier, and Thomas D Meyer. 2013. Design to promote mindfulness practice and sense of self for vulnerable women in secure hospital services. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*, 2647–2656. https://doi.org/10.1145/2470654.2481366

[86] Panagiotis Tsiamyrtzis, Malcolm Dcosta, Dvijesh Shastri, Eswar Prasad, and Ioannis Pavlidis. 2016. Delineating the Operational Envelope of Mobile and Conventional EDA Sensing on Key Body Locations. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, 5665–5674. https://doi.org/10.1145/2858036.2858536

[87] Secil Ugur Yavuz, Monica Bordegoni, and Marina Carulli. 2018. A design practice on communicating emotions through sensory signals. *Concurrent Engineering* 26, 2: 147–156.

[88] Muhammad Umair, Muhammad Hamza Latif, and Corina Sas. 2018. Dynamic displays at wrist for real time visualization of affective data. In *DIS 2018 - Companion Publication of the 2018 Designing Interactive Systems Conference*. https://doi.org/10.1145/3197391.3205436

[89] Muhammad Umair and Corina Sas. 2019. *Problems in Practice: Critiquing on Thermochromic based Displays for Representing Skin Conductance*. Retrieved from

http://eprints.lancs.ac.uk/131738/4/Muhammad_Umair_Critiquing_on_Thermochromic_based_Displays_for_Representing_Skin_Conductance.pdf

[90] Patricia Valdez and Albert Mehrabian. 1994. Effects of color on emotions. *Journal of Experimental Psychology: General* 123, 4: 394–409.

[91] Anna Vallgårda and Johan Redström. 2007. Computational composites. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '07*, 513–522. https://doi.org/10.1145/1240624.1240706

[92] Jay Vidyarthi and Bernhard E Riecke. 2013. Mediated meditation: cultivating mindfulness with sonic cradle. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems on - CHI EA '13*, 2305–2314. https://doi.org/10.1145/2468356.2468753

[93] Torben Wallbaum, Wilko Heuten, and Susanne Boll. 2016. Comparison of in-situ mood input methods on mobile devices. In *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia - MUM '16*, 123–127. https://doi.org/10.1145/3012709.3012724

[94] Lois B Wexner. 1954. The degree to which colors (hues) are associated with mood-tones. *Journal of Applied Psychology* 38, 6: 432–435.

[95] Mikael Wiberg. 2014. Methodology for materiality: interaction design research through a material lens. *Personal and Ubiquitous Computing* 18, 3: 625–636.

[96] Graham Wilson and Stephen A Brewster. 2017. Multi-moji: Combining Thermal, Vibrotactile & Visual Stimuli to Expand the Affective Range of Feedback. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17*, 1743–1755. https://doi.org/10.1145/3025453.3025614

[97] Graham Wilson, Dobromir Dobrev, and Stephen A Brewster. 2016. Hot Under the Collar: Mapping Thermal Feedback to Dimensional Models of Emotion. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, 4838–4849. https://doi.org/10.1145/2858036.2858205

[98] Graham Wilson, Martin Halvey, Stephen A Brewster, and Stephen A Hughes. 2011. Some like it hot: thermal feedback for mobile devices. In*Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, 2555–2564. https://doi.org/10.1145/1978942.1979316

[99] Graham Wilson, Pietro Romeo, and Stephen A Brewster. 2016. Mapping Abstract Visual Feedback to a Dimensional Model of Emotion. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 1779–1787. https://doi.org/10.1145/2851581.2892320

[100] Bin Yu, Rogier Arents, Mathias Funk, Jun Hu, and Loe M.G. Feijs. 2016. HeartPlotter: Visualizing Bio-data by Drawing on Paper. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 1794–1799. https://doi.org/10.1145/2851581.2892289

[101] Bin Yu, Nienke Bongers, Alissa van Asseldonk, Jun Hu, Mathias Funk, and Loe Feijs. 2016. LivingSurface: Biofeedback through Shape-changing Display. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '16*, 168–175. https://doi.org/10.1145/2839462.2839469

[102] Bin Yu, Mathias Funk, Jun Hu, and Loe Feijs. 2017. StressTree: A Metaphorical Visualization for Biofeedback-assisted Stress Management. In *Proceedings of the 2017 Conference on Designing Interactive Systems - DIS '17*, 333–337. https://doi.org/10.1145/3064663.3064729

[103] Welltory: measure and manage your stress & energy. Retrieved January 7, 2019 from https://welltory.com/how-it-works/

[104] (r)evolution Board Kit BT. Retrieved January 7, 2019 from https://bitalino.com/en/board-kit-bt

[105] Grove - GSR Sensor. Retrieved January 7, 2019 from http://wiki.seeedstudio.com/Grove-GSR_Sensor/

[106] Moving average. Retrieved January 7, 2019 from https://en.wikipedia.org/wiki/Moving_average

[107] Heating Pad - SparkFun Electronics. Retrieved January 7, 2019 from https://www.sparkfun.com/products/11288

[108] E4 wristband. Retrieved January 7, 2019 from https://www.empatica.com/en-int/research/e4/