ThermoPixels: Toolkit for Personalizing Arousal-based Interfaces through Hybrid Crafting

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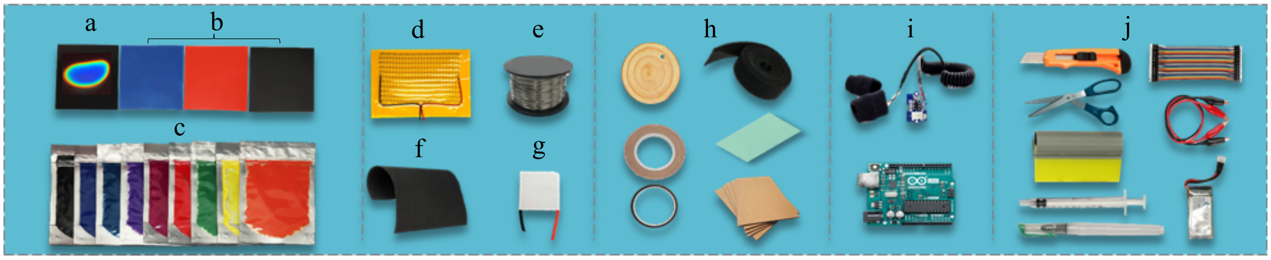

Figure 1: ThermoPixels components: a) liquid crystal sheet b) rub-and-reveal sheets c) thermochromic paints d) heating pad e) nichrome wire f) conductive fabric g) Peltier element h) insulation materials i) GSR sensor and Arduino and j) support tools

ABSTRACT
Much research has shown the potential of affective interfaces for reflection on, and understanding of bodily responses. Yet, people find it difficult to engage with, and understand their biodata which they have limited prior experience with. Building on affective interfaces and material-centered design, we developed ThermoPixels, a toolkit including thermochromic and heating materials, as well as galvanic skin response sensors for creating representations of physiological arousal. Within 10 workshops, 20 users with no expertise in biosensors or thermochromic materials created personalized representations of physiological arousal and its real-time changes using the toolkit. We report on participants' material exploration, their experience of creating shapes and the use of colors for emotional awareness and regulation. We discuss embodied exploration and creative expression, the value of technology in emotion regulation and its social context, and the importance of understanding material limitations for affective sense-making.

Author Keywords
Toolkit; thermochromic materials; arousal representations; personalization; affective interfaces; biosensors

CSS Concepts
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INTRODUCTION
Affective health and wellbeing is a growing area of research within HCI. Many researchers have developed technologies to support affective health [15,63] through interfaces that provide interactive feedback on physiological signals. Such work involves sensing bodily signals such as heart rate [36,48,79], breathing patterns [18], electroencephalography (EEG) [24], galvanic skin response (GSR) [28,29,82], or movement [55] in order to mirror them back through visual [24,36,65], auditory [18,55] or haptic [6,82,89] feedback. Through this, people can engage in self-reflection and arguably increase emotional awareness or regulation [45], both fundamental skills for emotional wellbeing and affective health [22,23]. Either as research prototypes or as commercial technologies [49,82,91], most such systems have been provided to users as ready-made, black-boxed devices to be merely used rather than personalized. Although the design and making of complex technologies are not trivial for non-experts, there are strong benefits from user involvement as shown in end-user development research [4,16,31,46]. Such benefits include increased agency [20], personalization [51], adoption and attachment to the device [56,70], as well as an understanding of technologies' inner workings and even how to repair [61,68].

While an affective state can be understood both in terms of arousal and valence [62], arousal is arguably easier to measure reliably, for instance through galvanic skin response (GSR) [64]. Previous findings have indicated its role in emotional reflection and regulation [29,82], although little is known about users' preference for the personalization of arousal-based interfaces. We argue that the emerging body of HCI work on smart materials and actuators for representing biosensing data in general [6,49,90], and visualizations of changes in physiological arousal in particular [28,73], could open up novel design opportunities for the creation of affective interfaces. This paper presents the design and evaluation of ThermoPixels (Figure 1), a toolkit containing digital and physical materials for fabricating interactive thermochromic displays that change color when heated. They are low cost and can be easily assembled by placing a heating and an insulation layer underneath the thermochromic material to create shapes and patterns with input from GSR sensor. The toolkit was evaluated through workshops with 20 participants with limited experience of prototyping with biosensors and thermochromic materials, who created personalized representations of physiological arousal through hybrid crafting [21]. We address the following research questions:

- How do less technical users explore and understand ThermoPixels' material qualities?
- How is the toolkit used to create personalized representations of arousal and how are these experienced?
- What is the value of ThermoPixels for affective interfaces design?

The contributions of this paper include new ways for both technically skilled and novice users to design personalized affective interfaces through combined material exploration and hybrid crafting approach, unpacking participants' exploration of toolkit components to reveal their affordances, constraints, and inner working, understanding the role of colors and shapes for personalizing interfaces for awareness and regulation of arousal, and novel design opportunities for affective interfaces.

RELATED WORK

Affective Interfaces for Emotional Awareness and Regulation

Much HCI research on affective interfaces has focused on supporting emotional wellbeing [15,49,65], memory awareness [50,66], as well as reflection on emotions [29,47,82]. Such work on affective states, usually conceptualized in terms of arousal or intensity, and valence as positive/negative emotions [62], has explored visual representations of both dimensions of affect through colors, shapes, or patterns such as abstract bubbles [50], spirals [64], or anthropomorphic bodily postures [74]. The exploration of affective interfaces in HCI has focused on supporting an increase in the awareness of one's emotional states and an increase in emotional regulation, or adaptively controlling emotional states. Both emotional awareness and emotional regulation are important skills for wellbeing and affective health [22,23]. Consistent findings have shown that being able to control one's negative emotions for instance by lowering their arousal can improve emotional wellbeing, while the inability to moderate one's emotional responses can deteriorate it [37]. While technologies targeting emotional awareness tend to mirror affective responses, those targeting emotional regulation tend to support changing these responses. Landmark HCI work on the former include systems such as AffectiveDiary [74] and AffectAura [50], while examples for the latter include systems such as AffectiveHealth [15] and others [6,7,18,49,52,57,78,82] targeting mostly regulation of high arousal negative affect. These systems help users to modulate their ongoing emotions through the provision of real-time interventions commonly employing visual or haptic feedback, albeit with limited exploration of how they can be designed and personalized by users. Most of these technologies are developed by researchers and evaluated with users. However, users' building of such technologies has been limitedly explored.

While emotional valence is more difficult to measure through existing biosensors [50], physiological arousal has been reliably captured through electrodermal activity, i.e. measured using GSR changes [5] with commonly employed mapping of physiological arousal to visual representations on traditional displays involving the match of changed colors to the changes in arousal [65]. However, while such research on affective interfaces has involved screen-based displays, work on alternative interfaces, especially those in the space of smart materials such as thermochromic ones, have recently started to emerge [28,29,82].

Thermochromic Materials

Thermochromic materials are non-emissive temperature-sensitive materials that actuate by changing color when heat is applied to them and come back to their original state as heat dissipates. Unlike those on traditional screens, visualizations enabled by thermochromic materials are abstract and ambiguous, have low resolution and tend to be slow [9]. In order to actuate, all thermochromic materials require heat often delivered electrically, albeit with, or without integrated biosensors. Most commonly, thermochromic-based materials have been integrated into textiles [9,59,84] or wearables on the skin [33,86] as informational displays or interactive cosmetics [34] that do not usually involve biosensors.

More recent work has started to explore the integration of thermochromic materials with biosensors such as GSR, with actuation being electrically triggered when the measured physiological arousal exceeded a threshold. Such example studies include thermochromic t-shirts [28,29] and wrist-worn wearables [81,82] representing GSR changes. Findings from these studies indicate that thermochromic material qualities allow for open interpretation of biosensing data and can prompt emotional reflection and regulation i.e. the ability to modulate one's emotional responses [22]. To conclude, most of the biosensing-based affective interfaces rely on researchers' or designers' mapping of physiological arousal to colors and shapes but have minimal involvement from users in the design of such interfaces.

Material Exploration in HCI

An increasing HCI interest in material exploration [14,83] for interaction design has brought digital and smart materials under closer investigation in order to better understand and leverage their unique qualities within the design practice. Such research has not emerged in a vacuum, but builds on Schön's seminal work on designers' conversation with materials [69], and the broader turn to materiality in social sciences [8,25]. In his methodology for material-centered interaction design research, Wiberg [88] advocates a material exploration that should involve working back and forth with materials in order to understand their properties while paying attention to details and how materials may come together in new ways. Other materiality theoretical frameworks emphasize sensorial, emotional [12,19] or experiential and aesthetic qualities emerging through the interaction with materials [32], albeit with a few exceptions [60,76,77] their fieldwork investigation has been limited.

Toolkits for Design or Making of Technologies

Over the last decade, there has been a growing HCI interest in toolkits to facilitate the hands-on making of technologies by non-experts [40]. Toolkits consist of both electronic or non-electronic parts, that can be assembled usually with instructions for the making of a digital artifact [39,43]. Examples include kits with non-electronic parts for making paper-based ambient displays [58] or for communicating and designing for blockchain [35]. The electronic kits have focused mostly on the making of technology such as those aimed at physical visualizations of environmental data [27,39], tracking domestic energy consumption [68], supporting intimacy through flavors [17] and managing anxiety for young people living with autism [72]. Another relevant body of work which has an even longer tradition of empowering novices through the creation of personal prototypes is assistive technologies [26,30,54].

Key findings regarding toolkits to build technological solutions include people's enjoyment of handcraft, personalization [51], their increased understanding of the inner workings of the assembled artifacts [68], and attachment to them [56]. We have seen, however, limited use of toolkits for the design and making of technologies involving personalized representations of physiological data. In contrast, thermochromic materials are low-cost and easy to assemble, allowing also for the design of arousal representations [29,82]. Our work uniquely integrates these two strands of research by designing a toolkit for creating thermochromic visualizations of physiological arousal.

DESIGN OF THERMOPIXELS

Our work aims to design and evaluate a toolkit for representing physiological arousal that may be used by people with limited technical skills. To design the toolkit, we built on previous findings articulating key qualities of thermochromic materials such as responsiveness, duration, inertia, aliveness, range [82], ambiguity [9] and openness [15]. We also engaged in hands-on exploration of thermochromic materials, different heating and insulation materials, as well as GSR sensors. This allowed us to understand the behavior of thermochromic materials under different heating materials and temperature ranges. We studied different shapes of heating materials and their effect on the resolution of thermochromic visualizations [71]; how both these materials can be assembled with an insulation base in a multi-layered approach [33], and integrated with GSR sensors. We also explored different body placements for the sensor, i.e. wrist and fingers, and found the latter to be more responsive [80].

The ThermoPixels toolkit aims to support users to create personalized affective interfaces, visualizing representations of changes in physiological arousal. Its basic components include both digital and physical materials: thermochromic and heating materials, insulation to safeguard from the heat (i.e. wood, clear plastic sheets, cardboard, Velcro and silicon insulation tapes), GSR sensors, and supporting tools, i.e. Crayola markers of primary colors, paintbrushes, syringes, paint spreader for applying the paints, cutters and scissors (Figure 1). While designing the toolkit we aimed for a range of choices for the provided materials achieving a balance between a sufficiently large range to support personalization, and not too large that would overwhelm users.

ThermoPixels: Thermochromic Materials

The kit includes two types of thermochromic material: sheets and paints, which have been previously used for representing arousal [28,29,82]. Although available in a range of actuation temperatures, for safe use around the body, the kit only included thermochromic materials that actuate between 25°C and 40°C. In particular, we included two types of thermochromic sheets: liquid crystal, and rub-and-reveal. Liquid crystal sheets included in the kit change from black to vibrant dynamic colors varying from red to orange, green and blue (Figure 1a) when heated within 25 - 35°C range [92]. The toolkit also contains three types of rub-and-reveal sheets [93] which become translucent, from their default color of either black, red or blue, revealing anything hidden underneath when temperature reaches 28°C (Figure 1b). All types of sheets can be easily bent and cut, and their adhesive backing allows applying them to surfaces such as wood or plastic. The toolkit also contains two types of paints actuating at 31°C [94] (Figure 1c), which can be applied to materials such as paper, wood, plastic or textiles. The first type changes from its default color to another one when heated: purple to pink; sea blue to neon green; orange to neon yellow, and green to neon yellow, whereas the second type changes from its default bright color such as black, yellow, blue, magenta, red, or purple to clear (no color). To summarize, we provided 1 crystal sheet with dynamic change of color, 3 colors for rub-and-reveal sheets, and 10 colors for paints, with a balanced mix of warm and cool colors, which previous findings indicate that may be associated with high and low arousal, respectively [75,87].

ThermoPixels: Heating Materials

The toolkit included four types of heating materials: heating pad (Figure 1d) [95], nichrome wire (Figure 1e) [96], conductive fabric (Figure 1f) [97], and Peltier element (Figure 1g) [98], all previously used to actuate thermochromic materials [9,59,71,82,84]. Heating materials vary in size, thickness, and ability to generate and dissipate heat: Peltier element is rigid, whereas fabric, pad, and nichrome wire can be bent; nichrome wire and fabric can be cut into different shapes and sizes, while the other materials come in fixed sizes. Moreover, the amount of heat produced by the heating elements depends on their size, resistance, and current passing through.

ThermoPixels: GSR Sensor

The GSR sensor measures momentarily changes in human skin conductance caused by internal or external stimuli. Previous work on physiological arousal has reliably used GSR sensors to identify such changes and to trigger color changes on the associated interface when physiological arousal is above a threshold [29]. The ThermoPixels toolkit included a GSR sensor [99] attached to Arduino Uno [100] (Figure 1i), and a power supply. As arousal increases above a threshold [29], the Arduino would automatically close the circuit for power to be supplied to the heating element, ensuring the actuation of thermochromic materials.

CREATING AFFECTIVE INTERFACES FOR AROUSAL REPRESENTATION

To evaluate the toolkit and explore non-technical users’ interaction with it, we conducted 10 hands-on workshops. The ThermoPixels toolkit was designed for people with no expertise in prototyping physical and digital materials to support them represent personalized changes in physiological arousal. Through mailing lists and flyers within Lancaster university campus we recruited 20 participants (11 male, 9 female), (mean age = 27 years, age range 19 - 49 years), (8 undergraduate, 10 graduate students, and 2 employees), with diverse educational backgrounds (5 computing, 5 management sciences, 3 linguistics, 3 physics, 2 engineering, 1 design and 1 religious studies). While 8 had some experience of prototyping, none had experience of working with biosensors or thermochromic materials.

Each workshop session lasted for about 3 hours and included two participants working independently on separate tables. These two participants did not interact with each other during the workshop. Each session consisted of three parts detailed below (Figure 2), and each participant was rewarded the equivalent of a $40 Amazon gift card.

Part 1: Low fidelity prototypes for representations of emotional arousal. Participants were introduced to the concept of arousal as the intensity of both positive and negative emotions. They were asked to sketch representations of emotional arousal using colors (non-thermochromic), as well as changes from low to medium arousal, and from medium to high arousal. The aim was to understand how colors, shapes, and patterns can inform the design of personalized affective interfaces capturing arousal but not valence. Previous work on arousal-based interfaces [82] has suggested the importance of sensitizing participants to the distinction between arousal (as emotion intensity) and valence (as positive or negative emotions) because people’s intuitive understanding of emotions is predominantly built in terms of discrete emotions.

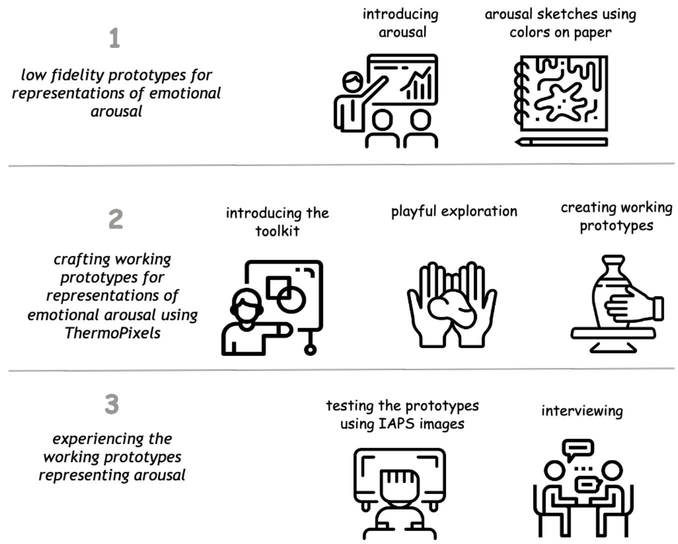

Figure 2: Workshop procedure consisting of three main parts
(Icons: ©Flaticon ©Freepik ©Pause08 ©Smalllikeart ©Justicon ©Smashicons ©Wanicon ©Becris)

Part 2: Crafting working prototypes for representations of emotional arousal using the ThermoPixels. Here, by using slides, participants were introduced to the ThermoPixels: its components (Figure 1), the standard fabrication process of thermochromic-based displays [33,86] and were asked to use the toolkit to create representations of arousal. After the presentation, participants engaged in a playful exploration of the materials to understand their properties while deciding which ones to progress with. In order to facilitate exploration, a researcher was available for each workshop to provide technical support if needed i.e. ensuring electrical terminals are safely connected and operating power supply. Once participants understood how the materials work and behave, they proceeded with the prototype building on their own, by crafting digital materials with physical construction [21] to create affective interfaces representing arousal, whose designs were informed by their color drawings of arousal representations. Each participant was provided with the complete range of thermochromic materials, and only one randomly selected heating material. This was in order to not overwhelm participants with choices, while still allowing for self-expression by keeping the range of colors unrestricted.

Part 3: Experiencing the working prototypes representing arousal. To support the experience of the prototypes, we decided to elicit arousal, which in turn would actuate the thermochromic-based interfaces. For this, participants were shown a set of 12 arousing pictures in random order with an interval of 30 seconds between each picture. The pictures were taken from the International Affective Picture System (IAPS), which has been shown to reliably elicit arousal [41]. In this way, participants could observe the real-time actuation of their prototypes, triggered by changes in their emotional arousal as captured by GSR sensor. The workshop concluded with individual interviews where we asked participants about their experience of using the

ThermoPixels, designing and making the prototypes, challenges, opportunities for personalization, and interests in using the built prototype in their daily lives. Interviews were fully transcribed and participants' experiences with the toolkit were analyzed using hybrid coding approach [13].

FINDINGS

We now describe participants' representations of arousal through colors and their engagement with the toolkit; followed by their exploration of its materials and how this impacted the design and building process of individual affective interfaces.

Low Fidelity Prototypes of Arousal-based Interfaces

Participants generated 20 representations of arousal while coloring on paper, all indicating the saliency of three visual elements representing arousal: colors, shapes (perimeter and area size) and patterns (how colors are applied to create and fill in the shapes). More than three-quarters of drawings were abstract (Figure 4 b-d & i-l), while the remaining 4 were representational and inspired by metaphors of arousal from nature, medical (ECG waveform in Figure 4a) and culture (symbols). P1, for example, associated high arousal with a high tsunami wave (Figure 3h): "*its blue color high tsunami wave. It is very strong that goes high […] which is aggressive, high, strong and bold*".

An important outcome is the two distinct types of representations that participants drew. One group represented arousal the way they understood it, while the other group represented arousal the way they would have liked the interface to respond to their arousal, or in other words how they would prefer to be helped by the interface to regulate their arousal.

We now discuss the use of colors and shapes by each group. The first group consisted of 14 participants, 13 of whom (P2, P3, P4, P5, P6, P8, P11, P12, P14, P16, P17, P18, P19) (9 Male, 4 Female) have used predominantly warm colors such as bright red; angular or sharp shapes such as squares, triangles, peaks, or spikes; and rich patterns such as those with multiple overlapping lines. The remaining one (P1) used sharp blue bigger shapes signifying height. The aim of these representations was to increase the awareness of one's high arousal as shown by four illustrative examples in Figure 4 a-d. The second group consisted of 6 participants (P7, P9, P10, P13, P15, P20; 5 Female, 1 Male) who used predominantly cold and muted colors such as green, blue, purple, pink, or white; soft shapes such as circles or ovals; and low density patterns involving limited lines like those created through large strokes. The aim of these representations was to regulate one's high arousal (Figure 4 i-l). For example, participant 9 describes her choice of color to regulate negative feelings and calm herself down: "*I used green to represent high arousal […] to let me know the intensity of the mood and feelings, and like to keep me in check whenever I am a bit too angry or too sad. If you know that, you can easily just fix it or ask you friend for help*" [P9]. This activity helped participants create associations between arousal and colors, shapes and their sizes: "*I think it's interesting how I personally made connections between different shapes and colors and sizes as well to emotions and also to arousal levels. Because, in my mind, I have these specific thoughts of how sharpness is more to angry side, to the fearful side as well, whereas softer shapes are more of a relaxed state*" [P20]. As this quote illustrates, people tend to think about arousal through discrete emotions. This is an important outcome, as arousal is a theoretical construct [62], not easy to grasp [82], so any interface supporting people to realize the distinction between arousal and valence would help revise less accurate mental models of arousal.

General Engagement with the ThermoPixels Toolkit

Findings indicate that participants enjoyed the experience with the ThermoPixels, describing the making of interfaces as "*straightforward and easy*" [P1, P3, P6, P14, P18], "*creative*" [P2, P12, P18, P19], "*fun*" [P4, P8, P9, P10, P15, P16, P18], "*engaging*" [P4], or "*playful*" [P7, P10, P11]. They also loved the opportunity to express themselves: "*I really enjoyed it because […] I was expressing some part of me there. I felt like a child because these things change color and they are magic"* [P7]. Participants also enjoyed creating an artifact from scratch and described the making experience as rewarding: *"it was pretty straightforward, easy enough to build, and entertaining to do and more so because you don't expect a physical object to actually describe how you feel so the experience was rewarding in the end"* [P3].

We also identified two motivations for engaging with the workshop. First, there was the desire to learn more about their emotions, expressed by 10 participants (6 female, 4 male): *"It was really fun and playful. I came here just to find out more about my emotions, how I am going to react to different things"* [P11], and potentially build something that they might use in daily life: *"I'd like to build something that can be useful during my work and my life and I can take it with me so I can see my current emotional status to make my response more reasonable. Not like, always angry if I'm not happy"* [P13]. This quote illustrates the interest in the interface's ability to also support the regulation of a potential negative emotional response. Interestingly, all the participants aiming to regulate emotions in the second group belonged to this category. The second motivation relates to the desire to make something with one's hands expressed by 10 participants (7 male, 3 female). While these experiences and pleasure of tinkering are often associated with making practices [68,85], the interest in learning more about one's emotions is particularly interesting.

Playful Exploration with the ThermoPixels' Materials

ThermoPixels motivated the use of play and the body to realize the material properties of the toolkit's components. Participants' journey with the materials started with their playful exploration through touching, feeling, bending, stretching, and placing them on the body to feel them and get to know how they behave. This exploration was important as the toolkit's materials were unfamiliar for most participants, and it continued throughout the entire workshop. Below, we discuss such explorations in detail.

Thermochromic Materials

Thermochromic materials were especially interesting to explore because of their unfamiliar color-changing features which participants tried to understand: "*first, I played with colors of thermochromic sheets and paints by warming them with hands and exhaling air onto them, because I had to check how they were going to change"* [P7]. They first explored actuation temperatures. As most thermochromic materials could be actuated close to the body temperature, participants used this affordance to actuate them by a range of *bodily interactions* such as placing hands on them (Figure 3a), tapping them, holding and pressing, rubbing, or even blowing warm air onto them (Figure 3b). These interactions for actuation offered an opportunity to experiment by observing the impact of bodily interaction on the change of color: when and how it appeared, and how and when it disappeared, or when the material returned to the original state. Several participants described this experimental tinkering with thermochromic materials as "*scientific*" [P14], "*surprising"* [P11], "*lots of fun*" [P18], and the range of actuations as interesting to observe: *"we had some really animating materials with lots of different colors. It was really interesting to see how all different things responded to heat"* [P10].

We now look at the specific material qualities that emerged as important through participants' exploration. The placement of the thermochromic sheets on top of other materials was perceived as easy to work with because of self-adhesive properties, and participants engaged in experimenting with these sheets in order to actuate them. Such experimentation involved placing a non-thermochromic paper with different colors and patterns on it, underneath the rub-and-reveal sheet (Figure 3h) and rubbing its surface to reveal the colors and patterns. Although limited in range of color (black), the liquid crystal sheets were perceived as alive when actuated, through their quick fluid-like pattern of color change, which can be perceived as high resolution flows of red, orange, green and blue colors (Figure 3c): "*the paint was much more easy but less alive compared to the liquid crystal sheet. I wanted something more alive and liquid crystal sheet could make it"* [P19].

In contrast, thermochromic paints are colorful viscous liquids requiring a different range of interactions to explore their actuation such as applying the paint on a paper using paintbrushes, letting it dry and then applying bodily temperature. This allowed participants to watch the changing of paint's color. As opposed to thermochromic sheets, the paints were available in a larger variety of colors which allowed for a more extensive exploration and an easier identification of the preferred color. They slowly change from one color to another or fade away when heated and take time to come back. Participants enjoyed the painting process using a brush and trying out different colors: "*the painting is very fun; you heat it then it goes from one color to another or go to clear. That's a lot of fun*" [P18]. They even engaged in combining them in different ways by juxtaposing or painting them side by side on paper, or by mixing the color first and then paint the new combined colors to watch their actuation. The change of color through the actuation of thermochromic paints tended to be slow, involving uneven color patterns with blurred boundaries, of limited brightness and resolution (Figure 3d): "*I loved how the color changed and moved over. That was really organic and beautiful"* [P10]. Thermochromic materials offer arguably a particularly embodied exploration as their actuations could be triggered by the body's temperature, visually experienced as having an aliveness quality and perceived as aesthetically pleasing.

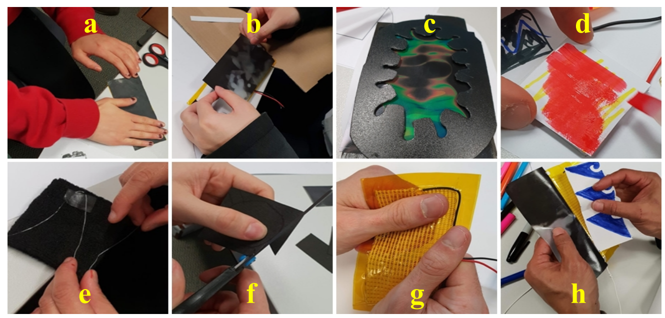

Figure 3: a-d (thermochromic) and e-h (heating) materials

Heating Materials

While the thermochromic colors offer the visible layer of the affective interfaces, the heating materials are concealed, playing however a key role in the pattern and shape of the actuated colors, as well as their temporal unfolding. Participants started their exploration of heating materials by connecting them to battery terminals; and by bodily experiencing the changes in their temperature, triggered by changes in the intensity of current passing through them. This bodily experience involved placing the heating elements on hands or arms (Figure 3g). In their exploration, participants played with both minor and larger changes of current intensity to feel the material's temperature going up and down and even attempted to identify the highest bearable temperature, at which point they would switch off the battery and wait for heat to dissipate. Participants also experimented with different combinations of thermochromic and heating materials by varying the current intensity in order to watch its impact on the actuated changes of colors, their speed and pattern movements.

We now look at the heating materials. The nichrome wire allowed for different interactions as participants cut, bent, twisted or shaped it (Figure 3e). However, its elasticity i.e. quickly returning to its shape, made it difficult to handle and attach it to other materials. For instance, P5, who shaped the wire in a 3D form by using a cylinder made of plastic sheets describes his frustration: *"I like heating wire to be able to create new shapes which I was very pleased with [...] the* *wire was difficult to attach to the cylinder and I was disappointed by that*” [P5]. Moreover, participants also found it difficult to create shapes with a larger surface area since this would require an increase in the wire’s length, which in turn would need more current and time to actuate. All participants working with the nichrome wire understood this constraint and kept the size of the shape made from the wire small.

Unlike nichrome wires, Peltier elements are square-shaped metal modules. They generate, almost instantaneously, heat on one side and cold on the other. Participants could immediately feel the heat and cold as they turned the Peltier element on and appreciated its immediate responsiveness. In contrast, they perceived the fixed shape and size of Peltier element as limiting the expressiveness of their designs (Figure 3d): “*I like the fact that it heats very fast, but I would like to have other shapes. It's just a square; too simple*” [P7].

Both the heating pad and the fabric are soft, textile-based materials, with reduced thickness, so they can be easily bent and shaped. While the fabric can be cut into any desired shape (Figure 3f), the heating pad has a fixed size and shape (Figure 3g). As a result, participants created different shapes out of the fabric by cutting it, while realizing that the surface area of the fabric determines how quickly it heats and cools down, i.e. the larger the surface area used, the longer it takes for heat to build up and dissipate. P8 created a rectangular surface by cutting the fabric and connected it to battery terminals and tried changing the current while placing the hand on the fabric to feel how long it takes for heat to appear and disappear: *“the fabric has a strong heating limitation. It takes time for heat to build up and then cool down. I wanted to see how if it can heat quickly like the other materials, but it couldn’t […] still it is cool to see the limitations”* [P8].

GSR Sensor

The GSR sensor has two electrodes which could be easily worn on the fingers, although this placement was described as uncomfortable after extended use. Participants wore the sensor on their fingers to understand how the real-time GSR signal shown on an auxiliary screen changed over time. They explored how they can deliberately actuate the GSR sensor by holding their breath or moving their fingers: “*the sensor is quite sensitive you know, you move [the finger] a little bit [and] it triggers [data change]*” [P1]. Through experimentation, some participants realized the more nuanced connection between emotions and perspiration, and that intense sweating may not necessarily reflect emotional arousal: “*I sweat a lot [so] how exactly can you measure arousal states?”* [P20].

Participants also wanted to find out the impact of other external or environment factors on the GSR sensor, the accuracy of its data, and its impact on the thermochromic materials connected to it: “*if we are outdoors and our fingers are cool, it would affect the sensor as well, it will need much time to get heat to get a good result [color]"* [P1]. Through experimentation, participants became aware of how the GSR sensor works in combination with other materials. Once participants figured how these materials work together, they tried to combine together the three basic components, often through trial and error and learning from mistakes. They examined the physical, thermal and electrical properties of the materials, realizing their constraints and potential and how they are to be combined together.

Crafting Working Prototypes of Arousal-based Interfaces

A key finding is two distinct motivations for designing the interfaces and their representation of arousal: for awareness or for regulation of high arousal. Participants built 20 different prototypes, three-quarters of which directly resembling their drawings while the remaining merely inspired by them. Interestingly, only half of prototypes were built to be used as wearable artifacts as wristbands shown in Figure 4e, g & m, clothing-based displays (Figure 4f), and accessories: necklace, and ring, In contrast, the other 10 were intended as ambient (on lamp) or decorative artifacts such as on bags (Figure 4p) or mobile sticker (Figure 4h).

Awareness of Increased Arousal: Angular Shapes, Warm Colors, and Rich Patterns

When converting drawings into prototypes, participants started with their heating material since its shape determines the visual representation of arousal, i.e. where on the interface, and how the colors would change [33]. In prototypes with angular shapes and warm colors to signify an increase in arousal (Figure 4e-h), participants used both

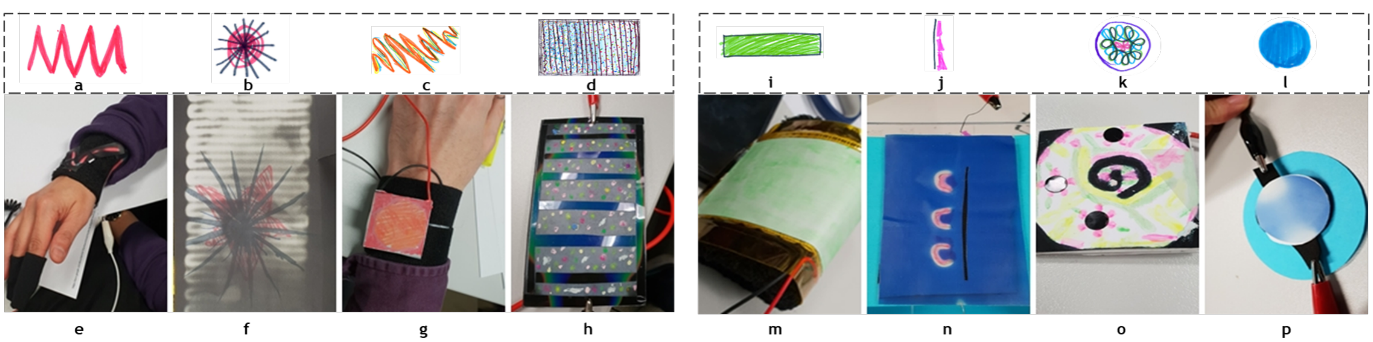

Figure 4: Participants drawings for high arousal using colors (a-d; i-l) and prototypes created using the toolkit (e-h; m-p): e) nichrome wire [P2] f) heating pad [P6] g) Peltier [P19], h) fabric [P8] m) heating pad [P9] n) nichrome wire [P13] o) Peltier [P7], p) fabric [P15]

heating materials and colors to create shapes. Heating elements are actuated by electric current, in turn actuating the thermochromic material through the generated heat at points of contact.

Through interaction with nichrome wire, P2 created a one dimensional (1D) sharp angular shape (wire weaved but not bent at 360 degrees) (Figure 4e). Similarly, P5, represented the increase of arousal using wire carved in a 3D shape (wire weaved in height creating sculptural shapes) which resembled spikes as the physical form was deemed more important than color: "*I was more concerned about the shape rather than the colors. I discovered arousal may resemble a particular form and I wanted to reproduce it"* [P5]. In contrast to nichrome wire, the use of fabric was not particularly creative in the creation of shapes, despite offering more affordances. When interacting with the fabric as heating material, participants created basic geometric shapes such as rectangle (Figure 4h) and triangle [P3]. The remaining heating materials, i.e. the Peltier modules (Figure 4g) and heating pads (Figure 4f), were of fixed shape and size and thus could not be changed.

Alongside heating materials, participants also used colors to create shapes and patterns. P2 and P6 (Figure 4e, f) used red and angular shapes hidden under rub-and-reveal sheet: "*it's red and it's very sharp it means arousal is very high*" [P2]. P19 created a red-colored big angular shape on the Peltier (Figure 4g) and covered it with a black rub-and-reveal sheet. Other than red and angular shapes or height in terms of placement within its frame, participants used patterns of mixed colors to represent increasing of arousal. P8 used mixed colors combined in a pointillism technique of painting with small dots of different colors on top of the fabric (Figure 4h). As the fabric slowly heats up, it creates an interesting mix of animating colors symbolizing "*more*" [P8].

Regulation of High Arousal: Round Shapes, Cool Colors, and Light Patterns

The second group of prototypes (Figure 4m-p) were created using round shapes, cool, muted colors and light patterns to regulate high arousal negative emotions. Findings indicate that participants' use of round shapes, cool, muted colors and light patterns aided by the slowness of thermochromic materials and coupled with in-the-moment interaction were meant for the decrease of high arousal negative emotions [36]. For instance, participant P13's creation of three small flower-shaped curves using nichrome wire to represent three levels of arousal i.e. low, medium and high, was particularly interesting (Figure 4n). She painted purple to pink thermochromic paint on top of and around the wire. Each curve could be separately turned on to reveal pink underneath and to show three levels of arousal: "*I need to control my emotions sometimes. I'm so angry sometimes. I think it [three levels representation] would help me […] to change it*" [P13]. Similarly, P5's blue to green changing wristband created with Velcro tape (Figure 4m) and P15's circular blue handbag sticker (Figure 4p), made with heating fabric and hosted on a double-sided tape, were meant for the regulation of high arousal negative emotional responses. P7 used bright multicolor (green, pink, yellow) curvilinear patterns on top of Peltier element as a way to calm herself down. She even used small circular patches of thermochromic liquid crystal sheet on four corners of square-shaped Peltier to make it look circular (Figure 4o): "*If I get angry at work or very frustrated, I would use it to hold it in my hands and if it gets too bright […] I would use it just to see if it's true or even just forget about the frustration"* [P7].

Understanding Actuation: Arousal Awareness and Responsiveness

The toolkit successfully guided the meaning-making process for understanding arousal and exposed the material challenges that emerge in the creation of arousal representations. Actuations, either through electrical current or through GSR changes were associated with participants' efforts to understand arousal and its coupling with the toolkit's materials.

Richer Understanding of Arousal

An important finding is that by working with, and experiencing the toolkit's materials, participants developed a richer, visceral understanding of arousal, and its decoupling from valence. P13 created three small flower-shaped curves to represent three levels of arousal (Figure 4n): "*my prototype doesn't show if my emotion is negative or positive it's just like the different intensity levels*" [P13]. This quote is important, suggesting the understanding of the rather challenging to grasp distinction between emotional arousal and valence. This benefit may be particularly explored through the toolkit's components that can deliberately inspire multi-level representations of arousal [82]. Since individual colors are more likely to be associated with discrete emotions, 4 participants (P7, P8, P10, P20) decided to avoid individual colors and instead used color mixture as illustrated in Figure 4c: "*I started out with black which is the absence of arousal. The rainbow of colors that come through the paper [liquid crystal] represents different kinds of emotions […] as that heats up that changes the color into wonderful morphos crystalline effect that sort of flows through the black thermochromic paper. I particularly like that because I think arousal sort of flows, comes and goes*" [P10]. Other participants also realized the distinction between arousal and valence, but only when experiencing the actuations through the IAPS pictures [41]: "*when I saw pictures and it made me angry and some pictures could make me at peace"* [P17].

Arousal and Responsiveness

We now describe participants' reflection on heating materials' responsiveness to physiological changes, and how this quality supported or hindered the communication of changes in arousal. Participants commented on its speed of actuation and de-actuation, and how it might relate to the raise and decay of triggering emotions. Participants using the Peltier heating elements, described it as very fast, whereas emotions are gradual: "*[Peltier] heated up too fast. […] was* *too binary. I like the idea of the change being kind of very slow. I have this idea of emotions that it is quite gradually changing"* [P4]. On the contrary, the increase of heat in the fabric and its dissipation was slower. Participants sometimes tried to change the speed of actuation by controlling the input current to the heating material. Thermochromic materials actuate when heated up, and de-actuate as heat dissipates. This means that while the starting point and speed of the actuation can be actively controlled by the current intensity and thus increase in heat, the de-actuation was outside participants' control. All participants reported this limitation of heating elements: "*I don't know how long it would take from being actuated and back to the original status again*" [P13]. This outcome highlights the importance of controlling the material's de-actuation time to signal the lowering of arousal.

Personalization through Handcrafting

Findings suggest that participants' personalization of arousal representations, handcrafting digital and physical materials, contributed to attachment with their designs, increased agency and understanding of technologies' inner workings.

P10's investment for injecting personal meaning into the interface design, has led to attachment with their crafted hybrid artifacts: "*it is my shape that represents arousal to me. It's my choice of colors. So, it speaks directly to me"* [P10]. The sense of authority and expression of self for P14 was particularly interesting: *"I think it was empowering, because really, emotions are, like, totally subjective things […] the whole process of decision making was from me, whether I was conscious about the decision making or subconscious about it... I feel this was a kind of embodiment of myself, how I approach my emotions"* [P14]. The process of exploring, creating and representing physiological arousal and by working around constraints of materials led to a clear understanding of how the materials behave and work as a whole. Such understandings of inner workings of the toolkit, i.e. how it works and how it may be fixed, meant being able to change the representations: "*I would love to build it for myself, I can create new representations of arousal for everyday*" [P17] and feeling of satisfaction after completing it: "*I felt sense of achievement, […] proud […] that I built it with my own hands and it was actually working*" [P12].

DISCUSSION

Reflecting on the findings from our study, we understood how participants explore and understand ThermoPixels' material qualities, their representations of arousal and how they experienced them. We now discuss design opportunities in order to expand future research on affective interfaces.

Embodied Exploration: From Assembling to Creative Expression

Findings indicate that complex technologies such as affective interfaces can in fact be crafted by people with limited technical skills, allowing for increased personalization and creative expression. This is an important outcome as, traditionally, toolkits provide a range of materials allowing people to assemble their components according to provided step by step instructions. This process leads to similar outcomes, leaving little room for personal expression and creativity [39,68]. In contrast, the ThermoPixels toolkit does not rely on assembling instructions but its provision of digital and physical materials enables open-ended exploration through hybrid crafting [21].

ThermoPixels' users often used their own bodies to explore with, and express their arousal through the toolkit's hybrid materials. They used the body both as an *actuating tool,* i.e. bodily heat to change the color of thermochromic materials, and as an *actuated tool,* i.e. changing current to feel the heat, shifting the role of the body as an input and output material. This type of engagement helped understanding the potential and limitations of materials in a richer, embodied way. The embodied engagement was not planned by us but happened spontaneously during the workshops through such bodily actuations and choices of materials. This became crucial in understanding the different material qualities, such as the aliveness of color change and its responsiveness; the time for heat to appear and dissipate and the impact of the heating element's shape and its heating qualities; the changes in GSR signal due to perspiration and ambient temperature. Moreover, these bodily actuations and prototypes' actuation through real-time physiological changes were particularly engaging. Existing HCI work on art therapy and crafts suggests the value of such practices for increased self-awareness [42]. Toolkits have been studied as creation tools for engagement and attachment to handmade artifacts [56]. However, they do not often allow for personal expression. In contrast, ThermoPixels enabled open exploration of its materials and their affordances, which led to creative expression through bodily engagement by giving equal importance to the process of creation as to the product of it. Future work will explore the impact of such personalization for adoption and long term use, possibly beyond the ones worn on the body integrating personal and public displays [10,11,38]. The leverage of bodily-based expressiveness for communicating affect has recently started to inspire novel design emphatic methods [67] and ThermoPixels may also be further explored for such purpose.

From Arousal Representations to Emotion Regulation

Our findings highlighted two important uses of the toolkit. ThermoPixels was used to design affective interfaces for both expressing and regulating emotions, each of these representing key skills for effective functioning in everyday life and emotional wellbeing [22,23]. This is a key outcome, as such interfaces have been predominantly developed by researchers in parallel strands of work. In contrast, our findings indicate that end users can engage in the hybrid crafting of affective interfaces, flexibly using the same materials for either of the two purposes.

Compared to prior work on visual interfaces for emotional expression and regulation, participants using ThermoPixels did not only create simple geometric shapes

[15,29,47,50,82], but also used the materials provided in the toolkit to create complex non-geometric shapes and patterns in 2D and 3D. Participants who designed interfaces for expression used warm colors such as red or orange, angular shapes, and dense patterns, whereas, participants motivated by the desire to regulate arousal chose to work with cold colors, round shapes, and less dense patterns. The ThermoPixels toolkit can be reflected upon in the context of the emerging frameworks for emotion regulation that employ physiological data to enable users to create their own haptic feedback patterns [52,53], by modifying their intensity or duration. ThermoPixels, instead, makes use of visual color-based materials both for expression and regulation by leveraging material exploration and hybrid crafting supporting users' stronger agency and self-expression. The regulation of emotions goes beyond expression, as knowing which emotions are being seen, and to what extent, is part of being in command of the emotions as they are experienced. The use of biosensing technology to regulate emotions has been previously explored [6,18,49]. Participants' design choices and their value for regulation has been previously addressed through findings indicating that cold colors and simple, curvilinear shapes are seen as soothing [2,3,36]. Using the toolkit motivates discussion on affective interfaces, letting users own and get attuned to both emotional awareness and regulation by involving them in the design process. However, its future use in design workshops should involve taking further steps in sensitizing participants to the challenges and benefits of each of these skills in contexts in which affective interfaces are to be designed for. The function of each affective interface and its scenario of use will need to be mindfully considered by participants to best suit their specific emotional needs, i.e. contexts in which vulnerable people experience power imbalance may benefit less from emotional awareness and more from regulation if they perceive the imbalance as high risk of being challenged; and may benefit more from emotional expression if they feel ready to challenge the imbalance.

Empowerment: From Actuation to De-actuation

ThermoPixels' users were able to grasp the distinction between arousal and valence. Previous research indicates that people often relate the emotional intensity i.e. arousal, to its polarity i.e. valence, and find it hard to differentiate them, even when explicitly told what these two concepts mean [82]. Participants' understanding of arousal was reflected in the representations they produced, i.e. three levels, use of increasing and bigger shapes suggesting intensity, and multiple colors to point out that arousal does not refer to discrete emotions but their intensity. Moreover, in their exploration participants became aware of the limitations of thermochromic and heating materials and the effect of sweating and movement on the GSR data. Heating materials were particularly interesting because participants could control their actuation but not de-actuation, which meant colors would only come back when the heat dissipated naturally. Thus, participants could question the prototype's actuation, i.e. either triggered through physiological arousal or because of the materials' limitations, giving them authority over the interface. Work on thermochromic color changes representing physiological arousal shows that people misinterpret the slowness of the display with the persistence of feelings, and invested an alarming degree of authority in the display rather than critically questioning it, as they were unaware of the underlying technology and how it works [29]. However, this was not the case in ThermoPixels' exploration as participants understood physiological arousal and the mechanics of the materials i.e. how they behave individually or when molded together to create a working interface.

ThermoPixels does not allow the de-actuation control which participants felt the need to, and future work should include active control of heating elements' de-actuation. For example, for Peltier element this can be achieved by changing the direction of current [44]. Future explorations of the toolkit should look into participants using two or more heating elements. The toolkit in its current form only contains color-based materials, but further extensions could include haptic actuators, i.e., vibration and temperature for multimodal feedback on affective states. To this end, we are inspired by couplings of biodata to body actuation [1] that draw upon somaesthetics. Compared to prior work on affective interfaces [29,82], ThermoPixels aims for empowering its users by allowing them to create personalized visual arousal representations and understand how these relate to their bodies. Prototypes, confronting arousal meaning making, enrich our work [81,82] beyond the wearable space. We propose that future work on affective interfaces developed by less technical users through hybrid crafting should also encourage a thorough exploration of their affordances and limitations before they are deployed in everyday life settings, to create a space for open critique and affective sense making.

CONCLUSION

We designed ThermoPixels, a toolkit containing thermochromic and heating materials, as well as GSR sensors measuring physiological arousal. The toolkit was explored by 20 participants with limited technical skills to create representations of arousal through colors, shapes and patterns. We found that participants were able to engage in creative exploration and build working prototypes of affective interfaces for both awareness and regulation of arousal, while using different visual elements such as color, shapes and patterns. We call for designers of affective technologies to empower end-users by involving them in the design process through embodied material exploration of toolkits like ThermoPixels that allows for richer understanding of arousal, personalization, and ownership.

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