Emotion Through Motion: How Shape-Changing Jewelry Conveys Emotions

Anke Brocker
RWTH Aachen University
Aachen, Germany
brocker@cs.rwth-aachen.de

Felix Kasteel
RWTH Aachen University
Aachen, Germany
felix.kasteel@rwth-aachen.de

Sören Schröder
RWTH Aachen University
Aachen, Germany
s.schroeder@cs.rwth-aachen.de

Heiko Müller
University of Oldenburg
Oldenburg, Germany
heiko.mueller@uni-oldenburg.de

Jürgen Steimle
Saarland University, Saarland
Informatics Campus
Saarbrücken, Germany
steimle@cs.uni-saarland.de

Jan Borchers
RWTH Aachen University
Aachen, Germany
borchers@cs.rwth-aachen.de

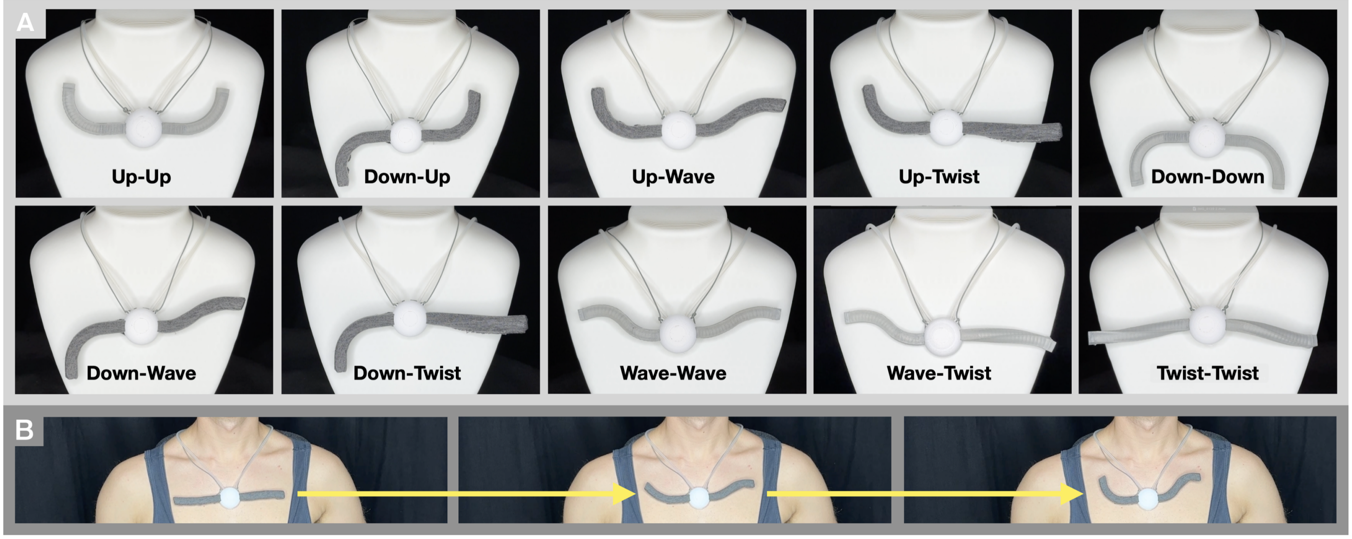

Figure 1: We conducted two user studies to examine how motion parameters of wearable shape-changing jewelry influence conveyed emotions for both observers and wearers. Participants tested a necklace that featured a 3D-printed round pendant with two pneumatic actuators, capable of executing specific motions via compressed air. Study 1 investigated the motion parameters of cuboid-shaped actuators systematically using videos to observe five basic motions (*bend up, bend down, wave, twist, elongate*), showing that motion type, speed, repetition, and amplitude can be isolated as factors that deliberately convey an emotional state. Study 2 evaluated the most salient factors using combined basic motions that participants first rated while wearing it (part B image above shows the motion *Up-Twist*) and then observed it in real (cf. part A image above). Symmetrical actuations were identified more accurately and received higher valence and arousal ratings. The image depicts our shape-changing wearable necklace prototype. Top: The ten different movement combinations from Study 2. Participants first felt these themselves as wearers, then saw them on a mannequin as observers. Bottom: The necklace executing an *Up-Twist* shape change while worn by a person. The wearable consists of a 3D-printed round pendant and two pneumatic cuboid soft finger actuators, inflated via thin tubes that also hold the necklace in place around the neck. We provide details of our process to design and fabricate actuators that actuate consistently enough for such studies.

Abstract

Shape-changing wearables are known to convey emotions to wearers and observers, and jewelry is commonly worn for self-expression and to be seen by others. But how do individual shape change parameters impact the emotions communicated? In a first study, participants observed a shape-changing necklace; the second included wearing it. The necklace uses pneumatic finger actuators; fabrication details are provided. We systematically varied motion type,

CHI '26, Barcelona, Spain

ACM ISBN 979-8-4007-2278-3/26/04
https://doi.org/10.1145/3772318.3791295

speed, amplitude and repetition, and exterior material to analyze emotions using Russell's circumplex model. Additionally, we asked users what they associated with each shape change. We found some surprising relationships between shape change parameters and the *valence* and *arousal* levels of emotions wearers and observers perceived. Symmetrical actuations were recognized more accurately and received higher valence and arousal ratings. Interestingly, even when wearers, who only felt motions, misidentified them, their ratings matched those from observers. Our findings support creating shape-changing interfaces that communicate emotions more precisely.

CCS Concepts

• **Human-centered computing** → *User studies*; **Empirical studies in HCI**; *Displays and imagers*; *Haptic devices.*

Keywords

shape-change, conveying emotions, wearables, jewelry, soft robots, valence, arousal, associations

ACM Reference Format:
Anke Brocker, Felix Kasteel, Sören Schröder, Heiko Müller, Jürgen Steimle, and Jan Borchers. 2026. Emotion Through Motion: How Shape-Changing Jewelry Conveys Emotions. In *Proceedings of the 2026 CHI Conference on Human Factors in Computing Systems (CHI '26), April 13–17, 2026, Barcelona, Spain.* ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3772318.3791295

1 Introduction

Wearable shape-changing interfaces are interactive devices that dynamically alter their physical shape for input or output. They pose numerous fundamental HCI research challenges regarding their design, implementation, and user experience [2]. They also expand our hardware design palette to create novel interactions, such as in haptics [5, 89] and personal fabrication [1, 5].

While one purpose of shape change is to convey information [2], research on communicating emotional states through it to the wearer and others is scarce. Shape-changing objects can convey an emotion [13, 88], and even different emotions [19, 32, 76, 85]. However, a detailed analysis isolating the various parameters on both sides of this effect is missing: the underlying fundamental parameters of shape change, such as repetition, amplitude, motion type, and visible surface material on the one hand, and the different aspects of the resulting emotional state that the shape change communicates on the other hand. We also lack an understanding of how the modality (feeling vs. seeing the shape change) impacts these effects.

We thus decided to investigate how fundamental design parameters of a shape-changing wearable influence valence and arousal levels of emotions conveyed to observers and wearers. To the best of our knowledge, this is the first study to address this question systematically.

Hence, we conducted two studies to isolate the effects of individual parameters of a soft shape-changing actuator on these different aspects of emotions conveyed, and to explore the differences between these effects on wearers who only *feel* the shape change and observers who only *see* it. Note that this is not about the wearer's or observer's own emotions; we studied what kind of emotion they thought each shape change *conveyed.* We analyzed those emotions according to their *valence* and *arousal levels* following Russell's established *circumplex model* [15, 74, 78]. It defines emotions by a linear combination of two dimensions: *Valence* describes whether an emotion is positive or negative, while *arousal* represents the range of the emotion from calm to excited. We also asked participants what they associated with each shape change to help us interpret our quantitative findings.

Isolating the impact of these characteristics helps researchers and practitioners understand how wearable shape-changing interfaces convey emotions and how perceptions differ between the wearer and the observer. This helps utilize shape change as an interpersonal communications layer for wearables. For wearable interfaces on the skin, comfortable, flexible, and safe mechanisms are crucial. Hence, we decided to use soft robot actuators to render motion, as those allow gentle and naturalistic [11] movements that can support subtle interpersonal communication. When integrated into wearables, they also tend to exhibit higher social acceptance than rigid alternatives, as their interaction with the environment is safer and more tolerant [45]. Our study focuses on finger actuators, a fundamental soft actuator of many shape-changing interfaces [7, 73, 86] and frequently used for bending and gripping tasks [63, 99]. Our soft robots utilize cuboid finger actuators, whose non-rotation-symmetric shape allows for all basic motions in our user study to be easily noticeable (cf. Sec. 3.1.1). Additionally, this should help others conclude what emotions more complex objects composed of such building blocks, like ChainForm [57], might convey when worn or seen. Choosing this basic shape also lets other researchers rebuild our actuators more easily for replication and follow-up research.

To ensure our study treatments were comparable, we required soft actuators that could perform motions with high levels of consistency. To this end, we developed a software toolkit for the parametric creation of design files and an associated fabrication workflow for our soft actuators, which we make available in the supplements.

Our wearable serves as both display and haptic interface. Wearable displays often take the form of clothing or jewelry, yet neck-worn artifacts have received comparatively little attention [98]. We chose a shape-changing necklace (Figure 1) as a form factor for our wearable interface[40, 55] because jewelry is commonly worn to be seen by others and already lets wearers express themselves [93], thus typically fulfilling an aesthetic and communicative rather than a functional goal. The neck has dense touch receptors, suitable for perceiving motion patterns via soft robot actuators [53, 98]. Since a necklace is worn on the neck, it is well-suited to display personal information such as emotions and can easily be seen by an observer. Even more, compared to other jewelry pieces such as bracelets or rings, a necklace is perceived as more personal [71].

In Study 1, we show participants videos of our physical prototypes actuating. This ensured that participants saw consistent movement behavior, despite our early soft actuator prototypes lacking closed-loop control [95]. By our second user study, we could control the actuators consistently, and participants experienced the actual necklace live, first by wearing it themselves to feel the actuations, then as observers by watching it actuate on a mannequin. Study 2 also used the findings of Study 1 to select the most salient conditions and focus on those that promised particularly interesting results. We report effect sizes and confidence intervals (CI) based on the *estimation approach* [17, 22] for a more complete picture in combination with the associations users reported.

Our results from Study 1 show that the connections between motion parameters and valence and arousal of conveyed emotions are complex, although users' associations help untangle them: Repetitive movements particularly increased arousal and valence ratings, while movements without repetition were associated with human facial expressions, like a smile or lifted eyebrow. We found categories for both dimensions for the *motion type*. For example, the *wave* motion conveyed more excitement (higher arousal ratings) to the observer than all other movements. Associations also exhibited a grouping of motion types: *up* and *down* movements were associated with humans, *elongate* and *wave* movements with concepts from nature. In contrast, *twist* was mainly associated with objects. Interestingly, motion repetition influenced the arousal level, but in a different order than what we had found in prior research. Also, high speed repetitions were often correlated with gestures. This explains their high arousal ratings, as gestures can indicate excitement quite well. Larger motion amplitudes correlated with the valence of a conveyed emotion, and participants associated larger amplitudes with social interactions.

Study 2 confirmed that repetitive motion increases arousal ratings, with live motion increasing ratings even more than videos. Participants observed the pendant and actuators as a whole when observing the necklace. They associated human beings more often with the motion when observing than when wearing the necklace, where motions were linked more often to emotions and actions. Symmetrical actuations were identified more accurately and received higher valence and arousal ratings, both for observing real shape changes and when wearing the necklace. Remarkably, even when participants misidentified motions by touch alone, their ratings were still similar to those of observed motions.

We derive design implications, such as using repetition to convey a more exciting motion to the observer and the wearer, or symmetric and asymmetric motion when designing shape changes to convey specific emotions. In summary, our key contributions are:

- Results of a first user study using videos of a shape-changing wearable to investigate the effects of shape-changing parameters (motion type, repetition, repetition, amplitude, and visible surface material) on the *valence* and *arousal levels* of emotions conveyed to observers. This includes analysing participants' associations with each shape change.
- Findings of a second user study letting participants wear the shape-changing necklace first to report what motion they felt and what emotion(s) each motion conveyed to them, and then observing it actuate live on a mannequin.
- The design process and software for creating our soft actuators to support replication and further research.

In the remainder of this paper, we review related work before presenting our two user studies on observing and wearing the necklace. We conclude with limitations and future research directions.

2 Related work

We review related work on communicating emotions, shape change and communication, shape-changing actuators, and smart jewelry in the context of shape change.

2.1 Communicating Emotions

Research into the communication of emotions is ongoing in HCI. Measuring emotions is not trivial, but we can benefit from measurement models that have evolved in behavioral science [15, 74, 78]. In particular, due to its reliability and simplicity, the *circumplex model* by Russell [74] is used widely in HCI research [69, 83, 85, 92]. It places emotions into a two-dimensional space created by the two orthogonal axes of *valence* and *arousal*. Valence describes whether an emotion is positive or negative, while arousal ranges from calm to excited [18]. Compared to other categorical approaches (e.g., [15]), the circumplex model better represents the emotional state [14].

Particular interest in communicating emotions can be found in social robots [8, 32, 83]. These are frequently equipped with anthropomorphic features to convey emotions to others, though researchers have also explored more abstract forms, such as textiles [19] and tactile displays [92]. Similarly, van Waveren et al. [91] investigated how different materials used for the exterior design of a social robot affect the extent to which users perceive it as positive and warm. Adding technology to fashion and garments turns them into communicating elements that can also embody emotions [90]. For example, Neidlinger et al. [61] created technology-enhanced clothes that let the wearer display inner states via shape change. Tan et al. [88] found that shape-changing objects can communicate basic emotions to humans. In two online surveys, Davis et al. [20] explored how to design a textile panel capable of changing shape based on a person's emotion, envisioning it as a means to support adapting emotions.

These studies suggest that further research into how the exterior appearance and motion of shape-changing objects influence emotions—compared to static objects—could position them as a medium for emotional communication. We aim to examine these characteristics in detail.

2.2 Shape Change as Communication

Shape-changing objects can change their physical form, dimensions, or other physical characteristics. Human interpersonal communication uses gestures and facial expressions, which are motions that communicate something to your partner. The emotion conveyed by a shape-changing textile depends on the observers' associations, their personal experience towards these associations, and the shape itself [19]. Davis [19] found that the valence and arousal ratings increase if the shape is moving vs. being still. Textile textures moving with a higher frequency are perceived to convey a higher level of arousal [19, 32]. Vekemans et al. [92] confirmed that low-frequency tactile stimuli on the wrist evoke calm, sleepy, and sad emotions. Strohmeier et al. [85] found that participants used symbolic shapes (e.g., hearts) to convey emotions, with shape reflecting valence and motion properties (speed, amplitude, area) reflecting arousal. Brocker et al. [6] revealed that participants often associated 3D renderings of soft robots with living organisms, everyday objects, and wearable applications. Hu and Hoffman [32] emphasized that observing motion in person conveys emotions more strongly than watching it on video. The project KnobSlider [44] investigated user preferences of a shape-changing knob, compared as tangible control inputs vs control input via video. They found that users preferred to execute slower shape-changes with the physical device and faster shape-changes with videos. Several projects, from giant shape-changing interfaces [3] to actuators the size of a finger [47], have let participants observe shape changes to study the emotional effects.

In human interactions, touch is an important channel to communicate emotions [32, 43, 82], ranging from anger and fear to love and gratitude [30]. A variety of projects with tactile shape-changing interfaces look at how humans can benefit from using them for well-being [4], to enhance virtual reality experiences [89], or to support remote communication [75]. Besides these practical aspects, tactile shape-changing interfaces are used to trigger emotional communication [53, 99], also over distance [76]. Tactile characteristics such as spikes can convey specific emotions to children on the valence and arousal scale (Russell [74]) [62].

All artifacts above were evaluated for their user experience, likability, etc. However, none of the research projects presented have investigated whether fundamental motion types, such as bending or twisting, and other motion parameters, such as different speeds, may be able to convey different emotions to an observer. The projects by Vekemans et al. [92] and Strohmeier et al. [85] used Russell's circumplex model to analyze emotions, but gave the participants a set of key emotions from Russell's model to characterize the emotions conveyed instead of letting them rate both dimensions individually. Davis [19] allowed a rating on these axes but focused on comparing the emotions perceived when a computational textile is presented via touch and vision to using vision alone; that study did not analyze motion parameters in detail. Vekemans et al. [92] and Hu and Hoffman [32] introduced an actuated object consisting of several identical air bumps to function as the skin texture, while Davis [19] used more complex computational textiles as shape-changing objects. Building on this work, we want to determine in detail what valence and arousal levels of emotions are conveyed when users observe or wear a soft shape-changing wearable.

2.3 Shape-Changing Actuators

With soft robotics, a multidisciplinary field combining knowledge from robotics [68], electromechanics [87], and material science [60], researchers can create shape-changing objects. Rasmussen et al. [73] provided a review of 44 papers to evaluate the design space of shape-changing interfaces. They identified eight transformed shape types, common interaction patterns, and functional and expressive purposes. The review also highlights understudied areas and outlines key open questions regarding design intent, unexplored shape transformations, and the need to better understand user experience. Kwak et al. [50] used a repertory grid method to explore how users perceive shape-changing interfaces, revealing dimensions such as personality, territoriality, and state of mind beyond typical categories such as appearance and product properties. Qamar et al. [70] presented a review of shape-changing interfaces in HCI, and of how shape-changing techniques have evolved. They categorise the type of shape change into mechanisms such as rollable, foldable, and inflatable. Soft robots are programmed using software and hardware control systems that manage their behavior [80]. Actuation methods include pneumatics [26, 36, 59], hydraulics [58, 96], mechanical forces [1, 19], and heat [23]. Various air pressure-based control systems have recently been developed [31, 64, 79]. Pneumatics are easier to use in practice than, e.g., hydraulics [7] and provide a particular advantage when measuring counterpressure. Regardless of the actuation method, tools that encode design expertise are essential to create reliable pneumatic soft robots effectively. For example, Siloseam [56] simplifies the mold–cast–cure process for creating custom inflatable silicone bladders, supporting basic inflation but not complex movements such as bending or elongation. SoRoCAD [7] is a software tool for designing silicone-based soft robots actuated by compressed air. It streamlines mold creation by integrating simulation into the design process, allowing users to easily and repeatedly evaluate motions during design. MorpheesPlug [46] supports the user by defining design parameters for six standardized widgets to create soft robots in Fusion 360[1]. Similarly, MiuraKit [12] is a hands-on construction kit to explore shape-changing structures using pneumatically actuated origami tubes. Many design tools for pneumatic soft robots exist. We needed very consistently actuating soft robotic finger actuators. Also, those actuators needed a cuboid outer form that is visible to the users. Morphees plug's building block and Miura Kit's origami building blocks are not in cuboid form. Siloseam's silicone bladders do not support motions besides inflation. SoRoCAD's soft robots have the right shape but tested actuators lacked the robustness needed for repeated actuations in our studies. The platform *Soft Robotics Toolkit* [31] provides modular and open-source hardware solutions.

Since no existing toolkit met our needs, we created a parametric OpenSCAD script[2] for generating molds for fiber-reinforced actuators, drawing on resources from the Soft Robotics Toolkit. We provide our script and design process as a supplement.

2.4 Shape Change and Jewelry

Integrating technology has significantly advanced jewelry over the past decade, leading to the emergence of *smart jewelry* [77, 84]. The scope ranges from functional smart jewelry [48, 65] to artistic pieces [93] and socio-cultural applications [94]. Woźniak et al. [98] developed a vibrotactile necklace (HaptiNecklace) for passive tactile perception on the sternoclavicular area and found in a user study (N=19) that directional vibrations were better recognized than single-point ones. Smart jewelry often provides output, either privately to just the wearer [25, 37, 72, 93] or perceivable by others [9, 35, 37]. Few projects, however, use shape change as an output channel. Shape-changing jewelry has been explored in bracelets [27, 29, 67], watches [24], and clothing accessories [42]. PneuHaptic [29] is an arm-worn pneumatic haptic interface that generates tactile sensations on the skin. Fan et al. [24] developed a watch with curvature-changing feedback for notifications, reporting positive user responses. Kao et al. [42] used Rovables [21] to create shape-changing jewelry that moves across clothing surfaces, forming new shapes. Smart jewelry research on emotions often explores

---

[1] https://www.autodesk.com/products/fusion-360

[2] https://openscad.org

the personal meaning jewelry provides to the wearer, such as storing valuable data [72, 93] or communicating intimate information between people [38, 51]. Inget et al. [37] further showed that placement preferences vary: head and neck for public, arms and hands for private information. Finally, the choice of exterior material appearance can significantly influence the aesthetics, comfort, durability, and overall impact of jewelry [48]. Hence, its visible materiality may play a crucial role in how a particular movement of an object is interpreted and what emotions it conveys to observers [91]. Related work shows that smart jewelry increasingly blends functionality, expression, and emotion, yet research on shape changes in jewelry to function as communicative channel remains shallow.

3 Study 1

Study 1 served to explore the effects of the various basic parameters of shape change on emotions conveyed to an *observer*, not the wearer. Therefore, our participants only observed the necklace actuating. In real life, people would not usually touch a necklace another person is wearing but merely observe it, making it a good fit for our study. Our necklace used two interchangeable basic cuboid actuators, one on each side of the pendant. In Study 1, we opted for actuating only one side of the necklace to isolate the effects of a single actuator, leaving the other side as a static reference. We also varied the exterior materiality of the actuator to see how this influences the emotions perceived.

In this first study, participants saw videos of our necklace with different shape-changing actuators in action. This guaranteed identical motions across users and trials despite our early actuator prototypes still exhibiting significant variance in their shape change between subsequent actuations.

After observing the necklace, we asked participants to rate the emotions they perceived along Russell's circumplex model dimensions of *arousal* and *valence*. Secondly, we asked them to describe what they associated with each movement, extending beyond emotions. This helped contextualize their quantitative ratings on the circumplex model and provided insights into their mental models. Study 1 thus addressed the following research question:

RQ1: "How do the fundamental design parameters of shape change influence the valence and arousal levels of emotions conveyed to an observer?"

These hypotheses, outlined below, are based on prior research (Section 2) and our assumptions about how specific shape changes convey emotions to an observer:

H1: *On average, downward motion leads to lower valence ratings ([19, 32, 85]), while upward motion leads to higher valence ratings [34, 39].* This is in-line with Image schema theory [39], which states that positive emotions and experiences are linked to the upward vertical direction, while negative ones are linked to the downward vertical direction.

H2: *Repeated motion of an actuator leads to higher average valence [32, 85] and arousal ratings [18].*

H3: *On average, faster motion repetition leads to higher arousal ratings [32] but does not affect valence ratings.* We assume repetition does not influence valence, as positivity or negativity seems tied to motion type rather than speed of repetition, because, e.g., a smile remains a smile regardless of how fast a person curls up the corners of her mouth.

H4: *On average, a larger motion amplitude leads to higher arousal [32, 85] and valence ratings.* Larger amplitudes can also be expected to increase valence because the motion looks bigger and is easier to recognize.

H5: *The exterior appearance (materiality) of an actuator influences the valence rating [91], with leather and textile actuators receiving higher valence ratings on average.* We expect leather and textiles to suggest more warmth than the other materials tested, and warmth mostly receives more positive associations than cold [91].

3.1 Study 1: Experimental Design

Prior work [19, 32, 92] has described several motion parameters influencing the conveyed emotion. Therefore, we manipulated the *motion type* (bend up, bend down, wave, elongate, twist), *repetition* (none, low, high), *amplitude* (half, full), and *actuator surface material* (leather, metal, fabric, silicone) as independent variables. Our dependent variables were the ratings of the *valence* and *arousal* dimensions of Russell's circumplex model and the associations with the necklace motions.

3.1.1 Motion Type. We used five motion types.

- A single bend up along its transverse axis (Fig. 3, *up*)
- A single bend down along its transverse axis (Fig. 3, *down*)
- Two bends along its transverse axis (upwards and downwards, respectively; (Fig. 3, *wave*)
- Twisting around its longitudinal axis (Fig. 3, *twist*)
- Elongation along its longitudinal axis (Fig. 3, *elongate*)

For consistency, all actuators were cuboid-shaped. We chose pneumatic actuators in the shape of cuboid fingers because they are a standard soft actuator [86], and their simple shape allows users to focus on the shape change, while researchers can apply our insights later to more complex forms based on it [57]. The non-rotation-symmetric shape of a cuboid (unlike, e.g., a cylinder) also ensures that twisting is easy to notice.

3.1.2 Speed of Repetition. We used three levels to repeat the motion in Study 1: *none* (motion is performed only once), *low* (motion repeats every 6 s), and *high* (motion repeats every 3 s).

Figure 2: Study 1 investigated how different basic shape change parameters of a necklace affect the emotions it conveys to an observer. When inflated with compressed air, the left actuator changed shape, while the right actuator remained still for reference. Study 1 tested five different motion types (from left to right: *bend up, bend down, wave, twist, elongate*). We also varied the appearance of the actuators' surface material.

Figure 3: Left: Each motion type in its unactuated state, at half and full amplitude (Bend includes Up and Down). Right: Surface materialities of the soft actuators: raw *silicone*, *leather*, *metal* (metallic fabric), and *fabric* (from left to right).

3.1.3 Amplitude. We defined the maximum movement our actuators could perform as the *full amplitude* level. As the second level, we defined the *half amplitude* (see Fig. 3, left).

3.1.4 Material. We covered our actuators with various gray fabrics that looked like different exterior *materials* commonly used for jewelry: *metal*, *fabric*, and *leather* (Fig. 3, right).

3.1.5 Total Conditions. Combining these four factors resulted in 120 conditions (5 *motion type* × 3 *repetition* × 2 *amplitude* × 4 *material*) for Study 1. Because a pilot study for this took over two hours, we made *material* a between-subjects factor, resulting in 30 trials per participant. We counterbalanced the conditions per group with a Latin square to mitigate carryover, learning, and novelty effects.

3.2 Study 1: Participants

Study 1 had 24 participants (14 male, 10 female) aged 14 to 59 years (M = 29.21 years, SD = 10.13 years). For participants under 18, our consent form included parental consent. Thirteen participants had never seen such actuators. Two had heard of them but never seen one, seven had seen them but not used them, and two had prior interaction with soft robots—one with artificial muscles and one with silicone actuators.

Fifteen participants had never heard of smart jewelry, five had seen other examples, and four had interacted with smart jewelry before. None had encountered our necklace or soft actuators before the study.

3.3 Study 1: Apparatus & Procedure

Below, we describe our setup for Study 1.

3.3.1 The Shape-Changing Necklace. The neck offers plenty of space for visible motion while remaining easily observable. Inget et al. [37] also stated that users perceive the chest as a suitable location for displaying information to other people. Also, the neck is physiologically well suited for tactile passive perception of cues [53, 98]. Other options for the design were possible. We could have integrated the actuators into the necklace chain, but this would not provide a neutral horizontal starting point for distinguishing up and down motions, and movement in the necklace chain would lead to motion on the uneven collarbone. We wanted to allow symmetric and asymmetric motions in our second user study. Hence, the necklace pendant integrates two actuators (Fig. 2), one on each side. We sized the pendant to hide all pneumatic connectors and chose a round shape to avoid sharp edges for comfortable wear. In Study 1, only the left actuator (as seen by an observer) was actuated with compressed air via a tube running up the chain.

In both studies, the necklace was worn by a mannequin instead of a human neck when participants observed it to avoid an unconscious bias through the person wearing the necklace [41, 97]. The videos of the necklace moving were 12-second clips plus short fade-ins and fade-outs.

3.3.2 Controller. To achieve precise actuator control, we implemented a hardware controller (Fig. 4) similar to the one used in [33], because common pumps for Arduino lack the accuracy needed for controlled air deflation and maintaining stable air pressure. The system consists of a computing unit and an actuation unit, which drives a custom 3D-printed piston inside a syringe. The computing unit connects to a stepper motor via an ACT DM542 driver controlled by an Arduino Uno. The Arduino connects to a control panel with LEDs and push buttons to control the soft actuator motions.

3.3.3 Study Procedure. Participants sat in a chair at a table and could see the actual necklace on the mannequin. We started with the consent form and asked participants about their prior knowledge. After introducing the topic and demonstrating the necklace, participants saw the videos on a MacBook Air (M1, 2020) for all 30 trials. Participants performed two practice trials before the 30 trials. Participants could ask questions anytime and view each video a second time if desired. After each video, participants rated their initial impression of the mood conveyed on each dimension of the circumplex model with a 5-point Likert scale. Arousal was labeled with "Relaxed Mood" (lowest) to "Stimulated Mood" (highest). Valence was labeled with "Negative Mood" (lowest) to "Positive Mood" (highest). Secondly, we asked the participants to state what they associated with the necklace and its motion. Afterward, participants could touch the actual necklace.

3.4 Study 1: Results

We interpreted Likert scales as interval data in accordance with most prior work [8, 19, 32, 85]. While we collected quantitative data by letting participants rate valence and arousal, this data is highly subjective. We therefore report confidence intervals (CI) and effect sizes (ES) based on the *estimation approach* described by Cumming [17] and Dragicevic [22] instead of using null-hypothesis

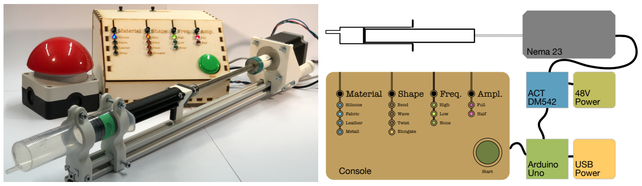

Figure 4: Photo (left) and diagram (right) of the hardware setup used to control the pneumatic actuators in our study. It consists of a syringe, a stepper motor mounted on an aluminum profile, and a separate control console. The console contains an Arduino Uno that controls an ACT DM542 stepper motor driver. The driver translates these commands into control sequences sent to a NEMA 23 stepper motor, which operates the syringe.

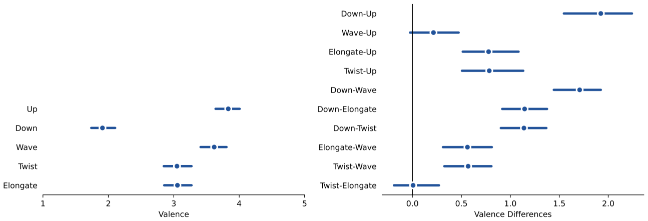

Figure 5: Left: overall *valence* rating for each motion type. Right: changes in valence (difference estimates, which is the difference of means) in the emotion the necklace conveys when changing from one motion to the other. Pairs were formed, and the point estimate is ≥ 0. Both diagrams display means with 95% CIs and $n = 24$. We see that motions sharing characteristics in their motion direction, such as *twist* and *elongate* (both move on the horizontal level) or *up* and *wave* (both move upwards), received similar ratings on the *valence* dimension.

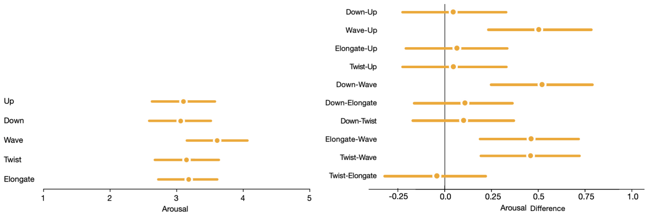

Figure 6: Overall *arousal* rating for each motion type (left), and change in valence (differences of means) between two motion types (right). Both graphs show means with 95% CIs and $n = 24$. For *arousal*, *wave* received higher ratings than all other motion types.

significance testing (NHST). This allows us to investigate whether the data is pointing towards the relations in our hypotheses and offers a differentiated interpretation of the result, especially in combination with our results from the associations that participants stated.

We averaged measurements for each participant to calculate CIs with a single measurement per participant [22]. Calculating the mean for each condition provided us with the corresponding point estimate. For retrieving 95% CIs, we used BCa bootstrapping [10]. Bootstrapping was performed with 1,000 replications, and a random but fixed seed was used to provide reproducible results. We performed a pairwise comparison for each within-subjects factor to understand the effect sizes. We interpret effect sizes as the estimate of the difference between the means of two factors to understand whether differences exist in the influences of those factors on the conveyed emotion. Hence, we always calculated the difference of means between two levels of a factor per participant. We then calculated point estimates and 95% confidence intervals, as described before, for the differences between the two levels.

3.4.1 ***Motion Type.*** Each motion type influenced both valence and arousal ratings with varying effects.

Valence. *Up* and *wave* motions have the highest *valence* rating (up: 3.83, wave: 3.62) (Fig. 5 left). The difference estimate of their means (mean = 0.215, lower = -0.024, upper = 0.472, cf. Fig. 5 right) points towards no difference between these two motion types. Nevertheless, with high probability, both conditions result in a considerably higher valence rating than the remaining three shapes (*down*, *twist*, and *elongate*). *Elongate* and *twist* have a valence rating estimate of about three (elongate: 3.06, twist: 3.05), and the pairwise comparison suggests no apparent difference between them (Fig. 5 right). In contrast, *down* has a low valence rating of 1.91 and is the most negatively perceived form. Moreover, it can be stated with a high probability that changing from *down* to *elongate* or *twist* will result in a more considerable increase in valence than changing from *elongate* or *twist* to *wave* (cf. Fig 5 *right*). These findings provide support for *(H1)*. However, not all five motion types resulted in particularly different estimates for the valence ratings. Motions sharing characteristics like *twist* and *elongate* (both stay horizontal in their movement) or *up* and *wave* (both move upwards) are more likely to convey emotions with similar valence.

Arousal. *Up* (mean = 3.12), *down* (mean = 3.07), *twist* (mean = 3.17), and *elongate* (mean = 3.17) have almost the same ratings (Fig. 6 left). *Wave* is the only outlier, receiving the highest rating of 3.63. These results point towards the *wave* motion conveying more excitement to the observer than the other motion types. This trend is also visible in Fig. 6 right. For all pairwise comparisons, including the *wave* motion, the estimates indicate a higher probability that a *wave* motion compared to any other motion will increase the arousal ratings more than any other pair of motions without *wave*.

3.4.2 ***Speed of Repetition.*** We evaluated the results regarding valence and arousal for all three repetition levels.

Valence. The overall valence rating for all three levels (Fig. 7 left) shows minor differences between the levels (*none:* mean = 2.97, *low:* mean = 3.06, *high:* mean=3.25). The results hint at an interesting difference between no repetition of motion and motions with high-speed repetitions. However, the CI ranges are still overlapping (*none:* CI = 2.86–3.14, *high:* CI = 3.1–3.39). Also, the difference of about 0.275 of a level on the 5-point Likert scale is relatively small compared to the observed effect of motion types in the previous section. Therefore, we have minimal support for *(H2):* valence conveyed by non-repetitive motions differs from that conveyed by repetitive motions. Again, even though there seems to be a difference between *none* and *high*, the effect size (the difference between the means – 0.275) is low. Additionally, for *(H3)*, which concerns the effect of repetition on valence, we cannot find

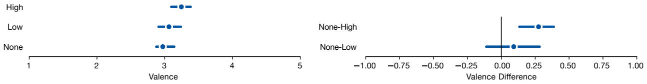

Figure 7: Overall *valence* rating (x-axis) for each repetition level (y-axis) (left), and change in valence (differences of means) between two repetition levels(right). Both graphs show means with 95% CIs and $n = 24$. Motion without repetition receives lower *valence* ratings than high-speed repetitive motions.

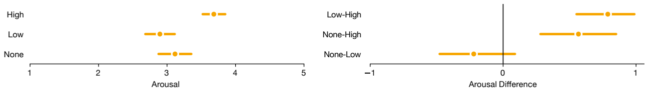

Figure 8: The overall *arousal* rating (x-axis) for the different repetition levels (y-axis) is shown on the left. The right graph shows the estimated change of *arousal* between two different repetition levels. Both diagrams show means with 95% CIs and $n = 24$. Interestingly, non-repeated motions received higher ratings for *arousal* than low-speed repetitions.

any evidence in the data because the CIs for *low* and *high* speed repetitions are very close (*low:* CI = 2.91–3.24, *high:* CI = 3.1–3.39).

Arousal. Arousal ratings for repetitive motion (cf. Fig. 8 left) show that non-repeating motions *(none)* (mean: 3.12) and *low*-speed (mean: 2.9) motions were both rated a little lower than *high*-speed motions, with an average rating slightly below four (mean: 3.68). Investigating the differences in Fig. 8 right also shows that *high*-speed motions were more likely to be rated as more aroused than non-repetitive motions (*none*) and slower repeating motions (*low*) (Fig. 8). The effect in the difference between *low*-speed motions vs. *high*-speed motions is likely to be much bigger than between non-repetitive motion vs. *low*-speed motions and non-repetitive motion vs. *high*-speed motions. These results support the hypothesis that speed affects perceived arousal *(H3)*. Similarly, we can see that the data support the second part of *(H2)*, as *no* repetition and *high* repetition have no overlapping CIs, i.e., the repetition of a motion does affect perceived arousal.

3.4.3 ***Amplitude***. Since amplitude is defined for each motion type separately, we analyzed the interaction between each motion type and each level of amplitude (*half* and *full*).

Valence. For *up*, *elongate*, and *wave* valence ratings for the *full* amplitude are (slightly) higher than for the *half* amplitude. All CIs overlap, and for *wave*, they are the widest (Fig. 9 left). *Down* does convey a negative emotion to the observer, in particular in the *full* amplitude (up = 4.04, down = 1.78, wave = 3.93, twist = 3.03, elongate = 3.08). *Up* and *wave* are perceived as positive. *Twist* and *elongate* ratings are almost identical. Here, the same assumption applies that we arrived at for the impact of motion type on the valence rating: Motions that stay horizontal in their motion and motions that move upwards convey emotions with similar valence. This stays alike in the *full* and *half* amplitude group (*half* amplitude ratings: up = 3.63, down = 2.04, wave = 3.31, twist = 3.07, elongate = 3.03). The estimates for the valence differences between full and half amplitude indicate a high probability for a bigger increase of valence ratings for the *wave* motion(mean = 0.625) than for *twist* and *elongate*.

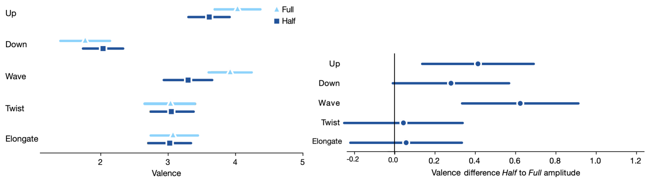

Figure 9: Left: *Valence* ratings for *full* and *half* amplitude per shape. Right: Estimates for valence differences between *half* and *full* for each shape. Both diagrams show means with 95% CIs, and $n = 24$. A full motion amplitude leads to a higher rating on both dimensions. The exception is *down* in the valence dimension, where a full amplitude leads to even lower ratings on the valence dimension, i.e., it conveys an even more negative emotion.

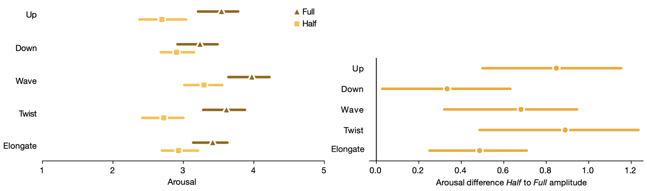

Figure 10: Left: *Arousal* ratings for *full* and *half* amplitude per shape. Right: Estimates for differences in arousal between *half* and *full* for each shape. Both diagrams show means with 95% CIs, and $n = 24$. The results show that a full amplitude of a motion leads to a higher rating on both dimensions.

Arousal. The left graph in Fig. 10 shows the arousal ratings for each amplitude level per motion type. The *full* amplitude is perceived as more aroused for all motions. Even though the estimates for differences between the *full* and *half* amplitude do not indicate large effects among all motion types, their CIs are relatively wide (Fig. 10 right). Possible differences between the amplitudes range from close to zero to around one step. The data show support for *(H4)* regarding the amplitude's impact on the perceived arousal.

3.4.4 ***Material***. For material, the ratings were quite close.

Valence. The average valence reported (cf. Fig. 11 left) shows no considerable difference based on the material of the movable part of the necklace. *Silicone* (mean = 3.15) and *fabric* (mean = 3.17) were rated slightly more positively than *metal* (mean = 3.0) and *leather* (mean = 3.02). Therefore, we found no evidence that the material influences the conveyed valence or that actuators looking like leather and textile are perceived more positively than those looking like metal or silicone *(H5)*.

Arousal. All materials were rated slightly above three on the 5-point Likert scale (Fig. 11 right). The most considerable difference exists between *silicone* (mean = 3.05) and *fabric* (mean = 3.42). No clear difference can be reported between all other materials. *Fabric* has the tightest CI (Lower = 3.23, upper = 3.57), just about half the CI of metal (Lower = 2.88, upper = 3.45). This may indicate that actuators from fabric convey a smaller variety of arousal states. None of the findings regarding the conveyed arousal of different materials support the hypothesis that the material influences the arousal of a conveyed emotion *(H5)*.

3.4.5 ***Associations***. We analyzed the reported associations of the users following *inductive development of categories* by Mayring [54, p. 86]. We reviewed our categories and subcategories after about 25% of the answers and merged similar codes and categories. This resulted in 704 codes. The most extensive theme is *human* with 434 codes. A big subcategory in this theme is *(mental) conditions*, which contains 120 codes for emotional associations. The other subcategories are fictional characters, characteristics, social interactions, attitudes, judgments, mimics, gestures, body motions, and body parts. There are two medium-sized themes: *nature* (81 codes) and *objects* (85 codes). Nature has animals, environment, and liveliness as subcategories. We formed two subcategories for objects: stationary and moving or movable objects. Additionally, there are three more minor themes with *mobility* (34 codes, subcategories: directions, motions), *actions* (32 codes, subcategories: results from action, actions/activities), and *sports* (38 codes, no subcategories).

3.5 Summary & Limitation of Study 1 Results

In summary, our data show trends supporting *(H1)*: Motion type impacts perceived valence and arousal. This matches the results of Davis [19], Strohmeier et al. [85], and Hu and Hoffman [32], but we were able to categorize the fundamental motion types for both model dimensions. Repetition also impacts both valence and arousal *(H2)*, something that had previously been reported only for valence [85]. Faster motions lead to higher perceived arousal (cf. [19, 32, 85]), but not perceived valence *(H3)*. The amplitude of a motion (*H4*) impacts perceived arousal, but high variance in the data made it challenging to quantify how strong the influence on a perceived emotion is. A larger amplitude intensifies perceived valence. These findings thus do not support *H5*. During fabrication, we realised that leather has an impact on the motion of the soft robot inside by restricting the possible expansion, especially over time, and compared to the other materials, because the soft robot needs more power to stretch the material. For our videos, this was not an issue because actuation with the leather was only needed a few times, and we changed the actuator after four to five actuations. However, for a soft robot moving live and real life, we believe leather is less suitable.

3.6 Study 1: Discussion

In the following, we discuss the key insights from these results into the impact that different motion parameters of actuators have on the emotions that a shape-changing wearable conveys to an observer.

3.6.1 *Motion and Emotions – H1, H2, H3, H4.*

We wanted to uncover implications for designing wearable shape-changing experiences with basic motions that convey emotions in a controllable manner.

More Repetitions – Higher Arousal and Valence. Repetitive motion led to more perceived arousal and valence than single motions. For valence, the data indicates a trend that ratings on the valence axes correlated with the number of repetitions, even though the estimates for the difference are small when comparing non-repetitive motion with the remaining two motion repetition levels (None vs. Low: mean = 0.12, None vs. High: mean = 0.26; see Fig. 9). Thus, we recommend using repetition to convey a motion more positively or negatively to the observer. In contrast, non-repetitive motions were linked to human facial expressions, like a smile or raised eyebrow.

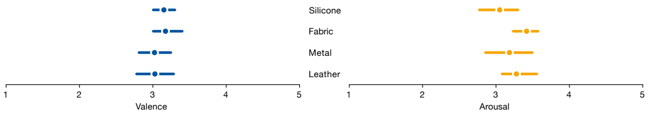

Figure 11: Results of *valence* and *arousal* for the different exterior materialities with mean as the point estimate, 95% CIs, and $n = 6$. For both dimensions, the ratings for all exterior materials are quite close.

No Repetition Causes More Arousal than Low-Speed Repetition. The finding that non-repetitive motions were perceived as more arousing than low-speed repetitive motions is interesting, as prior research describes that more motion corresponds to higher perceived arousal. But our data points to another order of repetitive motions (repetition with high speed > no repetition at all > repetition with low speed) with a visible effect in the difference of the ratings comparing *low*-speed motions to *high*-speed motions and non-repetitive motion to *low*-speed motions. This could be explained by participants perceiving tension in the actuator's shape as reflected in some of their reported associations, likely related to our definition of the non-repetitive condition. Because gestures were often associated with high-speed repeated motions, we believe it might be feasible to convey higher arousal emotion using high-speed repetitive motions resembling gestures that also communicate a high arousal value. High-speed motions were associated with gestures, and low-speed motions with facial expression characteristics. This accompanies higher arousal ratings for high-speed motions, as gestures can express excitement well. Low speeds indicated characteristics of a human personality to participants, maybe because a personality characteristic is something permanent, and therefore, low speeds indicate a characteristic that is permanent. Motion repetition seems to have little effect on perceived valence, likely because participants associated different repetition-speeds with varied terms.

Amplitude as Valence Intensifier. From our data, it is hard to determine the magnitude of the effect caused by the change in amplitude on the arousal dimension. This becomes particularly clear when comparing the differences between the amplitude levels for the motion types *up* and *down* (Fig. 10). Their only difference is their respective upward or downward bending direction. However, estimates of the size of the change between the *half* and *full* amplitude levels differ across the two shapes. For the valence dimension, we found that in the amplitude groups, the ratings correlate similarly to the ratings of the motion type. The interesting part is that *full* amplitudes emphasize how positively or negatively emotions are perceived (between 0.4 and 0.6 points on the rating scale, Fig. 9).

Motion Direction as Valence Indicator. The motion type with its movement direction can be interpreted as an indicator of the level of perceived valence in a positive or negative direction. We could observe that for the perceived valence, motions can be grouped by characteristics such as their movement direction (Fig. 5). The associations suggest that motions form distinct groups rather than being defined by individual types, requiring abstraction into key characteristics to generalize their effects.

Motions Resembling Associations and Experience. We recommend creating motions mimicking gestures to convey an emotion with a particular valence level. An apparent effect on the conveyed *valence* was caused by the different motion types, such as *bend.* The motion types of our study can be arranged into three groups: "positive motion", "negative motion", and "neutral motion". Participants felt a negative emotion for the actuator bending *down*, which could be justified by the symbolism reported by Strohmeier et al. [85]. Humans often associate downward-pointing motion with negative evaluations, such as a thumbs-down gesture in sports contexts. Thus, the *down* motion seems to be particularly suitable for expressing more negative emotions. Looking at research on mental patterns, image schema theory [34, 39] gives a suitable explanation for this observation. Image schema theory describes mental patterns derived from repeated, multimodal bodily experiences, not just visual experiences, and interactions with the physical world. This theory incorporates the UP-DOWN Schema, derived from our basic physical experience of gravity and movement, in which 'up' represents the direction away from the ground and 'down' toward it. Hurtienne [34] explain that humans commonly associate 'up' with positive concepts, in our case, a positive emotion, and 'down' with negative ones. We could observe a similar fact for (*wave* and *up*) that were perceived more positively (Fig. 5). The *wave* motion elicited higher excitement from observers than the other four motions, possibly because it evoked associations with ocean waves and exciting vacations. *Twist* and *elongate* motions were perceived as a "neutral motion", and were more often associated with terms without any clear negative or positive association. We assume that the absence of an immediate positive or negative impression may lead people to relate the shape to familiar shapes instead [49]. The associations of motion types can also be grouped into three categories. *Up* and *down* were associated with humans, for *elongate* and *wave*, participants stated terms from nature, and *twist* was mainly associated with objects. We also saw frequent associations of *wave* with facial expressions, i.e., for wave, it appears to be crucial in what context the motion is executed.

3.6.2 Materiality Correlates to Experience – H5.

However, the many different associations for each material suggest that individual perceptions of a material's emotional qualities can vary widely. The association diversity could indicate factors not investigated thoroughly in our explorations. E.g., Crippa et al. [16] discuss that an emotion evoked correlates highly with a particular object's known functionality in combination with the object's material. Hence, the data about associations warrants further differentiation. According to our data, motion parameters have a greater effect on the valence and arousal conveyed. Thus, we can conclude that the outer appearance of a basic actuator likely has a negligible influence on the conveyed emotion. This does not imply that designers do not have to consider materiality. The chosen material may interact with other factors that we did not consider.

4 Study 2

In Study 1, we investigated shape-changing motions purely from the perspective of an observer. To ensure consistent actuations, participants in Study 1 also observed shape changes only in videos; however, we know this conveys emotions less strongly than in-person observation [32]. Therefore, Study 2 used a live actuating prototype rather than recorded videos, and the study gathered feedback not only from observers, who only see the shape change without feeling it, but also from the *wearer*, who only feels it on their skin but without seeing it. We wanted to understand how wearers perceive the motions as tactile sensations and whether the emotions conveyed differ between observing a motion and feeling it on the skin.

Understanding how shape change may communicate emotions to the wearer also helps us explore a different and intriguing channel of communication: The emotions a wearable communicates to its wearer could be triggered by another person, e.g., a far-away partner sending messages to the wearer, or multiple other people, e.g., the crowd at a live concert sending messages to the performer wearing the device. In this way, Study 1 can be regarded as a setting of one-to-many communication from the wearer to any observers using a visual communication channel, while Study 2 also looks at haptic many-to-one communication from potentially several other people to the wearer using a haptic communication channel.

Study 2 thus addressed the following research questions:

1. *RQ2: "How do the fundamental design parameters of shape change influence the valence and arousal levels of emotions conveyed to an observer watching a live actuating wearable?"*
2. *RQ3: "How do the fundamental design parameters of shape change influence the valence and arousal levels of emotions conveyed to the wearer of a live actuating wearable?"*

Study 2 was split into two setups to isolate experimental factors better. The first setup allowed participants to wear the necklace themselves, enabling them to experience the haptic sensations of its motions on their skin. The second setup let them observe the necklace, this time live, but again on a mannequin to avoid confounding factors from the person wearing it.

Finally, in Study 2, we moved the actuators on both sides. This lets us combine different motion types to create symmetric and asymmetric overall shape changes. In both setups in Study 2, we asked users to rate the emotions they perceived in Russell's circumplex model and to state the associations conveyed to them.

4.1 Study 2: Experimental Design

We reduced the motion parameter space from Study 1 based on its results. Below, we discuss the remaining conditions and why others were removed. In general, we continued to manipulate the *motion type*, *repetition*, *amplitude*, and *actuator surface material* as independent variables. Dependent variables were again participants' ratings along the *valence* and *arousal* dimensions of Russell's circumplex model and the associations conveyed to the participants. Additionally, we asked participants to rank the motions at the end of the user study and answer questions in a semi-structured interview.

4.1.1 Necklace Modality.

Participants had to wear the necklace and observe its motions on a mannequin.

4.1.2 Motion Type.

Our pilot studies revealed that users could not differentiate *elongate* and *twist* when wearing the necklace. Additionally, Fig. 9 and Fig. 10 show that valence and arousal ratings for *elongate* and *twist* are pretty close in both amplitude. Hence, we removed *Elongate* from our conditions.

In contrast to Study 1, we wanted to investigate combinations of motion types after having studied the single actuator moving.

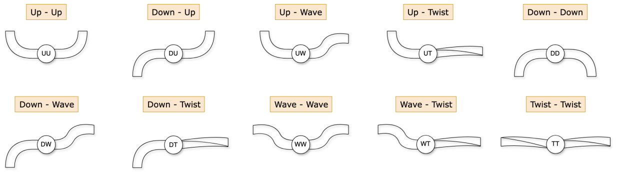

Figure 12: Sketches of all ten motion types investigated in Study 2. Participants used a version without any of the labels inside the pendant and above each motion (e.g. Up-Up) to tick which motion they felt while wearing the necklace.

Because we removed *elongate*, we reduced the combined motions for our user study from fifteen combinations to ten: *DD (Down-Down), DT (Down-Twist), DU (Down-Up), DW (Down-Wave), TT (Twist-Twist), UT (Up-Twist), UU (Up-Up), UW (Up-Wave), WT (Wave-Twist), WW (Wave-Wave)* (see Fig. 1 and Fig. 12).

4.1.3 Speed of Repetition. We removed the *low* speed repetition condition as the results of Study 1 pointed towards a small difference below 0.1 between the *low* and *none* conditions for valence ratings (cf. Figure 7) and almost no difference for arousal (cf. Fig. 8). Hence, we only kept motion with *none* and *high* speed repetitions. Our data indicated a difference in the effects of those two conditions on the valence and arousal scales.

4.1.4 Amplitude. Study 1 revealed that a *full amplitude* intensifies the corresponding *half amplitude* valence or arousal rating, but no other effects became apparent. Hence, we removed the *half amplitude* condition.

4.1.5 Material. Our first study showed no clear emotional effect of outer material. For the second study, we chose not to focus on material as a standalone factor but still ensured external validity by randomizing two materials that were well-liked in Study 1. We only used silicone and fabric. The metal condition used a metallic-look textile that did not feel like real metal. Leather can restrict the range of possible actuator motions, especially for motions that happen live, making its usage as cover material complicated, as already discussed in section 3.5.

4.1.6 Total Conditions. Combining these four factors resulted in 80 conditions (2 *necklace modality* × 2 *material* × 10 *motion type* × 2 *repetition* × 1 *amplitude*). A pilot study showed that this duration exceeded three hours, so we treated the material condition as a randomised factor for external validity, not an experimental condition, reducing the load to 40 trials per participant. We used a balanced Latin square to counterbalance conditions across groups, reducing carryover, learning, and novelty effects.

4.2 Study 2: Participants

We had 30 participants (15 female) aged 20 to 83 years (M = 34.7 years, SD = 17.99 years). Eight participants had never seen soft robotic actuators, fourteen had only heard of them, six had seen but not used them, one had prior interaction with soft robots (including silicone actuators), and one did not answer.

Seven participants had never heard of smart jewelry, four had only heard of it, three had seen examples, and sixteen had previously interacted with such devices. None had encountered our necklace or actuators before the study.

4.3 Study 2: Apparatus & Procedure

Our apparatus consisted again of the shape-changing necklace and the controller from Study 1. For Study 2, we let participants experience motion in reality, increasing the external validity of our user study. Based on our prior experience, we could now produce actuators that actuated consistently enough for a study with live motion. Our reduced factors further helped to alleviate any remaining inconsistencies in actuation. E.g., going from full and half amplitudes to only looking at full amplitudes reduces the need to have an exact half amplitude of a motion pattern, which also leads to fewer possible points of failure. We measured each actuator on a cutting mat with millimetre precision in both actuated and resting states to ensure consistent size.

4.3.1 The Shape-Changing Necklace. The necklace was placed on a 3D-printed mannequin (for observing) or at the wearer's neckline. Motions continued again for 10 s in total.

4.3.2 Controller. We housed the same controller from Study 1. Since participants now encountered the necklace live, we placed the controller inside a sound-insulated case to prevent the stepper motor or syringe noise from distracting them.

4.3.3 Study Procedure. Participants were sitting at the table to observe and wear the necklace.

After filling out the consent form and demographics, we introduced the topic and demonstrated the necklace to them without moving the actuators. All participants then started with the wearer setup to prevent any bias from recalling motions they would have observed beforehand. To ensure direct tactile perception, participants wore shirts with uncovered necklines, allowing the soft actuators to be positioned on the skin about 10 cm below the neck. Participants wore a shirt with an uncovered neckline, or we provided a suitable alternative. For both wearing and observing, participants rated their initial impression of arousal and valence on 5-point Likert scales after every single movement and reported associations for each motion. The only difference was that while wearing the necklace, participants also reported which motion they believed they had felt from the overview (Fig. 12), in addition to rating it and reporting associations. We concluded with a semi-structured interview and a ranking of the motions.

4.4 Study 2: Results

We used the same approach to analyze and report our data as in Study 1 (see Section 3.4). We looked at the data from the worn and the observed scenario separately, but also in combination.

4.4.1 ***Motion Type****.* In general, Figure 13 shows that the ratings for valence and arousal appear closer for all motion types when wearing the necklace compared to observing it. For both scenarios, *UU* was the most positive and exciting motion, and *DD* the least.

Worn. Figure 13 (left) shows the valence and arousal ratings of all ten motion types within the wheel of emotions in the worn condition. The rating for the motion *UU* and *DD* lies in the positive or respective negative area of emotions. *UU* and *WW*are the motion

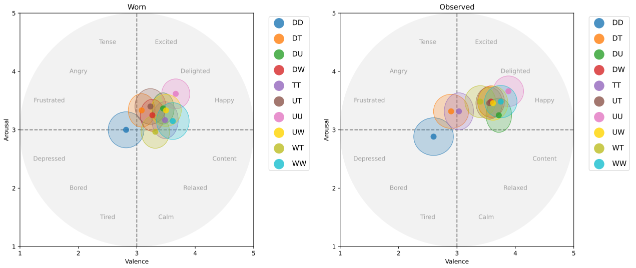

Figure 13: *Valence* and *Arousal* ratings for all motion types for wearing (left) and observing the necklace (right). Both images show means with 95% CIs as ellipses around the mean data point (n = 30). For both scenarios, *UU* was the most positive and exciting, *DD* the least, but some motion types like *WT* conveyed rather different emotions to wearers and observers. (Full data in the supplements.)

types with the highest *valence* rating *(UU: 3.75, WW: 3.6)* (Fig. 13 left). *DU*, *TT* and *UW* share almost the same valence rating of 3.5. In contrast, *DD* is the most negatively perceived form with a low valence (2.85). For arousal ratings in the *worn* setup, the data shows *UU* also has the highest rating (3.6), but all other motion types share a close arousal rating, although *DD* and *WT* are lowest.

Observed. Fig. 13 (right) shows that *UU* got almost the same values for both axes as in the *worn* setup. *DD* received slightly lower values for both axes during observation. Observers gave *DU*, *UU*, and *WW* high valence ratings. For arousal ratings in the *observed* setup, the data also shows no interesting effects except that the ratings for *WT* have the biggest rise from *worn* to *observed* of all motions.

In general, all symmetrical motions, whether mirrored along the horizontal *(UD)* or vertical axis *(DD, UU, WW)*, were rated higher in both valence and arousal than the asymmetrical motions. Hence, participants observed and felt less aroused emotions and less valence for the two different motions on each side. Out of the four on the vertical axes, *TT* does not have higher ratings than the asymmetrical motions. Motion types including a *twist* have lower valence ratings than the other vertical symmetric motions.

4.4.2 ***Speed of Repetition.*** Fig. 14 and Fig. 15 visualise that *high*-speed repetitions raised valence and arousal ratings for all motion types, leading to more positive and exciting emotions in both setups. Comparing Fig. 14 and Fig. 15, you can see that for wearing the necklace, the ratings depicted by the bubbles appear closer together. When the necklace was repeating the motion, ratings for all motion types shifted up on the arousal scale for both conditions.

Valence Worn. The overall valence rating for both levels (Fig. 16 left) shows minor differences between the levels (*none:* mean=3.28, *high:* mean=3.41). The CI ranges are sharing a great overlap (*none* CI: , *high* CI:). Also, the difference of about 0.15 of a level on the 5-point Likert scale is small. Hence, for *worn*, there seems to be no evidence that repetitive motions have an effect on perceived valence.

Arousal Worn. For the *worn* condition, *(none)*-repeating motions (mean: 2.91) were rated lower than *high* speed repeated motions (mean: 3.60). Investigating the differences in Fig. 17 (right) also shows that *high*-speed repeated motions were more likely to be rated as more aroused than non-repetitive motions (*none*) (Fig. 17). These results confirm the finding from Study 1 that speed affects perceived arousal *(H3)* also for the worn necklace.

Valence Observed. The overall valence ratings (Fig. 18 left) show minor differences between the levels (*none:* mean=3.24, *high:* mean=3.62), hinting at an interesting difference between no repetition of motion and high-speed repetitions. The CI ranges are also not overlapping. The difference of about -0.38 of a level on the 5-point Likert scale is relatively small. Looking more closely into the data of each single motion type, *high*-speed motions are increasing the valence score for *DD* from 1.2 to 3 and for *UU* from 3.4 to 4.3. The difference

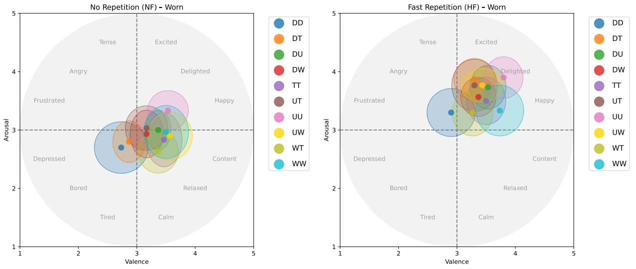

Figure 14: Left: 2D view of arousal and valence ratings for each motion type when participants *wore* the necklace and the motion was *not* repeated. Right: 2D view of arousal and valence ratings for each motion type when participants *wore* the necklace and the motion was repeated at *high* speed. For both, the circle shows the mean, and the ellipses around the circle represent the CIs for n = 30. *High*-speed repetitions raised valence and arousal ratings for all motion types. (Full data in the supplements.)

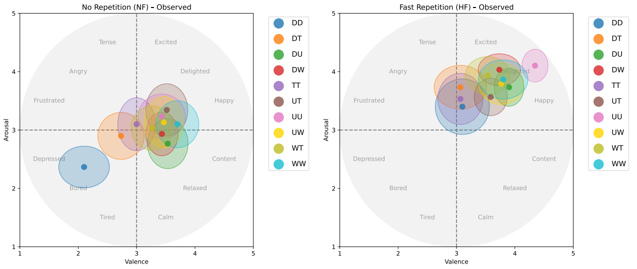

Figure 15: Left: 2D view of arousal and valence ratings for each motion type when participants *observed* the necklace and the motion was *not* repeated. Right: 2D view of arousal and valence ratings for each motion type when participants *observed* the necklace and the motion was repeated at *high* speed. For both, the circle shows the mean, and the ellipses around the circle represent the CIs for n = 30. *High*-speed repetitions raised valence and arousal ratings for all motion types. (Full data in the supplements.)

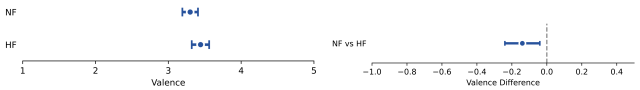

Figure 16: Left: *Valence* ratings for *none* and *high*-speed repetition when the necklace was worn. Right: Estimation for differences in valence between *none* and *high*-speed repetition. Both diagrams show means with 95% CIs, and $n = 30$. The results show that *high*-speed repetition most likely has no effect.

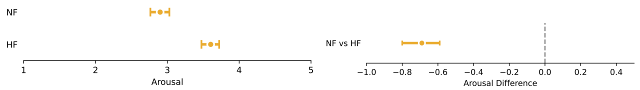

Figure 17: Left: *Arousal* ratings for *none* repitition and *high*-speed repitition when the necklace was worn. Right: Estimation for differences in valence between *none* and *high*-speed repetition. Both diagrams show means with 95% CIs, and $n = 30$. The results show that *high*-speed repetition most likely has an effect.

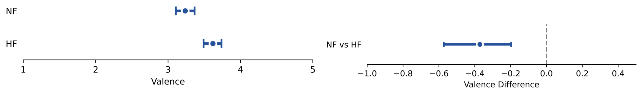

Figure 18: Left: *Valence* ratings for *none* repitition and *high*-speed repitition when the necklace was observed. Right: Estimation for differences in valence between *none* and *high*-speed repetition. Both diagrams show means with 95% CIs, and $n = 30$. The results show that *high*-speed repetition most likely has an effect.

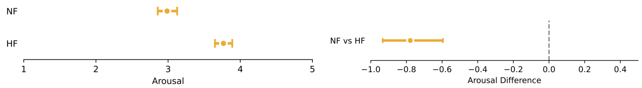

Figure 19: Left: *Arousal* ratings for *none* and *high* speed repetition when the necklace was observed. Right: Estimation of differences in valence between *none* and *high*-speed repetition. Both diagrams show means with 95% CIs, and $n = 30$. The results show that *high*-speed repetition most likely has an effect.

for *UU* (0.9) and for *DD* (1.2) is quite high compared to the other differences. Like in Study 1, our data points towards *(H2):* Valence conveyed by non-repetitive motions differs from that conveyed by repetitive motions. Here, the effect size (mean difference of 0.38) is slightly higher than in Study 1 for live observations versus video, aligning with the findings of Hu and Hoffman [32].

Arousal Observed. Observing the necklace (cf. Fig. 19 left) led to lower ratings for non-repeating motions *(none* (mean: 2.99) than for *high*-speed repeated motions (mean: 3.77). Investigating the differences in Fig. 19 (right) also shows that *high*-speed repeated motions were more likely to be rated as more aroused than non-repetitive motions (*none*, Fig. 19). These results support the findings of Study 1 that speed affects the perceived arousal *(H3)*. Again, the effect is more pronounced in this live condition than when videos were observed.

4.4.3 ***Material****.* For completeness, we examined ratings across all motion types for both materials, but arousal and valence scores again showed no notable differences. Full data is available as a supplement.

4.4.4 ***Overlapping Emotions****.* So far, we have discussed valence and arousal ratings per motion. Our analysis revealed several motion pairs that users rated almost identically. When wearing the necklace, this applies to the following pairs:

- *DU* – *UW*: Between delighted and happy
- *TT* – *WW*: Between happy and pleasant

The pair *DD* – *UU* marks the most delighted (*UU*) and the most unpleasant (*DD*) emotions, framing the most extreme emotions when wearing the necklace.

When observing the necklace, the same emotions apply to the following pairs:

- *DW* – *UW* – *UT*: Between delighted and happy
- *DT* – *TT*: Almost neutral but a little excited because of the arousal rating above 3

The pair *DD* – *UU* marks again the most delighted (*UU*) and the depressed (*DD*) emotions, framing the most extreme emotions when observing the necklace. Observers perceived a wider range of emotions than wearers.

4.4.5 ***Feeling Motion****.* Our user study focused on evaluating the conveyed emotion; however, we also looked into the provided data on shape recognition. Participants wearing the necklace identified its motion correctly in 38.4% of cases. Of course, the 38.4% also includes motions identified by chance, and this chance was 10% per motion type, given that we tested 10 different motions. Interestingly, participants were better at correctly identifying the motion type for symmetric motion directions with the highest agreement applying to the motion types *DD*, *TT*, and *UU* (cf. Fig 20). For each of those, 50% of the motions felt were identified correctly. Fig. 20 also shows that as soon as one of the motions in symmetric motion types is replaced by a different, asymmetrical motion, the agreement lowers. Participants also favored the symmetric motions in their rankings in both setups. We see that *UT* was most likely confused with *WT*. This indicates that *up* as a single motion is more complex to identify when not combined with a *bend*. *UW* is mixed up with *WW* or *UU*, pointing again towards the fact that participants struggled more to identify asymmetric motions, believing that they were symmetric instead. This may be a result of the *Gestalt Law of Good Shape* [66] that describes the tendency of human perception and memory towards simplifying shapes. Interestingly, the direction of *bend* also frequently gets confused when combined with *twist*, because *DT* was often misinterpreted as *UT*.

We already discussed that, for some motion types, wearers were able to identify about 50% correctly (see Fig. 20). Our main goal was to see if a shape-changing necklace conveys similar emotions to wearers and observers, revealing an unexpected and intriguing

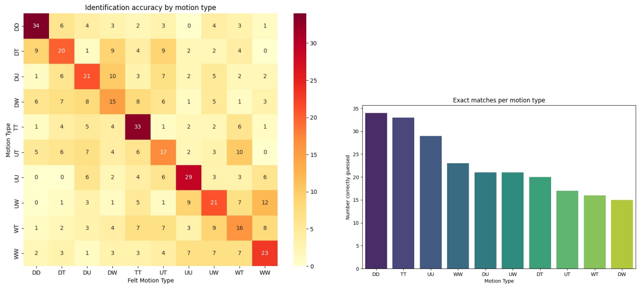

Figure 20: Left: Heatmap of correct motion identifications when wearing the necklace. Maximum possible identifications were 60, as each motion type was presented to 30 participants twice across two repetitions. *DD, TT* and *UU* were identified correctly almost 50% of the time. Interestingly, *UW* was often misidentified as *WW*. Right: Total correct identifications of each motion type.

finding. Even for those motion types where users got about 50% of the motions wrong (*DD* and *UU*), they still rated the *emotional effect* of those motions similarly to when they saw the same motion later in the *observed* scenario. Even for correct identifications below 50%, the ratings stayed similar. The only outliers are *TT* for valence ratings and *WT* for arousal ratings (cf. Fig. 13).

4.4.6 *Motion Associations.*

We kept the same approach as in Study 1 to analyze the associations reported by participants, following *inductive category development* by Mayring [54, p. 86]. Our analysis resulted in 792 codes. The most extensive theme is *emotion* with 214 codes, followed by the *movement* associations (162 codes). Within *movement*, the most prominent subcategories were *dancing* (40 codes) and *waving* (54 codes). There are three medium-sized themes: *animal* (96 codes), *massage/tickle/hug* (96 codes), and *human being* (85 codes). Additionally, there are three more minor themes: *objects* (55 codes), *growth* (18 codes), and *navigation* (25 codes). Compared to study 1, the emerged categories overlap partially, such as associated emotions, humans, and movement. Across motion patterns, some shapes shared similar associations. The shapes *DT*, *UT*, and *WT* were mostly interpreted as dancing or pointing. The shapes *DD* and *WW* were associated with a mustache. *WW* was additionally as well as *TT* also mostly associated with animals like snakes and birds.

4.5 Study 2: Discussion

With Study 2, we gathered knowledge about how live shape changes convey emotions to the observer and the wearer. Furthermore, we explored whether wearers could identify movements felt on their necklines.

4.5.1 *Motion and Emotions – RQ2, RQ3.*

Study 2 confirmed some results discussed in Study 1 (cf. 3.6).

1. Repetitive motion leads to higher arousal ratings, also for live observations of shape change, and when wearing the necklace. For both scenarios, the arousal ratings are even higher than for videos. This confirms our recommendation to use repetition to convey a more exciting motion to the observer and the wearer, and the result of Hu and Hoffman [32] that live motion leads to even higher ratings.
2. Participants still recalled their everyday experiences to associate the movements with objects, emotions, or anything else that came to mind. In contrast to Study 1, participants associated several movements with human beings, such as a police man [e.g., P3, P7], a traffic controller [e.g.,. P12, P19], a weightlifter [P17, P23], a person waving his arms [20/30 participants], or animals such as birds [13/30 participants]. We attribute this to the two actuators changing shape, with the pendant in the middle being interpreted as a body.

4.5.2 *Humans Favor Symmetric Movements – RQ2, RQ3.*

Our bodies are built up symmetrically and favor symmetrical objects, even symmetric faces [81], which might be why participants rated symmetric motions with higher arousal and valence ratings for observed and felt motions. Still, when shape changes are felt, symmetric motions tend to convey more positive emotions than observed, possibly because symmetry evokes safety and comfort. Associations show that *WW* and *UU* were associated with positive objects, e.g., a smile or a flying bird [e.g., P2, P17, P24] resembling freedom and being light. *TT* was ranked lower than *WW* and *UU* when wearing the necklace; one reason might be that some participants associated the felt motion with, e.g., a worm or snake, i.e., with something related to being "scary" [P17]. Still, opinions differed for *TT*, as other participants associated calmness with it [P16]. We can categorise motions further by the influence of a single motion. Generally, any motion with a *twist* had elements related to being tired, bored [P22, P25], or some crawling animal (snake, worm) [e.g., P3, P6, P13]. Any *bend down* actuator lets the participants associate less happy objects, persons, or emotions. Any *bend up* leads to happier objects, persons, or emotions. This can again be explained with the help of image schema theory because up means happy and sad is down [34]. Participants identified symmetric motion directions more accurately. The neck area is well equipped with processors to recognize touch events, even better than, e.g., the back [98]. Woźniak et al. [98] stated that compared to single-point vibrations, directional patterns are better recognized for vibrotactile feedback. All our motions are directional patterns, but the study by Woźniak et al. [98] also described that the human ability to differentiate touch locations decreases with an increasing number of actuators. Even with two actuators, this effect appeared for different motion patterns. Future work could quantify the limit.

4.5.3 *Observing vs. Feeling Emotions.*

When observing the motions, participants perceived the pendant and actuators as a whole, letting the shape transform into new objects (cf. Section 4.5.1)—an effect consistent with object grouping [66]. In Study 1, no merging occurred, as only a single actuator was in motion. When participants wore the necklace, they focused on sensing the motion rather than forming a complete object out of actuators and the pendant. This led to more associated emotions or actions, such as dancing or waving [19/30 participants], instead of objects like animals, humans, or waves. We recommend designing wearable shape-changing interfaces for symbolic communication through visually perceivable shape changes, while employing tactile shape changes as stimuli to encourage interpreting the motions as single cues to your body.

We believe this surprising result — misidentified motions still receiving similar ratings — may show that the human sense of touch cannot be "betrayed" in what a motion feels like emotionally, even when our brain may have arrived at a different abstract picture of this motion. When creating haptic shape-changing interfaces, the gap between the sense of touch and what the human brain captures should be kept in mind, and shape changes should be applied carefully. We recommend limiting the number of simultaneous motions on the skin to prevent confusion. We recommend using no more than two different motion types simultaneously on the skin, as users already struggle to identify them. For using the same motion type on the neck, simultaneous motions should not exceed four, aligning with Woźniak et al. [98], who report that their 4-actuator design performed best. The amount of simultaenous motions on the skin also depends very much on the tactile acuity of that specific part of the body [53]. For other skin areas, which can be smaller or bigger, exact limits of the tactile acuity should be verified in future studies considering established methods to test tactile acuity [28]. Still, 28/30 participants agreed that getting touched by the necklace was a positive feeling, which encourages designing shape-changing interfaces for future use on the human body. Participants also underline this by associating motions with a hug, massage, or tickling, which are generally associated with warmth and positive feelings.

5 Implications For Design

Key design implications from both studies for wearable shape-changing interfaces include:

1. Use repetition of motion to strengthen the emotional tone perceived by an observer or wearer, i.e., how positive or negative an emotion is conveyed.
2. Use repetition to convey a more exciting motion to the observer and the wearer.
3. Design motions that mimic gestures to convey an emotion with specific valence levels.
4. Use low-speed repetitive motions instead of non-repetitive motions for less aroused motions.
5. For wearing the necklace: Use symmetric motions to convey a particular positive emotion and asymmetric motions for less positive emotions.
6. Use visible shape changes of observable wearable shape-changing interfaces for symbolic communication, as observers tend to form a full symbol out of the whole pendant and soft robots.
7. Use tactile shape changes as stimuli to encourage interpreting the motions as single cues to your body that users can recall from their experience with tactile cues, as wearers tend to interpret the single motions of the robots instead of forming them into one full object.
8. Limit the number of simultaneous tactile motions on the skin to avoid overwhelming the wearer.

6 Limitations and Future Work

Our prototype featured only cuboid-finger actuators, limiting our results' generalizability. Future studies should explore other shapes, such as spheres or cylinders, to assess shape-dependent effects for more generalizable findings. Investigating the effect of even faster repetition may require another actuation mechanism, such as *FlowIO* [79].

Another factor not included in our study is the color of the jewelry piece, although color can convey certain emotions [52].

The non-balanced presentation order may have influenced how participants imagined the robots when wearing them, since they had not yet seen the motions before. Fatigue effects were mainly possible in the observing condition. A future study could use a between-subjects design to examine how emotional responses compare to our findings. Finally, our studies did not collect physiological data, such as heart rate, breathing rate, or electrodermal activity, which could provide deeper insights into how specific shape changes are perceived. The wearer's physiological data may also help a device to decide which shape change to execute.

7 Conclusion

This work investigated the individual impact of several parameters of shape change, such as *motion type*, *repetition*, *repetition*, *amplitude*, and exterior materiality, on the emotions that this shape change conveys to observers and wearers. In our two user studies, we investigated how participants rated the emotions conveyed on *valence* and *arousal* dimensions of Russell's circumplex model in three different setups: observing a shape-changing necklace on videos (Study 1), observing it in reality (Study 2), and feeling its shape change while wearing it (also Study 2). Both studies revealed that motion type, repetition, and amplitude can be isolated as factors that deliberately convey an emotional state. All these shape change parameters generate complex correlations with effects on the *valence* and *arousal levels* of emotions conveyed. Study 2 showed that symmetrical actuations were identified more accurately and rated higher in valence and arousal when observing real shape changes and when wearing the necklace. Additionally, even when wearers misidentified motions by touch alone, their emotional ratings still aligned with those of observers. To better understand these effects, we collected participants' associations with each motion, offering us insights into their mental models and experiences.

To support replication and future research, we provide details on our fabrication process and our design tool to generate molds to fabricate customized fiber-reinforced actuators, as well as all supporting files, such as 3D models, actuator videos, and data from our results, as supplementary materials to this paper.

Overall, our work provides results that shed more light on the complex interplay of fundamental shape change parameters and the emotions thus conveyed. We hope our findings will help researchers and designers create shape-changing interfaces that communicate emotions to their environment more precisely and predictably.

References

[1] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19).* Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300414

[2] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. 2018. Grand Challenges in Shape-Changing Interface Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18).* Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3173574.3173873

[3] Bijetri Biswas, Emma Powell, Robert Nixdorf, Richard Sewell, and Anne Roudaut. 2025. Encounter with the Giants: Understanding Interaction with Large-scale Inflatable Soft Robots. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, Article 734, 15 pages. https://doi.org/10.1145/3706598.3713673

[4] Bhargavi Rao Bondada, Shrutee Dwa, Upama Thapa Magar, Jerry Denning, Meherunessa Tania, and Jerry Alan Fails. 2025. Soul Support: Designing Hopeful Wearables for Children's Emotional Wellness. In *Proceedings of the 24th Interaction Design and Children (IDC '25)*. Association for Computing Machinery, New York, NY, USA, 1163–1165. https://doi.org/10.1145/3713043.3737389

[5] Anke Brocker, Jose A. Barreiros, Ali Shtarbanov, Kristian Gohlke, Ozgun Kilic Afsar, and Sören Schröder. 2022. Actuated Materials and Soft Robotics Strategies for Human-Computer Interaction Design. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 81, 7 pages. https://doi.org/10.1145/3491101.3503711

[6] Anke Brocker, Ekaterina Nedorubkova, Simon Voelker, and Jan Borchers. 2023. Exploring Shape Designs for Soft Robotics and Users' Associations with Them. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI EA '23)*. Association for Computing Machinery, New York, NY, USA, Article 120, 7 pages. https://doi.org/10.1145/3544549.3585606

[7] Anke Brocker, Jakob Strüver, Simon Voelker, and Jan Borchers. 2022. SoRoCAD: A Design Tool for the Building Blocks of Pneumatic Soft Robotics. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 330, 7 pages. https://doi.org/10.1145/3491101.3519770

[8] Paul Bucci, Lotus Zhang, Xi Laura Cang, and Karon E. MacLean. 2018. Is It Happy? Behavioural and Narrative Frame Complexity Impact Perceptions of a Simple Furry Robot's Emotions. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3173574.3174083

[9] Oğuz 'Oz' Buruk, Çağlar Genç, İhsan Ozan Yıldırım, Mehmet Cengiz Onbaşlı, and Oğuzhan Özcan. 2021. Snowflakes: A Prototyping Tool for Computational Jewelry. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3411764.3445173

[10] James Carpenter and John Bithell. 2000. Bootstrap Confidence Intervals: When, Which, What? A Practical Guide for Medical Statisticians. *Statistics in medicine* 19, 9 (2000), 1141–1164. https://doi.org/10.1002/(SICI)1097-0258(20000515)19:9<1141::AID-SIM479>3.0.CO;2-F

[11] Nick Cheney, Josh Bongard, and Hod Lipson. 2015. Evolving Soft Robots in Tight Spaces. In *Proceedings of the 2015 Annual Conference on Genetic and Evolutionary Computation* (Madrid, Spain) *(GECCO '15)*. Association for Computing Machinery, New York, NY, USA, 935–942. https://doi.org/10.1145/2739480.2754662

[12] Mark Coulson. 2004. Attributing Emotion to Static Body Postures: Recognition Accuracy, Confusions, and Viewpoint Dependence. *Journal of Nonverbal Behavior* 28, 2 (2004), 117–139. https://doi.org/10.1023/B:JONB.0000023655.25550.be

[13] Stephen Coyle, Carmel Majidi, Philip LeDuc, and K. Jimmy Hsia. 2018. Bio-inspired Soft Robotics: Material Selection, Actuation, and Design. *Extreme Mechanics Letters* 22 (2018), 51–59. https://doi.org/10.1016/j.eml.2018.05.003

[14] Adam K. Coyne, Andrew Murtagh, and Conor McGinn. 2020. Using the Geneva Emotion Wheel to Measure Perceived Affect in Human-Robot Interaction. In *Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction* (Cambridge, United Kingdom) *(HRI '20)*. Association for Computing Machinery, New York, NY, USA, 491–498. https://doi.org/10.1145/3319502.3374834

[15] John R Crawford and Julie D Henry. 2004. The Positive and Negative Affect Schedule (PANAS): Construct Validity, Measurement Properties and Normative Data in a LargeNnon-clinical Sample. *British Journal of Clinical Psychology* 43, Pt 3 (2004), 245–265. https://doi.org/10.1348/0144665031752934

[16] Gaia Crippa, Valentina Rognoli, and Marinella Levi. 2012. Materials and Emotions: A Study on the Relations Between Materials and Emotions in Industrial Products. https://api.semanticscholar.org/CorpusID:169718969

[17] Geoff Cumming. 2013. The New Statistics: Why and How. *Psychological Science Psychol Sci* 25, 1 (2013), 7–29. https://doi.org/10.1177/0956797613504966

[18] Felecia Davis. 2015. A Study Relating Computational Textile Textural Expression to Emotion. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 1977–1982. https://doi.org/10.1145/2702613.2732739

[19] Felecia Davis. 2015. The Textility of Emotion: A Study Relating Computational Textile Textural Expression to Emotion. In *Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition* (Glasgow, United Kingdom) *(C&C '15)*. Association for Computing Machinery, New York, NY, USA, 23–32. https://doi.org/10.1145/2757226.2757231

[20] Felecia Davis, Asta Roseway, Erin Carroll, and Mary Czerwinski. 2013. Actuating Mood: Design of the Textile Mirror. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 99–106. https://doi.org/10.1145/2460625.2460640

[21] Artem Dementyev, Hsin-Liu (Cindy) Kao, Inrak Choi, Deborah Ajilo, Maggie Xu, Joseph A. Paradiso, Chris Schmandt, and Sean Follmer. 2016. Rovables: Miniature On-Body Robots as Mobile Wearables. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 111–120. https://doi.org/10.1145/2984511.2984531

[22] Pierre Dragicevic. 2016. Fair Statistical Communication in HCI. In *Modern Statistical Methods for HCI*, Judy Robertson and Maurits Kaptein (Eds.). Springer International Publishing, Cham, 291–330.

[23] Jiachun Du, Panos Markopoulos, Qi Wang, Marina Toeters, and Ting Gong. 2018. ShapeTex: Implementing Shape-Changing Structures in Fabric for Wearable Actuation. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 166–176. https://doi.org/10.1145/3173225.3173245

[24] Zhuzhi Fan, Alexis Sanson, Thomas Rames, and Céline Coutrix. 2024. Design and Perception of a Soft Shape Change Beneath a Smartwatch. , 23 pages. https://doi.org/10.1145/3676495

[25] Jutta Fortmann, Erika Root, Susanne Boll, and Wilko Heuten. 2016. Tangible Apps Bracelet: Designing Modular Wrist-Worn Digital Jewellery for Multiple Purposes. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, QLD, Australia) *(DIS '16)*. Association for Computing Machinery, New York, NY, USA, 841–852. https://doi.org/10.1145/2901790.2901838

[26] Kevin Galloway, Panagiotis Polygerinos, Conor Walsh, and Robert Wood. 2013. Mechanically Programmable Bend Radius for Fiber-reinforced Soft Actuators. , 6 pages. https://doi.org/10.1109/ICAR.2013.6766586

[27] 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* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 109–117. https://doi.org/10.1145/3126594.3126598

[28] Daniel S. Harvie, Joan Kelly, Hayden Buckman, Jonathan Chan, Grace Sutherland, Mark Catley, James Novak, Neil Tuttle, and Michele Sterling. 2017. Tactile acuity testing at the neck: A comparison of methods. *Musculoskeletal Science and Practice* 32 (2017), 23–30. https://doi.org/10.1016/j.msksp.2017.07.007

[29] Liang He, Cheng Xu, Ding Xu, and Ryan Brill. 2015. PneuHaptic: delivering haptic cues with a pneumatic armband. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers* (Osaka, Japan) *(ISWC '15)*. Association for Computing Machinery, New York, NY, USA, 47–48. https://doi.org/10.1145/2802083.2802091

[30] Matthew Hertenstein, Julie Verkamp, Alyssa Kerestes, and Rachel Holmes. 2006. The Communicative Functions of Touch in Humans, Nonhuman Primates, and Rats: A Review and Synthesis of the Empirical Research. *Genetic, social, and general psychology monographs* 132 (03 2006), 5–94. https://doi.org/10.3200/MONO.132.1.5-94

[31] Donal P. Holland, Colette Abah, Marielena Velasco Enriquez, Herman Maxwell, J. Bennett Gareth, Emir Augusto Vela, and J Walsh Conor. 2017. The Soft Robotics Toolkit: Strategies for Overcoming Obstacles to the Wide Dissemination of Soft-Robotic Hardware. *IEEE Robotics and Automation Magazine, Special Issue on Open Source and Widely Disseminated Robot Hardware* 24, 1 (2017), 57–64. https://doi.org/10.1109/MRA.2016.2639067

[32] Yuhan Hu and Guy Hoffman. 2019. Using Skin Texture Change to Design Emotion Expression in Social Robots. In *Proceedings of the 14th ACM/IEEE International Conference on Human-Robot Interaction* (Daegu, Republic of Korea) *(HRI '19)*. IEEE Press, 2–10. https://doi.org/10.1109/HRI.2019.8673012

[33] Yuhan Hu, Zhengnan Zhao, Abheek Vimal, and Guy Hoffman. 2018. Soft Skin Texture Modulation for Social Robotics. In *2018 IEEE International Conference on Soft Robotics (RoboSoft)*. IEEE, 182–187. https://doi.org/10.1109/ROBOSOFT.2018.8404917

[34] Jörn Hurtienne. 2011. *Image Schemas and Design for Intuitive Use.* Ph. D. Dissertation. https://doi.org/10.14279/depositonce-2753

[35] Jonna Häkkilä, Romina Poguntke, Emmi Harjuniemi, Lauri Hakala, Ashley Colley, and Albrecht Schmidt. 2020. BuSiNec - Studying the Effects of a Busyness Signifying Necklace in the Wild. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference (DIS '20)*. Association for Computing Machinery, New York, NY, USA, 2177–2188. https://doi.org/10.1145/3357236.3395455

[36] Filip Ilievski, Aaron D. Mazzeo, Robert F. Shepherd, Xin Chen, and George M. Whitesides. 2011. Soft Robotics for Chemists. *Angewandte Chemie International Edition Angew. Chem. Int. Ed.* 50, 8 (2011), 1890–1895. https://doi.org/10.1002/anie.201006464

[37] Virve Inget, Heiko Müller, and Jonna Häkkilä. 2019. Private and Public Aspects of Smart Jewellery: A Design Exploration Study. In *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia* (Pisa, Italy) *(MUM '19)*. Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/3365610.3365613

[38] Pradthana Jarusriboonchai, Hong Li, Emmi Harjuniemi, Heiko Müller, and Jonna Häkkilä. 2020. Always with Me: Exploring Wearable Displays as a Lightweight Intimate Communication Channel. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 771–783. https://doi.org/10.1145/3374920.3375011

[39] Mark Johnson. 2016. *A Definition of an Image Schema (1987).* De Gruyter (A), Berlin, Boston, 104–105. https://doi.org/doi:10.1515/9783050093833-018

[40] Alexandra Ling Ju and Mirjana Spasojevic. 2015. Smart Jewelry: The Future of Mobile User Interfaces. In *Proceedings of the 2015 Workshop on Future Mobile User Interfaces* (Florence, Italy) *(FutureMobileUI '15)*. Association for Computing Machinery, New York, NY, USA, 13–15. https://doi.org/10.1145/2754633.2754637

[41] Frederike Jung. 2022. It's Not Warm But That's Okay: About Robots That Avoid Human Stereotypes. In *Nordic Human-Computer Interaction Conference* (Aarhus, Denmark) *(NordiCHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 48, 15 pages. https://doi.org/10.1145/3546155.3546695

[42] Hsin-Liu (Cindy) Kao, Deborah Ajilo, Oksana Anilionyte, Artem Dementyev, Inrak Choi, Sean Follmer, and Chris Schmandt. 2017. Exploring Interactions and Perceptions of Kinetic Wearables. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (Edinburgh, United Kingdom) *(DIS '17)*. Association for Computing Machinery, New York, NY, USA, 391–396. https://doi.org/10.1145/3064663.3064686

[43] Dacher Keltner, Disa Sauter, Jessica Tracy, and Alan Cowen. 2019. Emotional Expression: Advances in Basic Emotion Theory. https://doi.org/10.1007/s10919-019-00293-3

[44] Hyunyoung Kim, Céline Coutrix, and Anne Roudaut. 2018. KnobSlider: Design of a Shape-Changing UI for Parameter Control. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173913

[45] Hyunyoung Kim, Celine Coutrix, and Anne Roudaut. 2018. Morphees+: Studying Everyday Reconfigurable Objects for the Design and Taxonomy of Reconfigurable UIs. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3173574.3174193

[46] Hyunyoung Kim, Aluna Everitt, Carlos Tejada, Mengyu Zhong, and Daniel Ashbrook. 2021. MorpheesPlug: A Toolkit for Prototyping Shape-Changing Interfaces. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 101, 13 pages. https://doi.org/10.1145/3411764.3445786

[47] Amy Koike, Michael Wehner, and Bilge Mutlu. 2024. Sprout: Designing Expressivity for Robots Using Fiber-Embedded Actuator. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction* (Boulder, CO, USA) *(HRI '24)*. Association for Computing Machinery, New York, NY, USA, 403–412. https://doi.org/10.1145/3610977.3634983

[48] Nantia Koulidou and Robb Mitchell. 2021. Art Digital Jewellery: Practitioners' Perspectives. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3430524.3440648

[49] Lester E. Krueger. 1975. Familiarity Effects in Visual Information Processing. *Psychological Bulletin* 82, 6 (1975), 949–974. https://doi.org/10.1037/0033-2909.82.6.949

[50] Matthijs Kwak, Kasper Hornbæk, Panos Markopoulos, and Miguel Bruns Alonso. 2014. The design space of shape-changing interfaces: a repertory grid study. In *Proceedings of the 2014 Conference on Designing Interactive Systems* (Vancouver, BC, Canada) *(DIS '14)*. Association for Computing Machinery, New York, NY, USA, 181–190. https://doi.org/10.1145/2598510.2598573

[51] Hong Li, Pradthana Jarusriboonchai, Heiko Müller, Emmi Harjuniemi, and Jonna Häkkilä. 2020. Emotional Communication Between Remote Couples: Exploring the Design of Wearable Ambient Displays. In *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society* (Tallinn, Estonia) *(NordiCHI '20)*. Association for Computing Machinery, New York, NY, USA, Article 34, 5 pages. https://doi.org/10.1145/3419249.3420139

[52] Diana Löffler, Nina Schmidt, and Robert Tscharn. 2018. Multimodal Expression of Artificial Emotion in Social Robots Using Color, Motion and Sound. In *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction* (Chicago, IL, USA) *(HRI '18)*. Association for Computing Machinery, New York, NY, USA, 334–343. https://doi.org/10.1145/3171221.3171261

[53] Flavia Mancini, Armando Bauleo, Jonathan Cole, Fausta Lui, Carlo A. Porro, Patrick Haggard, and Gian Domenico Iannetti. 2014. Whole-body mapping of spatial acuity for pain and touch. *Annals of Neurology* 75, 6 (2014), 917–924. https://doi.org/10.1002/ana.24179

[54] Philipp. Mayring. 2015. *Qualitative Inhaltsanalyse: Grundlagen und Techniken.* Beltz.

[55] Cameron S. Miner, Denise M. Chan, and Christopher Campbell. 2001. Digital Jewelry: Wearable Technology for Everyday Life. In *CHI '01 Extended Abstracts on Human Factors in Computing Systems* (Seattle, Washington) *(CHI EA '01)*. Association for Computing Machinery, New York, NY, USA, 45–46. https://doi.org/10.1145/634067.634098

[56] Hedieh Moradi and César Torres. 2020. Siloseam: A Morphogenetic Workflow for the Design and Fabrication of Inflatable Silicone Bladders. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 1995–2006. https://doi.org/10.1145/3357236.3395473

[57] Ken Nakagaki, Artem Dementyev, Sean Follmer, Joseph A. Paradiso, and Hiroshi Ishii. 2016. ChainFORM: A Linear Integrated Modular Hardware System for Shape Changing Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 87–96. https://doi.org/10.1145/2984511.2984587

[58] Ryuta Nakajima, Shuichi Shigeno, Letizia Zullo, Fabio De Sio, and Markus Schmidt. 2018. Cephalopods Between Science, Art, and Engineering: A Contemporary Synthesis. *Frontiers in Communication* 3 (2018). https://doi.org/10.3389/fcomm.2018.00020

[59] Ryosuke Nakayama, Ryo Suzuki, Satoshi Nakamaru, Ryuma Niiyama, Yoshihiro Kawahara, and Yasuaki Kakehi. 2019. MorphIO: Entirely Soft Sensing and Actuation Modules for Programming Shape Changes through Tangible Interaction. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 975–986. https://doi.org/10.1145/3322276.3322337

[60] Yashraj S. Narang, Joost J. Vlassak, and Robert D. Howe. 2018. Mechanically Versatile Soft Machines through Laminar Jamming. *Advanced Functional Materials Adv. Funct. Mater.* 28, 17 (2018), 1707136. https://doi.org/10.1002/adfm.201707136

[61] Kristin Neidlinger, Lianne Toussaint, Edwin Dertien, Khiet P. Truong, Hermie Hermens, and Vanessa Evers. 2019. Emotional Prosthesis for Animating Awe through Performative Biofeedback. In *Proceedings of the 2019 ACM International Symposium on Wearable Computers* (London, United Kingdom) *(ISWC '19)*. Association for Computing Machinery, New York, NY, USA, 312–317. https://doi.org/10.1145/3341163.3346939

[62] Isabel Neto, Yuhan Hu, Filipa Correia, Filipa Rocha, Guy Hoffman, Hugo Nicolau, and Ana Paiva. 2024. Conveying Emotions through Shape-changing to Children with and without Visual Impairment. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 49, 16 pages. https://doi.org/10.1145/3613904.3642525

[63] Madalina Nicolae, Claire Lefez, Anne Roudaut, Samuel Huron, Jürgen Steimle, and Marc Teyssier. 2024. SoftBioMorph: Fabricating Sustainable Shape-changing Interfaces using Soft Biopolymers. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference* (Copenhagen, Denmark) *(DIS '24)*. Association for Computing Machinery, New York, NY, USA, 496–508. https://doi.org/10.1145/3643834.3661610

[64] Jifei Ou, Felix Heibeck, and Hiroshi Ishii. 2016. TEI 2016 Studio: Inflated Curiosity. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 766–769. https://doi.org/10.1145/2839462.2854119

[65] Matthew Pateman, Daniel Harrison, Paul Marshall, and Marta E. Cecchinato. 2018. The Role of Aesthetics and Design: Wearables in Situ. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI EA '18)*. Association for Computing Machinery, New York, NY, USA, 1–6. https://doi.org/10.1145/3170427.3188556

[66] B. Petermann. 1929. *Die Wertheimer-Koffka-Köhlersche Gestalttheorie und das Gestaltproblem Systematisch und Kritisch dargestellt: ein Kapitel aus der Prinzipienrevision in der Gegenwärtigen Psychologie.* Barth. https://books.google.de/books?id=zgVVAAAAMAAJ

[67] Henning Pohl, Peter Brandes, Hung Ngo Quang, and Michael Rohs. 2017. Squeezeback: Pneumatic Compression for Notifications. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 5318–5330. https://doi.org/10.1145/3025453.3025526

[68] Panagiotis Polygerinos, Zheng Wang, Johannes T. B. Overvelde, Kevin C. Galloway, Robert J. Wood, Katia Bertoldi, and Conor J. Walsh. 2015. Modeling of Soft Fiber-Reinforced Bending Actuators. *IEEE Transactions on Robotics* 31, 3 (2015), 778–789. https://doi.org/10.1109/TRO.2015.2428504

[69] Jonathan Posner, James A. Russell, and Bradley S. Peterson. 2005. The Circumplex Model of Affect: An Integrative Approach to Affective Neuroscience, Cognitive Development, and Psychopathology. *Development and Psychopathology* 17, 3 (2005), 715–734. https://doi.org/10.1017/S0954579405050340

[70] 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* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–23. https://doi.org/10.1145/3173574.3173948

[71] Inka Rantala, Ashley Colley, and Jonna Häkkilä. 2018. Smart Jewelry: Augmenting Traditional Wearable Self-Expression Displays. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays* (Munich, Germany) *(PerDis '18)*. Association for Computing Machinery, New York, NY, USA, Article 22, 8 pages. https://doi.org/10.1145/3205873.3205891

[72] Inka Rantala, Ashley Colley, and Jonna Häkkilä. 2018. Smart Jewelry: Augmenting Traditional Wearable Self-Expression Displays. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays* (Munich, Germany) *(PerDis '18)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3205873.3205891

[73] Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. 2012. Shape-changing interfaces: a review of the design space and open research questions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 735–744. https://doi.org/10.1145/2207676.2207781

[74] James A. Russell. 1980. A Circumplex Model of Affect. *Journal of Personality and Social Psychology* 39 (1980), 1161–1178. https://doi.org/10.1037/h0077714

[75] Mona Safari. 2025. HiPalm: Wearable Device for Affective Tactile Interpersonal Communication. In *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '25)*. Association for Computing Machinery, New York, NY, USA, Article 63, 8 pages. https://doi.org/10.1145/3689050.3705974

[76] Mona Safari, Kate Hartman, and Nick Puckett. 2025. SOFT OBJECTS: Prototyping for Tactile Interpersonal Communication. In *Proceedings of the 2025 ACM Designing Interactive Systems Conference (DIS '25)*. Association for Computing Machinery, New York, NY, USA, 331–346. https://doi.org/10.1145/3715336.3735440

[77] Erno Salmela and Ivary Vimm. 2017. Digital Smart Jewelry: Next Revolution of Jewelry Industry? In *Digital Transformation in Smart Manufacturing*, Antonella Petrillo, Raffaele Cioffi, and Fabio De Felice (Eds.). IntechOpen, Rijeka, Chapter 7. https://doi.org/10.5772/intechopen.71705

[78] Klaus Scherer, Vera Shuman, Johnny Fontaine, and Cristina Soriano. 2015. The GRID Meets the Wheel: Assessing Emotional Feeling Via Self-report. In *Components of emotional meaning: A sourcebook.* Oxford University Press, 281–298.

[79] Ali Shtarbanov. 2021. FlowIO Development Platform – the Pneumatic "Raspberry Pi" for Soft Robotics. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems (CHI EA '21)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3411763.3451513

[80] Ali Shtarbanov, Anke Brocker, Adriana Cabrera, Yuhan Hu, Heiko Müller, and Alex Mazursky. 2023. Soft Robotics and Programmable Materials for Human-Computer Interaction. In *Companion Publication of the 2023 ACM Designing Interactive Systems Conference* (Pittsburgh, PA, USA) *(DIS '23 Companion)*. Association for Computing Machinery, New York, NY, USA, 110–113. https://doi.org/10.1145/3563703.3591460

[81] Leigh Simmons, Gillian Rhodes, Marianne Peters, and Nicole Koehler. 2004. Are Human Preferences for Facial Symmetry Focused on Signals of Developmental Instability? *Behavioral Ecology* 15 (06 2004), 864–871. https://doi.org/10.1093/beheco/arh099

[82] Jocelyn Smith and Karon MacLean. 2007. Communicating Emotion Through a Haptic Link: Design Space and Methodology. , 376-387 pages. https://doi.org/10.1016/j.ijhcs.2006.11.006 Evaluating affective interactions.

[83] Sichao Song and Seiji Yamada. 2017. Expressing Emotions through Color, Sound, and Vibration with an Appearance-Constrained Social Robot. In *Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction* (Vienna, Austria) *(HRI '17)*. Association for Computing Machinery, New York, NY, USA, 2–11. https://doi.org/10.1145/2909824.3020239

[84] Yi Song. 2019. Innovation of Smart Jewelry for the Future. *International Journal of Performability Engineering* (01 2019). https://doi.org/10.23940/ijpe.19.02.p23.591601

[85] Paul Strohmeier, Juan Pablo Carrascal, Bernard Cheng, Margaret Meban, and Roel Vertegaal. 2016. An Evaluation of Shape Changes for Conveying Emotions. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 3781–3792. https://doi.org/10.1145/2858036.2858537

[86] Yi Sun, Yun Seong Song, and Jamie Paik. 2013. Characterization of Silicone Rubber Based Soft Pneumatic Actuators. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 4446–4453. https://doi.org/10.1109/IROS.2013.6696995

[87] Koichi Suzumori, Shoichi Iikura, and Hiroohisa Tanaka. 1991. Flexible Microactuator for Miniature Robots. In *[1991] Proceedings. IEEE Micro Electro Mechanical Systems*. IEEE, 204–209. https://doi.org/10.1109/memsys.1991.114797

[88] Haodan Tan, John Tiab, Selma Šabanović, and Kasper Hornbæk. 2016. Happy Moves, Sad Grooves: Using Theories of Biological Motion and Affect to Design Shape-Changing Interfaces. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, QLD, Australia) *(DIS '16)*. Association for Computing Machinery, New York, NY, USA, 1282–1293. https://doi.org/10.1145/2901790.2901845

[89] Shan-Yuan Teng, Tzu-Sheng Kuo, Chi Wang, Chi-huan Chiang, Da-Yuan Huang, Liwei Chan, and Bing-Yu Chen. 2018. PuPoP: Pop-up Prop on Palm for Virtual Reality. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 5–17. https://doi.org/10.1145/3242587.3242628

[90] Seçil Uğur, Raffaella Mangiarotti, Monica Bordegoni, Marina Carulli, S. A. G. Wensveen, and I. Laura Duncker. 2011. An Experimental Research Project: Wearable Technology for Embodiment of Emotions. In *Proceedings of the 2011 Conference on Designing Pleasurable Products and Interfaces* (Milano, Italy) *(DPPI '11)*. Association for Computing Machinery, New York, NY, USA, Article 32, 8 pages. https://doi.org/10.1145/2347504.2347539

[91] Sanne van Waveren, Linnéa Björklund, Elizabeth J. Carter, and Iolanda Leite. 2019. Knock on Wood: The Effects of Material Choice on the Perception of Social Robots. In *Social Robotics*. Springer International Publishing, Cham, 211–221. https://doi.org/10.1007/978-3-030-35888-4_20

[92] Verindi Vekemans, Ward Leenders, Sijie Zhu, and Rong-Hao Liang. 2021. MOTUS: Rendering Emotions with a Wrist-Worn Tactile Display. In *2021 International Symposium on Wearable Computers (ISWC '21)*. Association for Computing Machinery, New York, NY, USA, 159–161. https://doi.org/10.1145/3460421.3480390

[93] Maarten Versteeg, Elise van den Hoven, and Caroline Hummels. 2016. Interactive Jewellery: A Design Exploration. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 44–52. https://doi.org/10.1145/2839462.2839504

[94] Anna Walczak, Mikołaj P. Woźniak, Aleksandra Wysokińska, Magdalena Wróbel-Lachowska, Heiko Müller, Andrzej Romanowski, and Susanne Boll. 2023. 'There's More to It than Allure...' – Navigating Socio-Cultural Roles of Digital Jewellery. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI EA '23)*. Association for Computing Machinery, New York, NY, USA, Article 278, 7 pages. https://doi.org/10.1145/3544549.3585851

[95] Walker, Zidek, Harbel, Yoon Jin-Ha, Strickland, Kumar, and Heonseop Shin. 2020. Soft Robotics: A Review of Recent Developments of Pneumatic Soft Actuators. *Actuators* 9 (01 2020), 3. https://doi.org/10.3390/act9010003

[96] Michael Wehner, Ryan L. Truby, Daniel J. Fitzgerald, Bobak Mosadegh, George M. Whitesides, Jennifer A. Lewis, and Robert J. Wood. 2016. An integrated design and fabrication strategy for entirely soft, autonomous robots. *Nature* 536, 7617 (08 2016), 451–455. https://doi.org/10.1038/nature19100

[97] Ronald Wheeler. 2015. We All Do It: Unconscious Behavior, Bias, and Diversity. *Law library journal* 107 (03 2015), 325–331.

[98] Mikołaj P. Woźniak, Anna Walczak, Adam Jan Sałata, Magdalena Wróbel-Lachowska, Krzysztof Grudzień, Heiko Müller, Susanne Boll, and Andrzej Romanowski. 2023. Exploring Recognition Accuracy of Vibrotactile Stimuli in Sternoclavicular Area. In *Proceedings of the 2023 ACM International Symposium on Wearable Computers* (Cancun, Quintana Roo, Mexico) *(ISWC '23)*. Association for Computing Machinery, New York, NY, USA, 98–103. https://doi.org/10.1145/3594738.3611372

[99] Youchan Yim and Fumihide Tanaka. 2024. Integration of a Shape Memory Alloy with a Soft Pneumatic Actuator to Improve the Haptic Interaction Performance of a Soft Social Robot. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '24)*. Association for Computing Machinery, New York, NY, USA, Article 198, 8 pages. https://doi.org/10.1145/3613905.3650922