It's Touching: Understanding Touch-Affect Association in Shape-Change with Kinematic Features

Feng Feng
University of Bristol
Bristol, UK
f.feng@bristol.ac.uk

Dan Bennett
University of Bristol
Bristol, UK
db15237@bristol.ac.uk

Zhijun Fan
Shandong University
Jinan, China
Fanzhijun@sdu.edu.cn

Oussama Metatla
University of Bristol
Bristol, UK
o.metatla@bristol.ac.uk

pic2.png

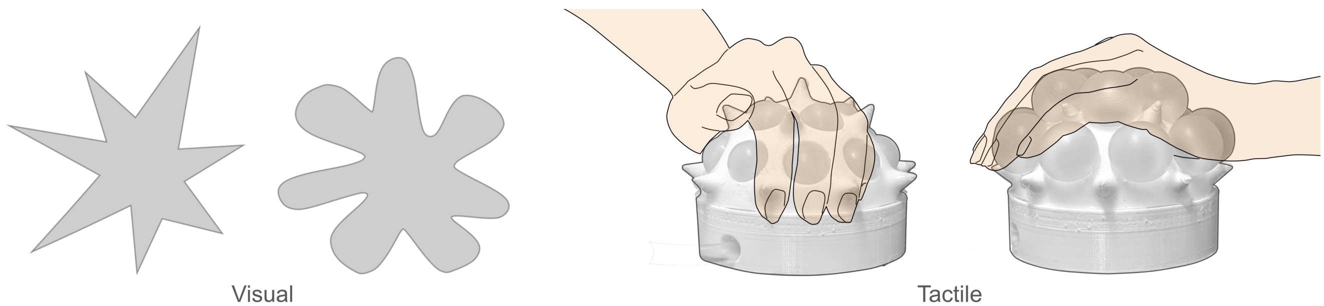

Figure 1: Visual [51] and tactile perception with "Bouba" and "Kiki" features.

ABSTRACT

With the proliferation of shape-change research in affective computing, there is a need to deepen understandings of affective responses to shape-change display. Little research has focused on affective reactions to tactile experiences in shape-change, particularly in the absence of visual information. It is also rare to study response to the shape-change as it unfolds, isolated from a final shape-change outcome. We report on two studies on touch-affect associations, using the crossmodal "Bouba-Kiki" paradigm, to understand affective responses to shape-change as it unfolds. We investigate experiences with a shape-change gadget, as it moves between rounded ("Bouba") and spiky ("Kiki") forms. We capture affective responses via the circumplex model, and use a motion analysis approach to understand the certainty of these responses. We find that touch-affect associations are influenced by both the size and the frequency of the shape-change and may be modality-dependent, and that certainty in affective associations is influenced by association-consistency.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; **Empirical studies in HCI**.

KEYWORDS

tactile, shape-change as it unfolds, affect, emotion, certainty, crossmodal, Bouba/Kiki

ACM Reference Format:
Feng Feng, Dan Bennett, Zhijun Fan, and Oussama Metatla. 2022. It's Touching: Understanding Touch-Affect Association in Shape-Change with Kinematic Features. In *CHI Conference on Human Factors in Computing Systems (CHI '22), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3491102.3502003

1 INTRODUCTION

Shape-change is increasingly relevant in affective interaction research [2, 65], with potential application areas for affective aspects of shape-change including therapeutics and social robotics where it has been demonstrated that shape-change functions can broaden communication capabilities [11, 20, 31]. As shape-change research expands and as applications proliferate, there is thus a real need to increase our understanding of affective responses to shape-change.

However, a recent paper on "grand challenges" in shape-change research has pointed to barriers to understanding affective responses in existing approaches to the study of shape-change [2]. The authors point out that while previous work has linked shape-change to the experience of particular feelings, this work has often

CHI '22, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9157-3/22/04...$15.00
https://doi.org/10.1145/3491102.3502003

failed to isolate particular factors and outcomes during the experience. They call for greater attention to "shape-change as it unfolds", and to the isolation of particular factors in the shape change experience. In particular they point to the difficulty in isolating effects of different modalities (e.g. visual, haptic), and the fact that understanding of the value introduced by non-visual changes is necessary to justify the cost and complexity of shape changing interfaces. In much work to date, even where the importance of tactile properties is emphasised, experiments have remained restricted to the visual modality (often for practical reasons, e.g. [65, 68]). Even in cases which focus on tactile effects, these are generally not isolated from visual experience. Isolating the effects of tactile and visual features of shape change is important both due to the dominance of the visual sense in multisensory experience [2, 45], and due to the need to understand interactions in the absence of vision - for example in eyes-free information display [32, 72], or in designing for populations with impaired or absent vision [54]. A more systematic approach to the effect of shape-change on affective response can address these issues, and help us to "develop a language which supports the articulation of properties, experiences, or sensations" in product design [2].

In this paper we introduce concepts and methods from psychology to help understand tactile experiences of shape-change in a systematic manner. We ground our work in theories of crossmodal interaction [34] and introduce methodologies from recent psychology on the analysis of mouse-trajectories to understand certainty in decisions and attributions [24]. Crossmodal interaction describes the phenomenon where perception in one sensory modality influences perception in other sensory modalities. One of the most well-known and well-investigated phenomena in this area centres on the so-called Bouba/Kiki paradigm [51]. In this phenomenon when presented with rounded and jagged 2D shapes, participants consistently associate the rounded shape with the arbitrary sound 'Bouba' and the jagged shape with the arbitrary word 'Kiki'. Later studies have shown that this crossmodal effect can occur across vision, audition, touch, and olfactory and that it even occurs at amodel levels such as semantics and emotions [33, 39, 52]. Previous work has also shown that haptic perception of tangible 'Bouba' and 'Kiki'-like shapes can be attributed to particular emotional categories, where jagged shapes tend to be high arousal, and rounded shapes with calmer affects [42]. In another study, touch sensations on similar Bouba/Kiki tangible 3D shapes were found to be associated with levels of visual brightness, and to share the same affective valence [38]. We build on this line of research using the same Bouba/Kiki paradigm to extend understandings of touch-shape association, focusing on both affective responses to the process of shape-change as it unfolds, and the certainty of these responses.

To the best of our knowledge previous work has not investigated certainty of affective responses to shape-changing stimuli. It seems reasonable that speed or size of change may affect certainty, either due to the way these features affect the intensity of the sensation, or due to the way they interact with limitations in sensory processing. To understand the level of certainty in our user's attributions of affect we build on another well established paradigm in psychology - the analysis of mouse movements when making choices and attributions to provide a window on underlying cognitive processes. Grounded in Spivey's work on dynamical aspects of cognition [24], a large body of work in psychology has investigated the way cognitive processes unfold in time and leave traces in overt movement behaviour, in particular during decision and attribution tasks [5]. In recent years this work has passed over into application research and researchers in affective computing and elsewhere have applied the infer uncertainty and emotion [70].

We develop two experiments studying affective responses to shape-change as it unfolds. The first of these focuses on the size of shape-change stimuli, and the second on its frequency. In both experiments participants touch a palm-sized shape-change gadget which we developed for these experiments. This gadget can present both jagged (Kiki-like) and rounded (Bouba-like) touch-stimuli, and change continuously between the two. Participants touched this object, which was concealed to avoid presenting a visual stimulus, as it transformed between Bouba-like and Kiki-like states, then reported their affective responses on a Circumplex Model [57], using a methodology which supported the analysis of certainty in movement behaviour, as introduced above. Study 1 aimed to replicate the touch-affect associations identified in previous research [38, 42] with the same Bouba/Kiki paradigm and to study the effect of shape-change size on touch-emotion association and the certainty of these associations. Study 2 built on the foundation of study 1, to investigate the effect of shape-change frequency, again focusing on touch-affect associations and the certainty of these associations. Our work makes the following contributions:

- We introduce a systematic approach to affective response to shape-change, grounded in the established Bouba/Kiki paradigm, building directly on prior work on 2D and 3D crossmodal associations.
- We focus on tactile experience of shape-change as it unfolds, rather than the the final product of shape change.
- We introduce into shape-change research a mouse trajectory analysis paradigm from psychology to help us understand certainty in reporting on touch-affect associations.
- Where most previous work has focused on shape-change in a more-or-less holistic manner, our research isolates attention on touch-affect associations, avoiding confounds from other sensory information, such as visual stimuli and facial expressions [23, 31].

2 BACKGROUND

2.1 Shape-change and emotions

Understanding users' emotional responses has been identified as an important issue for the design of shape-change display, yet little research has engaged with this question [2, 65]. Pedersen *et al.* [48] studied shape-changing handheld devices rendered in videos, in which shape-change parameters such as area, curvature, amplitude, speed etc. were manipulated to convey emotions. Participants watched videos and evaluated hedonic and pragmatic qualities of shape-change. They found that the level of change had a strong impact on experience and an indication of urgency; and that smaller shape changes conveyed a nicer experience than larger shape changes. A recent research with a foucs on deformable device adopted a similar method, and provided further evidence showing that the direction of bending and convexity associated with emotional valence [37]. Strohmeier *et al.* [65] explored shape-change parameters and how these can be used for conveying emotions. In their study, a flexible surface equipped with flex-sensor arrays was designed to record shape changes. Participants were asked to produced shapes with this surface for 12 emotions. Results showed that "U"shape were often used to express contentment, delight and happiness, while a flat shape were often used to convey boredom and calmness. They also found in a further study that participants had a less agreement in interpreting those emotions. Tan *et al.* [66] explored affective responses on biological motions performed by a shape-change interface which was actuated by mechanical motors. Participants in this study observed (or observed and touched) a shape-changing interface conveying six basic emotions with motions, as well as 36 motions. Participants were asked to identify the emotion among six basic emotional list in one case, and in another case reflected on valence, arousal and dominance emotions. Their results showed that up-down and flat-leaning motion indicated positive-negative valence, and velocity positively correlated with valence, arousal and dominance. van Oosterhout *et al.* [68] compared visual feedback, force feedback, and a combination of force feedback and shape change. Results indicate that force feedback correlates to experienced dominance during interaction, while shape change mainly affects experienced arousal.

In general, research in shape-change and emotions employed two classes of emotion frameworks: categorical emotional frameworks and consistent dimensional frameworks [48, 65, 66].

Early emotion research identified six basic facial emotion families: anger, fear, joy, surprise, sadness, disgust [18, 44], which can be used to classify emotions as clusters, and to build up more complex emotions. However, categorical frameworks appeared to be insufficient in capturing and classifying complex emotional responses to shape-change features [13]. One of the best-known models for measuring emotions has suggested looking at emotions in terms of two dimensions: valence (i.e., positive and negative) and arousal (i.e., high and low) [36]. This model provides a simplified view of the circumplex model [6] by just focusing on the extremes (i.e., valence and arousal axes) [33], overcoming biases related to the introspective verbalization of emotions in self-report measurements. The emotion dimensions are also best captured with the Self-Assessment Manikin (SAM) [21], an affective rating system that not only includes valence and arousal but also a third dimension, dominance (the feeling of being in control or controlled). To assess those dimensions, the SAM uses graphic figures depicting the different values on the scale that indicate the emotional reactions. This system allow us to understand emotions along basic emotional dimensions, which represent more comprehensive emotions that are too much and too difficult to categorise with discrete emotional framework. [13]

In HCI and cognitive sciences we can find databases of standardized stimuli eliciting specific emotional reactions, however the stimuli used are always unimodal (e.g., auditory [55], visual [35], or haptic [43]) and only recently a database was extended to multimodal emotional stimuli [25] but not with concurrent presentation. There has been recent work that examined the impact of concurrent sensory presentation on emotion. For example, Akshita et al. explored how emotional cues presented in visual and haptic modalities interact and showed that the presence of a haptic stimulus affects the arousal of the visual stimulus without affecting valence [1]. Focus on specific sensory modalities could help untangle the challenges outlined in shape-change research around emotions and the need to isolate effects of different modalities. Here, because emotions are primarily elicited by stimuli received by our senses [27]. The impact of sensory modalities on emotions seem to be explained mainly by the emotional congruency effect (the so-called emotional crossmodal transfer [39]), amplifying an emotional reaction when two or more sensory stimuli are in the same emotional domain (e.g., same valance or same arousal). The present work contributes to extending this particular line of research by bringing in a focus on crossmodal interaction as an organising framework for assessing the emotion elicited by shape-change.

2.2 Crossmodal interaction

The study of crossmodal interaction is concerned with understanding how the signals we receive through one sense can influence how we perceive and interpret signals received through another sense [60]. As a basic example, consider our ability to associate the sound of a voice with the right speaker by, among other things, matching sounds to lip movements and spatial orientation. At a more fundamental level, research on crossmodal cognition has unravelled varied and deeper crossmodal interactions between the senses; e.g. that odours shift visuo-spatial attention [56], that colours influence flavour perception [49], and that pitch shifts perceptions of size and spatial position [7]. The terms congruence or crossmodal correspondences are often used to refer to these non-arbitrary associations that seem to exist across senses, and to be present across age groups [40] and cultures [9].

A particular class of crossmodal interactions are crossmodal correspondences (CCs) or associations. These refer to the non-arbitrary perceptual associations of stimulus features both within and across senses. In many cases, these associations arise from the natural correlations of physical properties [19]. For example, while large objects resonate at lower frequencies upon impact, small objects resonate with higher frequencies, leading to perceptual associations between visual size and auditory pitch [47]. However, some crossmodal associations appear more abstract and can be less easily explained by physical feature characteristics of the environment. The Bouba/Kiki crossmodal paradigm is an illustrations of this abstract level of association and attribution. For example, when asked to associate the names "baluma" and "takete" with two visually presented 2D shapes, one round and bulbous, the other angular and jagged, the vast majority of people will associates the round shape with "baluma" and the angular shape with "takete" [34] (more commonly, the "Bouba/Kiki" effect [51]). Despite this seemingly arbitrary coupling of visual shapes and auditory sounds, humans tend to associate these features at rates far above chance level. In fact, sound symbolism is extremely prevalent in many different languages, cultures and across different age ranges, with children exhibiting similar association preferences as adults [40]. Importantly, CCs have been repeatedly shown to enhance multisensory perception and behaviour both in temporal and spatial domains [46, 59].

Ideas of crossmodal interaction stem from advances in cognitive neuroscience, specifically new understandings of brain plasticity and sensory substitution, which refer to the brain's capacity to replace the functions of a given sense with another [4]. However, despite increasing capabilities of computing technology to support higher resolution sensory input and output, the application of insights from crossmodal cognition is only beginning to emerge in fields such as HCI. For instance, we now know that perceived quality of touchscreen buttons is correlated with visual and audio-tactile congruence [30] and that incongruent audio-visual displays improve distance perception in virtual environments [22]. Further work demonstrated that congruent audio-visual display produces higher engagement in game play involving estimation of order and spatial position [41]. Crossmodal effects between tangible and olfactory stimuli and their relationship to emotional activation in children have also been identified [42], which were then used to design more inclusive crossmodal storytelling tools [14]. Furthermore, sensory information conflicts have been shown to improve alignments of physical and virtual objects [3], and correspondences between 3D printed hair-like structures and the perception of texture have been explored demonstrating in this case that visual-haptic augmentations enhance the users' haptic perception in virtual reality [16]. The use of metamaterials to create transformable textures on 3D printed objects showed that varying spike length allowed users to perceive a larger set of material impressions [32]. This line of work demonstrates the potential impact of crossmodal interaction as a framework for guiding the design of interactive technology, but this potential has not been fully explored in shape changing displays, a gap we aim to contribute to addressing. Most recently research focused specifically on replicating and transferring the visuo-linguistic Bouba/Kiki crossmodal effect to haptic experiences in the context of tangible 3D objects and emotion [38, 42]. This line of work demonstrates the specific potential of a crossmodal framework for the systematic study of affect in interactive technology, but has focused on static tangible displays. We aim to extend this line of research to the realm of dynamic shape changing displays in this paper with a particular focus on examining affect in shape-change as it unfolds and on the potential of the analysis of active user movement as a window into the process of emotional attribution.

2.3 Movement during user response as a window on uncertainty

A large and growing body of work demonstrates that patterns in human movement can reveal dynamical aspects of cognition [24]. This work, often grounded in Spivey's work on dynamical accounts of cognition [62], investigates the way that cognitive processes unfold in time and leave traces in overt movement behaviour, driven by competition between probabilistically weighted, cognitive and sensory processes [5, 70]. It is now common practice in psychology research to capture and analyse mouse cursor trajectories during decision tasks, to observe traces left by cognitive processes. In this methodology participants begin with their mouse on a central point and then respond to a stimulus by moving their mouse cursor towards the correct response. The endpoint of the movement determines the participant's response, and the trajectory of the movement towards that response carries information regarding the decision process underlying [24, 63]. Such work has demonstrated that the psychological uncertainty underlying perceptual, cognitive, and emotional judgements is captured in the spatial and temporal properties of motion paths [26, 70]. As the evidence base for this effect has grown, the methodology has moved into application research, with researchers applying the approach to capture uncertainty and emotion in decision making – for example in affective computing [70]. We follow this approach in our research, using mouse cursor movement as a window on certainty in the participant's attribution of emotion.

While much early work in this area focused on the descriptive geometric analysis of trajectories, recent work has acknowledged limitations in this approach. Geometric analysis focuses on a trace left by the movement, and discards much information about the movement itself. It does not account for motor pauses, and can fail to characterise the noisy, irregular nature of empirical movement paths [10]. Many researchers now make use of kinematic features instead, including the two features used in our study – velocity peaks, and reversals along an axis, [5, 29, 70]. Velocity peaks have been shown to reveal competition between multiple responses-commitments (a description we can approximate in plain language as "uncertainty" or "ambiguity" in choice) [17, 29]. Reversals along an axis (or "x-flips", "y-flips") refers to the number of times the mouse trajectory changes direction along a decision axis this - can indicate more dramatic uncertainty and deliberation over time [15].

In the following sections, we present research details on how we apply this technique to understand not only the touch-affect associations with unfolding shape-changes, but the level of certainty of those associations based on people's tactile experiences.

Table 1: Independent variables for study 1

Manipulations	Condition 1	Condition 2	Condition 3
Shape-change Size	Small	Medium	Large
Shape-change Type	Static	Dynamic - KBK	Dynamic - BKB

3 STUDY 1: TACTILE PERCEPTION ON SHAPE-CHANGE SIZE

Our first study aimed to explore the touch-affect association provoked by tactile perceptions of shape-change as it unfolds. The experiment was designed with two purposes. First: to replicate previous results with static shapes, using a shape-change gadget, to facilitate comparison between our results and previous work. Second: to extend this prior work by investigating the effect of movement between shapes, and the scale of this movement on touch-affect associations. To address these aims, our study design had two independent variables: **Shape-change type** and **Shape-change size** (see table 1.)

The first independent variable, the **Shape-change type** has three levels: first, **static** with no transformation between rounded Bouba and sharp Kiki stimulus, and then two dynamic size transformation conditions. The first of these, **KBK**, begins with a Kiki stimulus, moving to a slightly larger Bouba stimulus and back to Kiki again), the second dynamic condition is **BKB**: starting at the larger Bouba stimulus, moving to Kiki and then back to Bouba. Precise definitions of these movements are given below in the description of the gadget, and transitions are illustrated in Figure 2.

The second variable – **Shape-change size** – has three conditions: small, medium and large, which describe the size of the gadget at the limit of its "Bouba" phase, and are defined precisely in our description of the gadget below. This description also explains the pneumatic actuation mechanism which we used to achieve the shape-change behaviour.

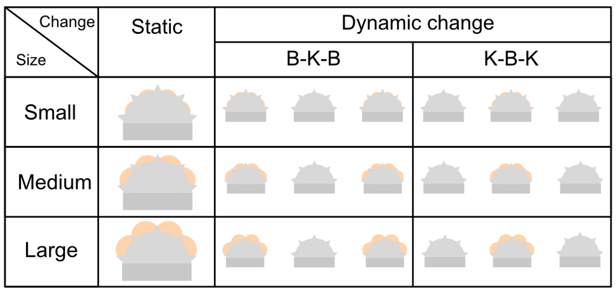

Figure 2: Shape-change types and their transitions.

3.1 Apparatus

Shape-change gadget - Building on previous work which has used the Bouba-Kiki paradigm to study multisensory interaction in HCI [38, 42], we developed a shape-changing tangible variant of a Bouba-Kiki stimulus (Figure 3). This device was composed of two parts: a rigid Kiki shell covering an elastic Bouba part. This was designed so that the Bouba part could be inflated to protrude through apertures in the Kiki shell and present a Bouba stimulus to the participant; or deflated to present a Kiki stimuli. The Kiki part is a 3D printed, semi-spherical, surface with fifteen spikes and fourteen apertures evenly located on its convex surface. The Bouba part is a soft, inflatable, silicon chamber contained within the Kiki surface. The Kiki part was coated with the same silicon material as the Bouba chamber. The transformation between Kiki and Bouba was performed by pneumatic control of the air pressure in the elastic chamber (using an SMC ITV0050-3BS regulator). By increasing air pressure in the Bouba chamber, we were able to cause the Bouba to grow through the fourteen apertures on the semi-spherical surface, presenting a soft bouba stimulus to the participant. By reducing air pressure the Bouba would recede, presenting the Kiki stimulus.

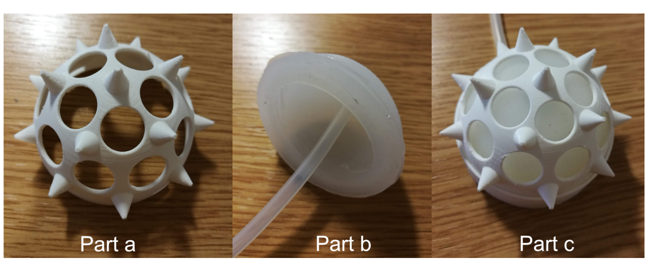

Figure 3: BK robot configuration. Part a is the rigid Kiki spikes. Part b is the soft silicon chamber. Part c is the assembled result.

Using this gadget, we defined three size conditions which varied the degree to which Bouba and Kiki stimuli were presented to the participant at maximum inflation:

Small-size : the height of Boubas H_b were equal or lower than half of that of Kikis $\frac{1}{2}H_k$ - when people put their hand on the gadget, the perception of Kiki is more haptically dominant than Bouba (Figure 4).

Medium-size: the height of Bouba H_b were higher than that of Kikis H_k and lower than $\frac{3}{2}H_k$ - when people put their hand on the gadget, the perception of Kiki has equal saliency with that of Bouba.

Large-size: the height of Bouba H_b were equal or higher than two times of Kikis' $2H_b$- when people put their hand on the gadget, the perception of Kiki is less dominant then Bouba.

In the static condition, the Bouba part of the gadget remains fixed at these defined sizes. In the dynamic conditions, these sizes define the maximum inflation of the Bouba part, at the limit of the "Bouba" phase of shape change. At the limit of the "Kiki" phase of shape-change, the Bouba part is completely deflated, presenting only the Kiki stimulus to the participant. Again, these conditions are illustrated in figure 4

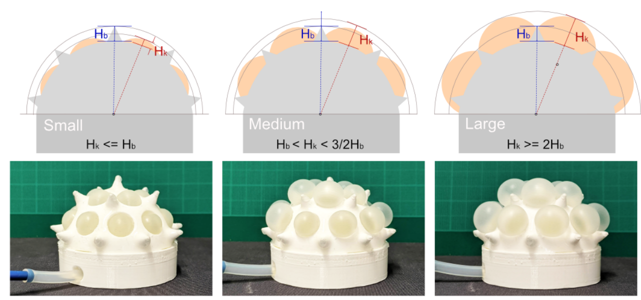

Figure 4: Three sizes of the shape-change: small, medium and large size. With a front-perspective, H_b in blue denotes the height of the spikes, H_k in red denotes the height of the bubbles.

Isolating tactile experience - Our experimental setup was arranged so that the participants only had tactile access to the shape change gadget, excluding confounds from other sensory information. The BK gadget was contained inside a plywood container, placed on participant's non-dominant hand-side. The box had a entrance allowing participants access to the device with their non-dominant hand. The entrance of box was covered with cloth so that participants can not see anything inside (Figure 5). Sound-blocking ear protectors (3M H540A) were provided to participants to block the sound from the pneumatic control.

Circumplex interface - Software displaying a circumplex model, composed of valence and arousal dimensions was displayed on Mac book pro, which was placed immediately in front of participants (Figure 6 a). A red point at the origin of the axes marked the neutral state, where affect is neither positive nor negative, neither high-arousal nor low-arousal. Participants were asked to move their mouse cursor to the neutral state before touching the shape-changing gadget. After each trial was complete they were asked setup photo.png

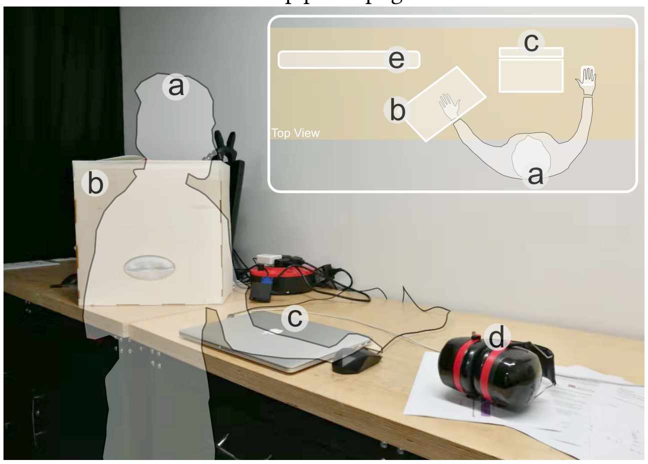

Figure 5: Experimental setup. a: participant, b: plywood box with shape-change gadget inside, c: experimental programme run on MacBook Pro, d: noise-cancelling ear mask, e: experimental control panel.

to draw from the origin to an endpoint that indicated the affect induced by the shape-change (Figure 6 b). This movement was captured by the system at 125hz. After each trial the circumplex was cleared so that participants were not influenced by representation of their previous actions.

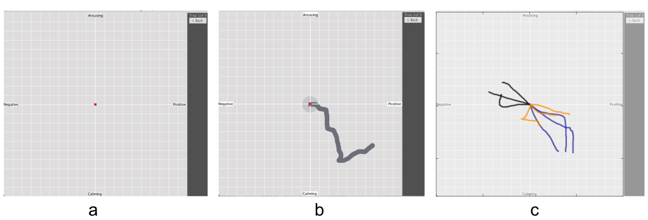

Figure 6: Circumplex interface. a: the circumplex interface in the begining of each trial. b: participant sketch out affect state of a shape-change process in one trial. c: a matlab plot of nine trials of one participant. Black denotes small-size trials, yellow denotes medium-size trials and blue denotes large-size trials.

3.2 Participants

Fifty-four participants took part in the experiment (aged 22-38, mean = 28.13, SD = 3.65). They were randomly allocated to three groups: static group, KBK group and BKB group, with eighteen participants in each group. All participants reported they were right-handed, having no injuries in hands and arms, and having normal sight (before or after correction). They were recruited through authors' institutions' E-mailing lists and personal social media contacts.

3.3 Procedure and tasks

Participants were asked to explore the shape-change as it unfolds with their non-dominant hand and reflect on their emotional responses along two dimensions of the circumplex model. Upon participants' arrival, an information sheet and a consent form were provided to participants explaining the purpose of the experiment and research ethics. Participants were told that the plywood box to their left contained a palm-sized shape-change gadget. Before the experiment began, the experimenter explained the circumplex model, how it represented affect, and how they should record their experiences on it. Participants were then asked to do a warm-up practice with the Circumplex interface to familiarize themselves with the system. They were allowed to practice until they felt comfortable with the interface. During each trial, participants placed their hand into the box, and onto the shape-change gadget. The shape-change procedure then began immediately, lasting around 5 seconds. At the end of the shape change the participants took their hand out the box and, using the circumplex as described above, responded to this question: *feeling the process of the shape-change with my hand made me feel...* We adopted a mixed-subject design to minimise the learning effect. In all three experimental groups (static, KBK and BKB group), participants performed nine trials in total: three shape-change sizes repeated three times. These trials were randomised with a 3*3 Latin-square method.

3.4 Measurements

We collected three measures from the participants' responses in the trials – where they were asked to draw from the circumplex's origin, to an endpoint which captured their affective response. The first of these measures was the **end point** – the final point of the participant's mouse trajectory (Figure 6). This measure had two dimensions: valence and arousal, mapped to the x and y axes of the circumplex respectively. As described above, the valence and arousal axes ranged from 0-800. For valence 0 indicates the most negative affect and 800 the most positive affect. For the arousal dimension, 0 indicates the lowest arousal and 800 the highest arousal. The origin coordinate in this interface is thus at (400, 400) and marks the neutral state, neither negative nor positive in valence, and neither low nor high arousal.

We also extracted two kinematic features from the participants' mouse trajectories towards these endpoints: number of **reversals** and number of **velocity peaks**. Both features have previously been associated with certainty in decision and attribution tasks [5, 29, 70]. A reversal in trajectory involves a change in movement direction along either axis. The number of velocity peaks on an axis indicates the number of times the movement slows down or speed up, which again suggests a level of uncertainty and hesitancy in evaluation of affect on that axis. Since reversals involve a change in direction they can be taken to reflect a stronger degree of uncertainty than velocity peaks, which involves change in speed but not direction. As discussed in our background section, the analysis of such measures in mouse trajectories is now a common methodology in psychology to understanding uncertainty.

4 RESULTS

We tested the effect of **shape-change size** on associations between touch and affect. Since our data did not meet the requirements for parametric tests, we used Friedman's ANOVA to test on three levels: the static-shape level, with the purpose to replicate results in previous research on 3D tangible shapes [38, 42]; dynamic levels with a shape transformation from Kiki to Bouba, as well as a reversed polarity from Bouba to Kiki. Wilcoxon tests were used for Post hoc processes, in which a Bonferroni correction was applied and so all effects are reported at a .025 level of significance. Then we tested the effect of the **shape-change type** with Kruskal-Wallis test, and a post hoc procedure with a Bonferroni correction and so all effects are reported at a .025 level of significance. A high level descriptive summary of results can be found in table 2, and the statistical details are presented below.

4.1 Measurement 1: End points - affect measurement with circumplex model

4.1.1 Shape-change Size - Valence and Arousal.

Valence - There were significant main effects of the size-condition in all three groups. Further, in all three groups (static, KBK, BKB) the results were consistent: larger sizes had significantly higher valences than smaller sizes. Figure 7 summarises the results.

For the **static** group, ($\chi^2(2) = 54.48, p < .05, w = .50$) the large-size condition (Mdn = 561.5) had significantly higher valence level than both the medium-size condition (Mdn = 408.5), $T = 108.0, p < .025$, and the small-size condition (Mdn = 274.5), $T = 41.0, p < .025$. The medium-size condition also had significant higher valence level than small-size condition, $T = 361.0, p < .025$.

For the **KBK** (Kiki to Bouba to Kiki) group, ($\chi^2(2) = 67.60, p < .05, w = .62$) the large-size condition (Mdn = 603.0) had significantly higher valence level than both the medium-size condition (Mdn = 339.0), $T = 39.0, p < .025$, and the small-size condition (Mdn = 260.0), $T = 15.0, p < .025$. The medium-size condition also had significant higher valence level than small-size condition, $T = 405.5, p < .025$.

For the **BKB** (Bouba to Kiki to Bouba) group, ($\chi^2(2) = 89.61, p < .05, w = .83$) the large-size condition (Mdn = 553.0) had significantly higher valence level than both the medium-size condition (Mdn = 331.0), $T = 53.0, p < .025$, and the small-size condition (Mdn = 237.0), $T = 12.0, p < .025$. The medium-size condition also had significant higher valence level than small-size condition, $T = 85.0, p < .025$.

Arousal- There was a significant main effect of the size condition only in the **static** group ($\chi^2(2) = 41.59, p < .05, w = .38$). Post hoc tests on the **static** group showed that the small-size condition (Mdn = 538.5) had significantly higher level of arousal than both the medium-size condition (Mdn = 435.0), $T = 314.0, p < .025$, and large-size condition (Mdn = 223.0), $T = 94.5, p < .025$. Medium-size condition also had significantly higher level of arousal than large-size condition, $T = 147.0, p < .025$.

4.1.2 Shape-change Type - Valence and Arousal.

Valence - There were no significant effects of the shape-change type along the valence dimension across any size-level (regardless of whether bouba or kiki stimulus dominated the shape change). The results do not indicate that shape-change type affects participants' tactile-affect associations along the valence dimension.

Arousal - For endpoints on the arousal dimension, a significant main effect of shape-change type was observed only in **large-size** level (where the Bouba stimulus dominated) ($H(2) = 21.09, p < .05, r = .37$). Post hoc procedures indicated that dynamic conditions resulted in higher arousal levels than the static condition, regardless of shape-change order. Both KBK (Mdn = 410.0) and BKB (Mdn = 360.0) shape-change types had higher arousal level than the static condition (Mdn = 223.0), . For KBK vs static $U = 23.86, p < .025$; and for BKB vs static $U = 5.67, p < .025$.

4.1.3 Overview.

For type of shape change, **dynamic conditions resulted in higher reported arousal than the static condition**, but we found no evidence that shape change type affected valence.

For **shape-change size** (the parameter which affected the degree to which Bouba or Kiki stimuli were presented)results were more complex: Size affected **valence** for both static and dynamic groups, but only affected **arousal** in the static group. In general **valence values increased (became more positive) as the Bouba stimulus became more dominant**, as size increased. This was true across both static and dynamic conditions and regardless of order of shape change (BKB or KBK). Where the Bouba stimulus dominated over the course of the shape-change, in the large-size condition, reported affects tended to be positive: the lower quartile of the distribution was above 400 for all shape-change types. Where the Kiki stimulus dominated, in the small-size condition, we saw a generally negative affect: the upper quartile of the distribution was below 400 for all shape-change types. Completing the pattern, valence in the medium condition fell between these two groups, clustering around 400 (neutral affect), though in the BKB condition a slight tendency towards negative affect was observed (upper quartile below 400, and lower quartile around 250).

Turning to **arousal**, only the static group showed a significant main effect. **In the static group, arousal tended to decrease as the Bouba stimulus became more dominant** (as size increased). In the small-size condition (where the kiki stimulus dominated) arousal levels tended to be high for all shape-change types, with lower quartiles above 400 for all. Medium-size (with more balance between bouba and kiki stimuli) also tended towards elevated arousal in both dynamic shape-change types, though here, upper quartiles were below 600, indicating only a slightly elevated arousal. In the large-size condition (where the bouba stimulus dominated), in the static condition, arousal was low - with upper quartile below 350. For both dynamic shape-change types, distributions were too wide to indicate either high or low arousal overall.

4.2 Measurement 2: Number of reversals - uncertainty in assigning affect

We measured the number of reversals in participants' mouse trajectories as they reported affect, using this to indicate their uncertainty in reporting on affect. Participants were considered to be more decisive, the less reversals in directions they made, during their movement towards the endpoint. We ran the same statistical tests as described in the measurement 1.

Table 2: Descriptive Summary of Results for Experiment 1

		Valence		Arousal	
Measure	**Variable**	**Trend**	**Detail**	**Trend**	**Detail**
Endpoint (affect)	Change-size	Higher valences for larger (more bouba-like) sizes	Significant for static and dynamic stimuli. Consistent over all size-comparisons	Higher arousal for smaller (more kiki-like) sizes	Static condition only. Consistent over all size-comparisons
	Change-type	no effect observed		Dynamic stimuli result in higher arousal than static stimulus	Only in the Large size group (where bouba-stimulus is more emphasised)
Reversals (uncertainty)	Change-size	no effect observed		Smaller sizes (more kiki-like) result in less peaks (less hesitation)	Only observed in one of the two dynamic groups (KBK)
	Change-type	Less reversals (more certainty) for dynamic stimuli	Only significant for the small and large stimuli, (kiki or bouba dominate) not medium (more mixed).	Less reversals (more certainty) with dynamic stimuli	Only significant in small and large groups, (kiki or bouba dominate), not medium (more mixed).
Velocity Peaks (hesitation)	Change-size	no effect observed		less velocity peaks (less hesitation in reporting) for smaller (more kiki-like) sizes)	Only observed in one of the two dynamic groups (KBK)
	Change-type	Less velocity peaks (less hesitation in reporting affect) for dynamic stimuli	Significant for all size conditions.	Less velocity peaks (less hesitation) for Dynamic stimuli	Significant for all size conditions.

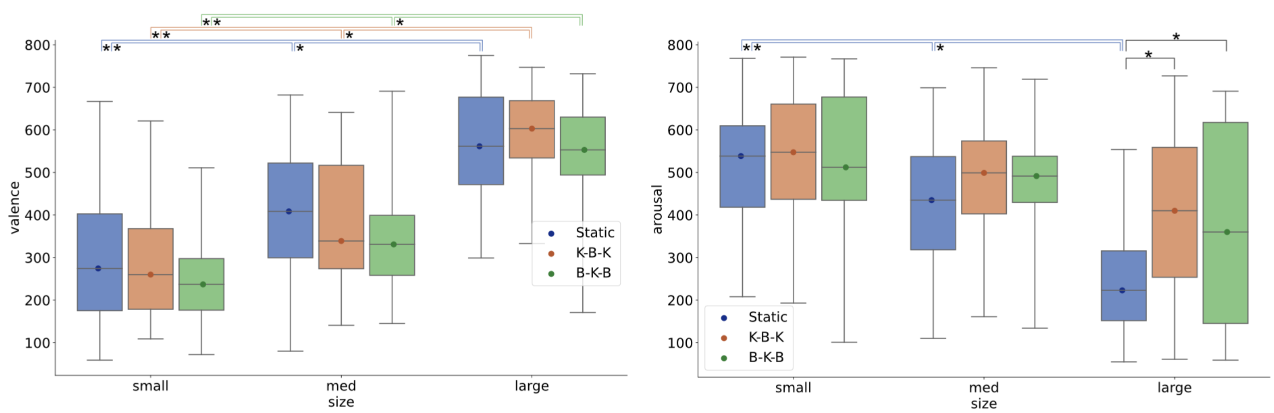

Figure 7: Experiment 1 - endpoint measures for valence (left) and arousal (right). Whiskers show 3IQR. Asterisks indicate significant differences in the pairs marked.

4.2.1 *Shape-change size - Valence and Arousal.*

We ran Friedman's ANOVA to test whether manipulation of **shape-change size** affected decisiveness and directness when reporting affect. No significant main effect was found in either the valence or arousal dimensions.

4.2.2 *Shape-change type - Valence and Arousal.*

We ran Kruskal-Wallis test whether manipulation of **shape-change type** affected decisiveness and directness when reporting affect.

Valence - Significant main effects on shape-change were observed in**Small-size** and **Large-size** levels In both size levels, the static group produced significantly more reversals than both dynamic groups, indicating less decisiveness in the static condition than in the dynamic condition where either bouba or kiki stimulus dominated. We observed no significant difference between KBK and BKB groups suggesting no evidence that order of shape change affects valence in this case.

In the **Small-size** level ($H(2) = 18.22, p = .00, r = .32$), the static group ($Mdn = 8.0$) had significantly more reversals than both dynamic groups – KBK group ($Mdn = 5.0$), $U = 949.0, p = .00$, and BKB group ($Mdn = 5.0$), $U = 1269.5, p = .00$ – indicating less decisiveness in the static condition.

In the **Large-size** level ($H(2) = 12.57, p = .00, r = .21$), the static group($Mdn = 7.0$) produced significantly more reversals than KBK group ($Mdn = 4.0$), $U = 953.5, p = .00$, and BKB group ($Mdn = 4.0$),

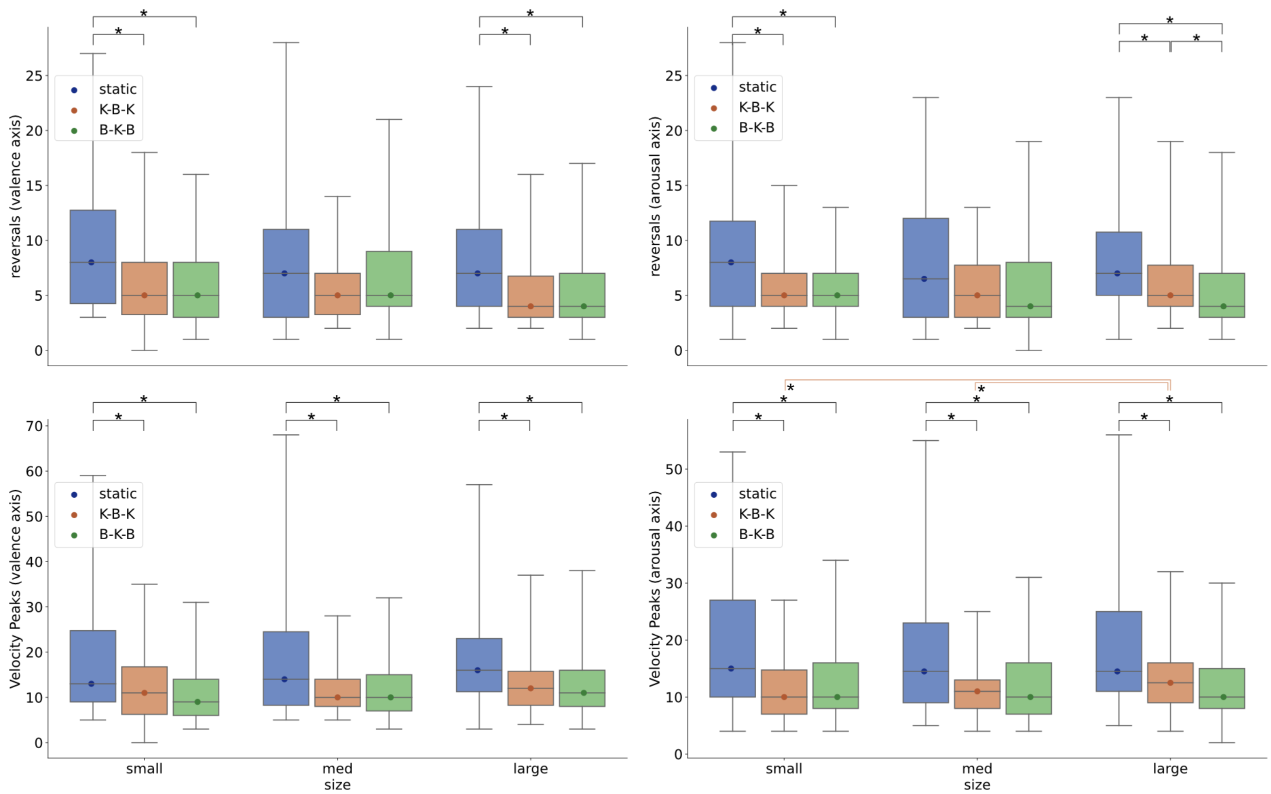

Figure 8: Experiment 1 - kinematic measures of certainty, for movement on valence (left) and arousal (right) axes. Whiskers show 3IQR. At the top, asterisks indicate significant differences in the pairs indicated

$U = 1496.0, p = .00$. There was no significant difference between KBK and BKB groups

Arousal - Results for decisiveness in reporting arousal were closely similar to those for valence. both the **Small-size** and **Large-size** levels, the static group produced significantly more reversals than both dynamic groups, indicating less decisiveness in the static condition than in the dynamic condition when either bouba or kiki stimulus dominates. Again, we observed no significant difference between KBK and BKB groups, indicating no evidence for any impact of order of shape-change.

In the **Small-size** level($H(2) = 11.24, p = .00, r = .18$) the static group ($Mdn = 8.0$) again produced significantly more reversals than both dynamic groups – KBK group ($Mdn = 5.0$), $U = 986.0, p = .00$, and BKB group ($Mdn = 5.0$), $U = 1529.5, p = .00$ – indicating less decisiveness in the static condition.

In the **Large-size** level ($H(2) = 16.40, p = .00, r = .28$), the static group ($Mdn = 7.0$) had significantly more reversals than KBK group ($Mdn = 5.0$), $U = 1044.5, p = .00$, and BKB group ($Mdn = 4.0$), $U = 1351.0, p = .00$. Again, there is no significant difference between KBK and BKB group.

4.2.3 *Overview:*

Figure 8 summarises the results for reversals. We found evidence that **shape-changing stimuli resulted in greater decisiveness in reporting affect than a static stimuli**, but we found no evidence that decisiveness was affected by shape-change size. At both the small-size (kiki-dominates) and large-size (bouba-dominates) levels, the static group produced more reversals than dynamic groups in both valence and arousal. In neither case whas there any evidence for an effect due to order of shape-change.

4.3 Measurement 3: Velocity peaks - hesitancy to arrive at certain affective state

We also measured the number of velocity peaks in the participants' mouse trajectories, as they reported affect. We took this to indicate their level of hesitancy in arriving at a certain affect. The less velocity peaks produced during the evaluation, the smoother the mouse trajectory would be, and the less hesitant participants were judged to be. Again we ran the same statistical tests as described above

4.3.1 *Shape-change size - Valence and Arousal.*

Valence - There was no significant main effects of shape-change size on the smoothness of the mouse trajectory.

Arousal - There was a significant main effect of the shape-change size on mouse trajectory smoothness in **KBK** group only ($\chi^2(2) = 6.99, p = .03, w = .06$). Here, the Large-size level ($Mdn = 12.5$) showed more velocity peaks than both the Medium size level (Mdn = 11.0), T = 286.5, p = .00 and the small size level (Mdn = 10.0), T = 408.0, p = .01

These results suggest that in KBK group, **as size decreased, and the Kiki stimulus dominated, participants were less hesitant** or uncertain about the affect induced.

4.3.2 Shape-change type - Valence and Arousal.

Valence - There were significant main effects of the shape-change type on mouse trajectory smoothness, and post-hoc results showed consistently higher velocity peaks in static condition, compared to both dynamic conditions.

In **Small-size** level, ($H(2)$ = 14.69, p = .00, r = .25), the static group (Mdn = 13.0) had significantly more velocity peaks than both the KBK group (Mdn = 11.0), U = 1003.5, p = .00, and the BKB group (Mdn = 9.0), U = 1365.5, p = .00.

In **Medium-size** level, ($H(2)$ = 11.39, p = .00, r = .25), static group (Mdn = 14.0) had significantly more velocity peaks than both the KBK group (Mdn = 10.0), U = 997.0, p = .00, and the BKB group (Mdn = 10.0), U = 1504.0, p = .00.

In **Large-size** level, ($H(2)$ = 15.50, p = .00, r = .26), the static group (Mdn = 16.0) had significantly more velocity peaks than both the KBK group (Mdn = 12.0), U = 997.0, p = .00, and the BKB group (Mdn = 11.0), U = 1343.0, p = .00.

Arousal - There were significant main effects of the shape-change type on mouse trajectory smoothness as well. Again, velocity peaks were lower (smoothness higher) in the dynamic groups, which we took to indicate less hesitancy in reporting on affect.

In **Small-size** level, ($H(2)$ = 13.72, p = .00, r = .23), the static group (Mdn = 15.0) had significantly more velocity peaks than both the KBK group (Mdn = 10.0), U = 911.5, p = .00, and the BKB group (Mdn = 10.0), U = 1498.0, p = .00.

In **Medium-size** level, ($H(2)$ = 13.13, p = .00, r = .22), static group (Mdn = 14.0) had significantly more velocity peaks than both the KBK group (Mdn = 11.0), U = 935.5, p = .00, and the BKB group (Mdn = 10.0), U = 1486.5, p = .00.

In **Large-size** level, ($H(2)$ = 12.91, p = .00, r = .21), the static group (Mdn = 14.0) had significantly more velocity peaks than both the KBK group (Mdn = 12.0), U = 1100.5, p = .00, and the BKB group (Mdn = 10.0), U = 1406.5, p = .00.

4.4 Summary of Study 1 Results

The results of the end point measurement suggest that **shape-change size** has a stronger influence on valence perception than arousal, regardless of shape-change type. In **valence** larger sizes (e.g. where Bouba stimuli were more emphasised) resulted in consistently higher valences than smaller sizes (where Kiki stimuli were more emphasised). There was no effect of **shape-change type** on valence. The effect of shape-change type on arousal was conditional on the degree to which Bouba or Kiki stimulus dominated: While higher **arousal** was observed in dynamic groups than in static, this was only observed at the large-size level, where the Bouba stimulus dominated over the course of the shape change.

Turning to measures of hesitancy and decisiveness: Results of the **reversals** and **velocity** peaks in the mouse trajectory indicated that shape-change type, rather than the size, had the greater effect on the directness of affective responses. Dynamic shape-change groups showed greater directness (less reversals) and hesitancy (less velocity peaks) for both arousal and valence than the static group. This effect was conditioned by shape-change size: It was observed in the small and large size groups, where kiki and bouba stimuli dominated, but not in the medium size condition. Velocity peaks were also affected by shape-change size: with participants' hesitancy in reporting arousal increasing in large-sizes (bouba-dominant) but only in the in KBK group.

5 STUDY 2: SHAPE-CHANGE FREQUENCY

Having found in our first experiment that shape-change size has effects on touch-affect associations, and no evidence that polarity of the shape-change influence affective responses, we were now interested in exploring another parameter of shape change: frequency. In our second experiment we observed the effect of frequency of change at each of the three size conditions used in study 1. We used three different frequency conditions: high frequency (**High-freq** for short), medium frequency (**Med-freq** for short), and low frequency (**Low-freq** for short). The shape-change frequency was controlled pneumatically with identical apparatus in study 1.

5.1 Control of shape-change frequency

A one-time shape-change involves four stages shown in Figure 9. 1. **ramp-up**: the air pressure is increased, inflating the Bouba chamber, and changing the presented stimulus from the Kiki state to the Bouba state. 2. **hold-up**: the air pressure remains stable and the gadget retains its shape. 3. **ramp-down**: the air pressure is reduced and the gadget moves back towards the Kiki state. 4. **hold-down**: the air pressure remain stable and the gadget remains in its Kiki state. When changing frequency in this experiment we manipulating the frequency via the transformation stages: ramp-up and ramp-down, not the time intervals between Bouba and Kiki shapes. It is thus the process, or unfolding of shape-change whose frequency is varied.

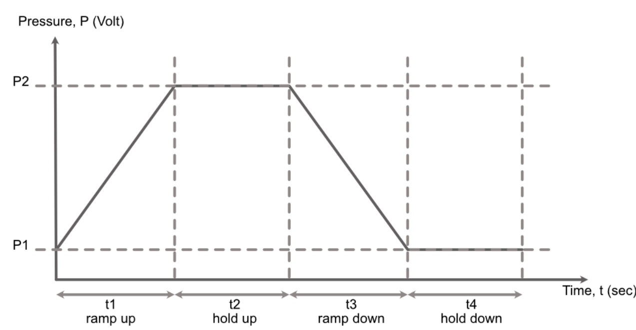

Figure 9: Stage control in shape-change frequency.

The three frequency conditions are defined as follows: *High-freq* has ramp-up and ramp-down times of 0.1s each. *Med-freq* has ramp-up and ramp-down times of 1s. *Low-freq* has ramp-up and ramp-down times of 1.9s. Each transformation in the high-freq condition is thus 0.9s slower than those in the med-freq condition, which are in turn 0.9s slower than in the low-freq condition. The hold-up and hold-down times for all frequencies were 0.8s. Table 3 summarises theses details. In the absence of guidance from prior

Table 3: Time control for shape-change frequency in seconds

	Ramp up	Hold up	Ramp down	Hold down
High-freq	0.1		0.1	
Med-freq	1	0.8	1	0.8
Low-freq	1.9		1.9	

work, and due to the need to tailor effects to the specific responses of materials used, these timings were arrived at by piloting. The four-stage process was repeated three times for each frequency condition.

5.2 Experimental design

As tactile perception and speed perception are influenced heavily by individual difference [58, 64], we used a within subject design to test the effect of shape-change frequency on tactile perception and affect. We tested the three frequency conditions described above, with each of the three sizes described in study 1. Since study 1 showed no effect of polarity, polarity was not considered in the second study. In total, each participant performed 27 trials (3 conditions * 3 size-levels * 3 repeated trials). To minimise potential confounds due to ordering, the order of trials was randomised, using a two-stage Latin-square method.

Thirty-two participants took part in study 2 (aged 22-40, mean = 29.13, SD = 3.80). All participants reported being right-handed, having no injuries in hands and arms, and having normal sight (before or after correction). They were recruited through authors' institutions' E-mailing lists and personal social media. The experimental procedures and tasks were identical with study 1.

6 RESULTS

A high level descriptive summary of the results is provided in table 4 and the statistical details are presented below.

6.1 Summary of Study 2 Results

6.2 Measurement 1: End points - affect measurement with circumplex model

6.2.1 Valence. There was significant main effect of shape-change frequency on affect evaluation only in the Large-size level where the Bouba stimulus dominated across the shape change ($\chi^2(2) = 9.02, p = .01, w = .05$). Post hoc procedures showed that lower frequencies resulted in higher valence.

Post hoc procedure showed that Low-freq condition (Mdn = 618.5) had significantly larger valence value than both the Med-freq condition (Mdn = 571.5), $T = 1547.0, p = .00$, and the High-freq condition (Mdn = 502.5), $T = 1200.0, p = .00$. Med-freq condition also had significantly larger valence than High-freq condition, $T = 1493.5, p = .00$.

6.2.2 Arousal. We observed significant main effects of shape-change frequency on affect evaluation in all levels. **In all sizes, whether Bouba or Kiki stimulus dominated over the course of the shape-change, higher frequencies resulted in higher arousal.**

In the **Small-size** level ($\chi^2(2) = 123.90, p = .00, w = .65$), High-freq condition ($Mdn$ = 672.5) had significantly higher arousal rating than both the Med-freq condition (Mdn = 524.0), $T = 95.0, p = .00$, and the Low-freq (Mdn = 470.5), $T = 84.0, p = .00$. Med-freq also had significantly higher arousal rating than Low-freq, $T = 1168.5, p = .00$.

In the **Medium-size** level ($\chi^2(2) = 147.15, p = .00, w = .77$), High-freq condition ($Mdn$ = 654.5) had significantly higher arousal rating than both the Med-freq condition (Mdn = 491.0), $T = 68.0, p = .00$, and the Low-freq (Mdn = 340.0), $T = 53.5, p = .00$. Med-freq also had significantly higher arousal rating than Low-freq, $T = 341.5, p = .00$.

In **Large-size** level ($\chi^2(2) = 158.25, p = .00, w = .82$), High-freq condition ($Mdn$ = 655.0) had significantly higher arousal rating than both the Med-freq condition (Mdn = 450.5), $T = 30.0, p = .00$, and the Low-freq (Mdn = 161.5), $T = 3.0, p = .00$. Med-freq also had significantly higher arousal rating than Low-freq, $T = 219.5, p = .00$.

Above results are shown in figure 10. To summarise, at the large-size Level, the effect of shape-change frequency influenced perception with valence. The Low-freq resulted in the most positive valence, High-freq resulted in the least positive valence, and the Med-freq in between. The effect of shape-change frequency influenced arousal perception, with Low-freq induced the lowest arousal level. High-freq induced the highest arousal value with the lower quartile of the distribution above 400 for all size levels, indicating overall high arousal. The Med-freq condition resulted in the arousal values set in-between, and the lower quartile of the distribution sat around neutral arousal value 400.

6.3 Measurement 2: Number of reversals - directness in reporting affective state

6.3.1 Valence. There were significant main effects on number of reversals along the valence dimension in medium and large sizes (in which Kiki stimuli are less emphasised), with high frequencies resulting in less reversals.

In the **Medium-size** level ($\chi^2(2) = 6.14, p = .046, w = .03$), High-freq condition ($Mdn$ = 9.0) produced significantly more reversals than the Med-freq condition (Mdn = 7.0), $T = 1204.5, p = .00$.

In the **Large-size** level ($\chi^2(2) = 14.31, p = .00, w = .07$), High-freq condition ($Mdn$ = 8.0) produced significantly more reversals than the Med-freq condition (Mdn = 6.0), $T = 971.5, p = .00$, and Low-freq (Mdn = 6.0), $T = 1413.0, p = .00$.

6.3.2 Arousal. There were significant main effects on number of reversals during mouse movement along the arousal dimension when assigning affect to the experience, with high frequencies resulting in less reversals.

In the **Small-size** level ($\chi^2(2) = 7.05, p = .03, w = .04$), Low-freq condition ($Mdn$ = 8.0) produced significantly more reversals than High-freq condition (Mdn = 7.5), $T = 1180.0, p = .00$.

In the **Medium-size** level ($\chi^2(2) = 9.65, p = .00, w = .05$), Low-freq condition ($Mdn$ = 7.0) had significantly more reversals than the High-freq condition (Mdn = 6.0), $T = 1207.5, p = .02$.

In the **Large-size** level ($\chi^2(2) = 24.64, p = .00, w = .13$), Low-freq condition ($Mdn$ = 8.0) had significantly more reversals than

Table 4: Descriptive Summary of Results for Experiment 2 (shape-change frequency)

	Valence		Arousal	
Measure	**Trend**	**Detail**	**Trend**	**Detail**
Endpoint (affect)	Higher valence for lower frequencies	Only in large-size (bouba-dominates)	higher arousal for higher frequencies	Consistent for all sizes, and all frequency comparisons
Reversals (uncertainty)	Less reversals (more certainty) for higher frequencies	Only significant for the medium size, (where neither kiki nor bouba stimuli are strongly dominant).	Less reversals (more certainty) with higher frequencies	Significant when comparing low and high freq for all sizes (both kiki and bouba dominant), but when comparing low and med, only significant for large-size (bouba dominates).
Velocity Peaks (hesitation)	More velocity peaks (more hesitation in reporting affect) for lower frequencies	Only significant for large-size (bouba-dominates) for all size comparisons, and medium-size when comparing low and medium.	Complex, see main results text	In all size levels Low-freq produced more velocity peaks (hesitancy) than at least one higher frequency condition, and this trend was clearest at the Large-size level (bouba-dominates). At Medium-size, high-freq produced more velocity peaks than medium-freq

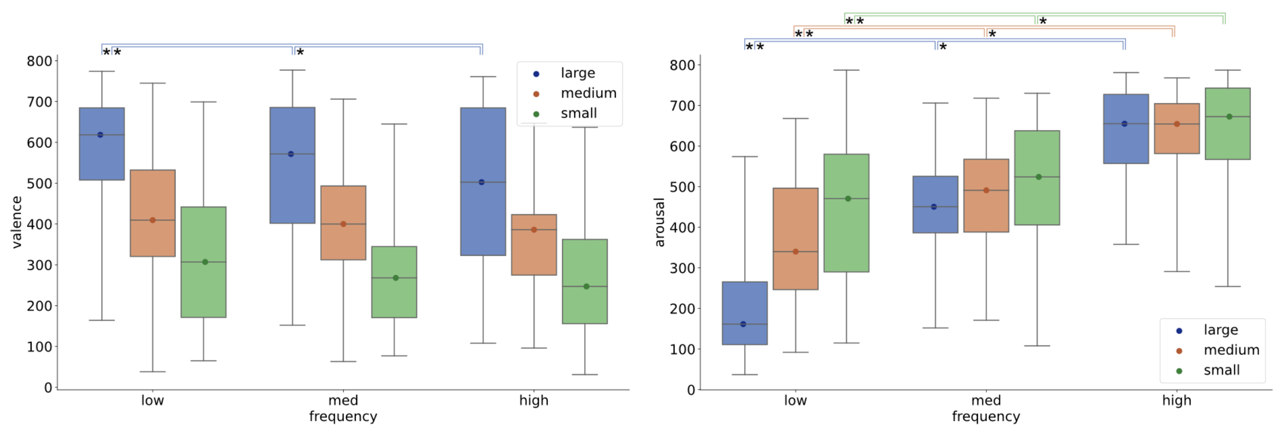

Figure 10: Experiment 2 - endpoint measures for valence (left) and arousal (right). Whiskers show 3IQR. Asterisks indicate significant differences in the pairs marked

the Med-freq condition (Mdn = 7.0), T = 1020.5, p = .00, and High-freq (Mdn = 6.0), T = 1217.0, p = .00.

These results are summarised in figure 11 (two upper plots). **In Overview**: at Medium-size and Large-size levels, the High-freq resulted in more reversals than Med-freq in valence dimension. At all size levels, the Low-freq produced more reversals than High-freq in arousal dimension.

6.4 Measurement 3: Smoothness of mouse trajectories - hesitancy in reporting affect

6.4.1 Valence. There were significant main effects on number of velocity peaks along valence dimension.

In the **Medium-size** level ($\chi^2(2)$ = 10.57, p = .01, w = .06), Low-freq condition (Mdn = 14.0, M = 17.69) produced significantly more velocity peaks than Med-freq condition (Mdn = 14.0, M = 16.31), T = 1344.5, p = .01

In the **Large-size** level ($\chi^2(2)$ = 35.32, p = .00, w = .18), Low-freq condition (Mdn = 21.0) produced significantly more velocity peaks than both the Med-freq condition (Mdn = 14.0), T = 897.5, p = .00, and the High-freq (Mdn = 14.0), T = 747.0, p = .00.

In general, in conditions where the Bouba stimulus was more dominant – both medium-size and large-size – low frequency changes resulted in more velocity peaks, which we take to indicate greater hesitancy in reporting affect.

6.4.2 Arousal. There were significant main effects on the number of velocity peaks along the arousal dimension. in **Small-size** level ($\chi^2(2)$ = 6.91, p = .03, w = .03): In the **Small-size** level ($\chi^2(2)$ = 6.91, p = .03, w = .03), Low-freq condition (Mdn = 17.5) produced significantly more velocity peaks than High-freq condition (Mdn = 15.0), T = 1588.0, p = .02.

In the **Medium-size** level ($\chi^2(2)$ =, p = .02, w = .04), Low-freq condition (Mdn = 14.5) produced significantly more velocity peaks than Medium-freq condition (Mdn = 13.0), T = 1349.0, p = .02. The

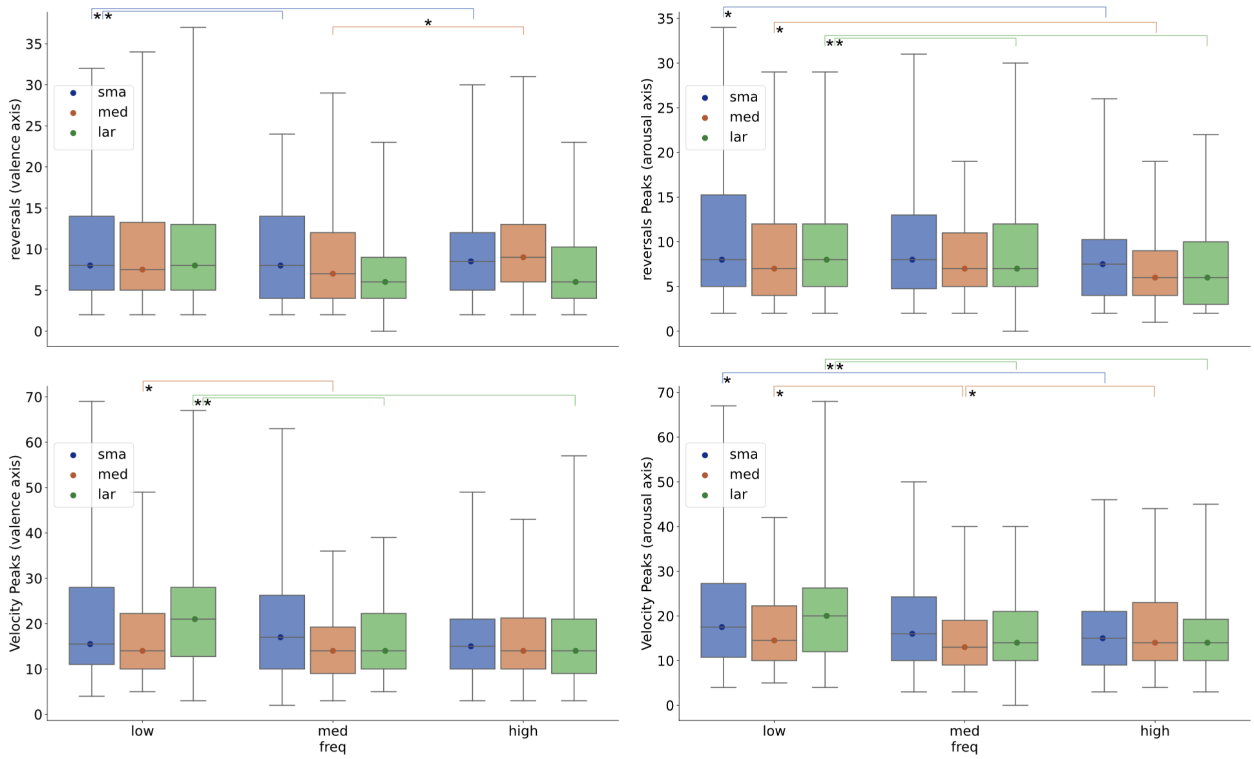

Figure 11: Experiment 2 - kinematic measures of certainty, for movement on valence (left) and arousal (right) axes. Whiskers show 3IQR. Asterisks indicate significant differences in the pairs marked

high-freq condition (Mdn = 14.0) also produced significantly more velocity peaks than Medium-freq condition as well, T = 1309.0, p = .01.

In the **Large-size** level ($\chi^2(2)$ =, p = .00, w = .15), Low-freq condition (Mdn = 20.0) produced significantly more velocity peaks than both the Medium-freq condition (Mdn = 14.0), T = 671.5, p = .00, and the High-freq condition (Mdn = 14.0), T = 875.5, p = .00.

Above results are shown in figure 11 (two bottom plots). **To summarise**, at Medium-size and Large-size levels, where the Bouba feature were more dominant, Low-freq condition produced most number of velocity peaks in valence dimension. Moreover, Low-freq resulted in the greatest number of velocity peaks in arousal dimension, no matter whether the Bouba or Kiki was more dominant. These suggest that in general, the Low-freq condition lead to less certainty in assigning an arousal level to the tactile experience.

First, results of the end point measurement indicate that as the shape-change frequency increased, the valence decreased and arousal increased. Second, results for reversals in the mouse trajectory told us that the High-freq resulted in less directness in valence reporting than Med-freq, and more directness than Low-freq in arousal reporting. Third, Low-freq resulted to the least uncertainty in reporting of both valence and arousal.

7 DISCUSSION OF RESULTS

Both of our studies used a specially designed shape-change gadget, based on the Bouba-Kiki paradigm, to understand the effects of dimensions of the process of shape-change (shape-change as it unfolds). Both studied the effects of unfolding shape-change on user's affective associations, and on the certainty of these associations. Having just discussed the second experiment above, we now re-summarize the purposes of the first experiment, to support discussing of knowledge gained from both experiments.

Study 1 explored the dimension of shape-change size, which in our gadget affected the relative dominance of two kinds of shape stimulus: Bouba (rounded) and Kiki (sharp). In this study we had two aims First: to replicate the effect of a previous experiment on static shapes of different sizes, using our shape change gadget, to validate further results. Second, to explore the effect of shape-change size on touch-affect association, both in static shapes and during shape change. We used two different shape-change types to allow us to isolate and understand the effect of ordering of change. The first, (**KBK**), began with a sharp Kiki stimulus, before moving to a rounded Bouba stimulus, then returning to the Kiki stimulus. The other (**BKB**) began with Bouba, moved to Kiki, and returned to Bouba. Based on the results from Study 1, Study 2 aims to further explore one of the dynamic features in shape-change as it unfolds - frequency, and its effect on touch-affect associations.

7.1 Effect of shape-change size and type on affect (study 1)

First, our results replicated previous results about touch-affect associations in static shapes [38, 42]. In our experiments, the static, Large-size condition presented a rounded, low-angularity, "Bouba", stimulus. As in previous work, this produced affects with the most positive valence values and lowest arousal values. Our Small-size condition presented a sharp, high-angularity, "Kiki", stimulus, and again, as in previous work this resulted in the most negative valence values and the highest arousal values. Finally our Medium-size condition, which sat between the other conditions in terms of angularity, resulted in a valence and arousal values whose distribution centres sat close to the neutral state - again in line with this previous work.

These results provide an important baseline for understanding our further results on shape-change, and they support comparison of our results with prior literature on touch-affect associations in the Bouba/Kiki paradigm. Our results in the dynamic conditions (KBK and BKB) stay within this Bouba/Kiki paradigm, extending it to understand shape-change. When comparing the effect of static and dynamic stimuli on affect, the only significant difference observed was in the large-size (Bouba-dominant) condition. Here the moving stimuli resulted in higher arousal than the static stimuli (discussed below). For valences, for both static and dynamic stimuli, there were significant differences between all three sizes. For arousal, however, we did not find significant differences between the size conditions. A plausible explanation for this may be that the high-angularity Kiki feature has the stronger effect on arousal level, so that in the dynamic shape-change conditions, where both Kiki and Bouba features are presented, it dominates the experience, possibly overwriting the unfolding shape-change's effect on arousal level.

In the Large-size condition there were significant differences between the static condition and both dynamic shape-change types, with the latter showing significantly higher arousal. These results suggest that with a sufficient shape transformation, the shape-change movement itself affects perception of arousal. This was observed regardless of the polarity of shape-change. This observation is partially consistent with previous research which found that where the participant has both visual and tactile access to the shape-change, kinematic properties of the shape-change can be positively correlated with valence and arousal [66]. While our results only demonstrated a positive association with arousal. Previous work has shown that where visual and haptic features are combined, the visual feature dominates perception [12, 28], and this difference may be due to the lack of visual stimulus in our study. These results together make a strong case for the value of isolating factors in shape-change research, and future work may wish to further investigate this difference in response to haptic-only access vs haptic-visual access to shape change.

Another factor that needs future investigation is the change in height of the gadget. In our apparatus this change is relatively minimal - up to a 5 % (2.5mm) change in height in the process of Bouba-Kiki transformation, though it may be the case that this introduces a systematic confound. However, we believe this effect will not be significant since this apparatus was able to replicate a previously observed effect in tactile experience with static bouba-kiki stimuli. In the absence of work on just-noticable-differences in tactile perception using comparable shape-change mechanisms, such effects are difficult to evaluate. We suggest that future work may use the just-noticable-difference paradigm to isolate and understand this effect in shape change.

7.1.1 Implications for design. These results confirm that Kiki-like, high-angularity features can be leveraged to draw people's attention or raise alert via a high-arousal stimulus, in an intimate and private manner via touch. Our results suggest this will be true for both static shapes and dynamic shape-change. Kiki-like features might be used in the same way to express low valence affects. Further, our results suggest that it may often be possible to actuated these shapes with sufficient shape transformation in order to increase arousal, without this having a significant effect on valence. Finally, these results emphasise that designers must consider the effects of perceptual modality when designing shape-change mechanism. Some results which hold true when there is both visual and haptic access, may not hold true in cases where vision is not the primary interactive modality, or where visual access is not possible.

7.2 Effect of shape change size and type on certainty (study 1)

By capturing the participants' mouse movements as they recorded their affective responses, we aimed to reveal not only the touch-affect associations, but also something about the participants' process of evaluating the experience. In line with a large body of work in psychology [24] we used kinematic features of shape-change to infer uncertainty in participants' responses. Specifically, we captured the number of reversals and velocity peaks which occurred in mouse trajectories as they moved towards the final recorded affect. These were used as indicators of participants' uncertainty in assigning affect to the experience.

The manipulation of shape change size did not have a consistent effect on users' certainty. We observed only one significant difference here, in **velocity peaks**: In the KBK group, participants in the large-size condition produced more velocity peaks than in the Medium-size and Small-size conditions, indicating a possible higher degree of uncertainty in assigning arousal in the large condition. In the number of **reversals**, we found no statistically significant differences between shape-change sizes. This suggests that shape-change size — affecting whether the Bouba or Kiki stimulus dominates — may have no important effect on the degree of indecision in assigning touch-affect associations. The effect in the KBK group might be explained in terms of contradictory perceptions: the increase in size, which increases the dominance of the Bouba stimulus, may conflict with the experience of the change starting and ending on a Kiki stimulus which, as we have noted, has opposing affective associations. The same effect was not observed in BKB group, where the Kiki feature dominates slightly less over the course of the change. However, in the absence of other results which support the narrative, it is best to remain cautious about this result, until it can be be clarified in future studies.

By contrast, the manipulation of shape-change type showed more interesting and consistent effects on uncertainty. In both the valence and arousal dimensions, we observed consistently higher reversals and velocity peaks in the static group than in either of the dynamic groups. The only exception to this was in the medium-size condition, where reversals in mouse trajectory (which can be taken to indicate a much stronger degree of indecision than velocity peaks) showed no statistically significant differences. These results suggest that perceptions of touch-affect associations were more certain in the presence of shape-change regardless of the shape-change polarities, and that this increase in certainty was perhaps lower in the medium change-sizes.

This approach to measuring certainty, adapted from work in the psychology of dynamic cognition [24], offers an interesting window onto reflection and certainty in touch-affect association. Touch-emotion associations studied in previous work emphasis on the visual perception and interpretation [2, 65]. Our study with kinematic feature analysis suggest that the unfolding of shape-change can help elucidate and clarify perceptions of emotions via touch, with shapes-change appearing to increase certainty in associations.

7.2.1 Implications for design. These observations suggest that affects communicated via touch may be communicated more clearly by shape-change than by static shapes. This insight which might inform future design exploration of affect communication in a range of domains, from realistic tactile perception in VR [16], to shape-change display [2, 32, 69], affective domestic gadgets [31, 72] and multisensory technology for visually-impaired populations [42, 61].

7.3 Effect of shape-change frequency on affect (study 2)

Our endpoint results indicated that, at least for the large size condition (where the Bouba stimulus dominated), shape-change frequency had a significant effect on valence. In this condition all frequencies tended towards positive valences. The low-freq condition gave the most positive valence, the high-freq condition resulted in the least positive valences and the medium-freq results fell between the two (Figure 10 left). In short, although when the Bouba feature dominated, all shape-change frequencies resulted in positive valence, this was still modulated by frequency: the slower the frequency, the more positive in valence.

No main effect was observed in either of the other size conditions. At the small-size level, where the kiki-stimulus dominated, valence distributions centred on negative values. All medians and means were below 400, and the upper quartiles of the medium and high frequency conditions were also below 400. At the Medium-size level, high-freq was slightly negative, low-freq was slightly positive, and the med-freq distribution centred around neutral values 10).

Frequency also had a significant effect on arousal, in all three size-levels (e.g. regardless of whether the Bouba or Kiki stimulus dominated). For all sizes, Low-freq resulted the lowest arousal level, High-freq induced the highest arousal level and Med-freq was between the two. Arousal values in the medium and high frequency conditions centred on slightly, and strongly positive values respectively (lower quartile > 500, medians = 650). Only in the low-freq condition did significant parts of the distribution fall below 400 - in the medium and large levels, with the latter in particular sitting mostly beneath 300 (Figure 10 right).

These results suggest a fairly strong, positive association between shape-change frequency and arousal. In particular, Low-freq change, where the bouba-stimulus dominates (large-size) seems to induce the strongest sense of calmness. Where the bouba-stimulus dominates less, this effect is less strong. In contrast, High-freq shape change seems to induce a sense of alertness regardless of the strength of the Bouba/Kiki features (with median and mean above 600, and lower quartiles above 500 in all size levels). The plot (figure 10, right) suggest that as the size became larger, the effect size of shape-change frequency also became larger. However, we were unable to test this statistically due to the need to use non-parametric statistics. As such this remains for investigation in future work.

7.3.1 Implications for design. There have recently been calls to increase empirical understandings of the ways in which people engage with shape-change mechanisms for meditation and emotional regulation purposes [2, 67]. Our results are interesting in that context. They complement existing research by providing empirical evidence on touch-affect association in the absence of visual stimuli, with identifiable design implications. Specifically, Low-freq shape changes, where Bouba-like features dominate, might be leveraged to induce a sense of calmness, for meditation or mental-health support. High-freq shape change where either Bouba-like or Kiki-like features dominate could be used to raise alertness. A particularly interesting implication of the results is that rounded, bouba-like, objects may be particularly versatile in this context, since these results indicate they can be actuated to produce both alertness and calmness. The results also point to opportunities to modulate arousal level by combining shape-change frequencies with Bouba/Kiki-like features. For example: Low-freq changes with overall Kiki-like features can still raise alertness, but is likely to be milder than High-freq actuation of the same Kiki-like stimulus.

At present, these implications should be treated as guidance for further investigation in design. The results for these shape-change frequencies may be relative, or range-specific: moving to other frequency ranges or sizes may result in quite different effects when sizes and frequencies are combined. Further empirical investigation of other frequency ranges is required to test effects of perceptual relativity in relation to the size of the shape-change.

7.4 Effect of shape-change frequency on certainty (study 2)

On the valence axis, when the stimulus presented had more Bouba-like features (Medium-size and Large-size level) the High-freq shape changes resulted in the most reversals, and Low-freq changes produced most velocity peaks. On the arousal axis, Low-freq changes produced more velocity peaks and reversals than High-freq changes, no matter whether the stimulus presented features which were overall more Bouba-like (large-size) or more Kiki-like (small-size). It is interesting that the High-freq condition, which resulted in the least positive valence when Bouba-like features dominated, also resulted in most reverses - which we take to indicate greater uncertainty. The reason could be explained by reference to results from both studies. Shape-changes with more Bouba-like features were associated with increased valence, while increase in frequency was associated with decreased valence. As a result, these opposed associations may have resulted in reduced certainty in touch-affect association. Continuing the discussion on certainty from the previous section, the kinematic analysis results suggest that when two shape-change features which have opposed affective associations are combined, this can modulate the perceive affect, and reduce the certainty of the perception. These results also showed that Low-freq changes, which resulted in lowest arousal level, resulted in less certainty and more hesitancy on both the valence and arousal axes. In contrast, High-freq changes produced the highest arousal level, and also resulted in less reversals than Low-freq changes. A possible interpretation of this could be that low-arousal affects may be less striking, less clear and distinct. This points to an opportunity for future work to clarify the connection between certainty in assigning emotional values, and the level of arousal assigned.

8 GENERAL DISCUSSION AND CONCLUSION

8.1 Extending the Crossmodal Bouba/Kiki paradigm to Understand Shape-Change

Building on research with the crossmodal Bouba/Kiki framework in 2D shapes and 3D tangible interaction [38], the research in this paper brings the Bouba/kiki paradigm into research on shape-change display as a means of systematically investigating touch-affect associations. Though we designed the shape-change gadget with different materials and different stiffness than previous tangible Bouba/Kiki objects, we were able to replicate the results in touch-affect association observed with those previous objects in our study. This demonstrates a continuity which will allow results from prior research in affective tangible interaction to inform research on shape-change. Building on the Bouba/Kiki framework allowed us to relate the effects of dynamic shape transformations to known effects with these well studied shapes. In particular this approach allowed us to separate out the effects of tactile perception of static shape, and shape change on affect. It also allowed us to show where associations formed by Bouba/Kiki shape changes were not affected by the polarity of the change. Both polarities of dynamic transformations elicited higher arousal levels relative to the static shape, and we found no evidence in either polarity of an effect of shape change on valence. Such results indicate the value of grounding the study of shape-change in a well established methodological paradigm such as the crossmodal framework we apply. Such an approach can support the systematic accumulation of empirical understanding over a variety of shape-change features and mechanisms, as discussed in [53].

Such grounding opens up a range of opportunities to extend the experimental prototcols presented in this paper. Future research might explore the density factor of Bouba/Kiki features [38], the stiffness and curvature factors of the shape-change gadget [53], multisensory factors as well as the material and texture factors in the shape-change mechanism [50].

8.2 Touch-affect association with Shape-change features

In both studies, we observed an association between Bouba/Kiki features and valence perception, with Bouba-dominant shape-change associated with positive valence, and Kiki-dominant features associated with negative valence. Across the three frequencies, the underlying effect of Bouba/Kiki features was still easy to observe: shape-changes in which Bouba features dominated were associated with positive valence, while those in which Kiki-features dominated were associated with negative valence. Effects of frequency then appeared to modulate these basic features. As the frequencies increased, the differences between Bouba-dominant and Kiki-dominant shape-changes appeared to become smaller, and the effect of the frequency dominated. At lower frequencies by contrast, the positive valence associations of Bouba-dominant shape-changes could be amplified by lowering the frequency of the shape-change, since lower frequencies are associated with more positive valences.

A possible complication here, however comes with the results on certainty: lower frequencies appeared to reduce users' certainty in assigning an affect to the experience. We speculated that this might be due to the way slower frequencies permit users to perceive individual phases of the shape change, and their potentially conflicting associations, as distinct. However further work would be required to understand this effect.

While our results are complex in places, and we point in our discussion to subtleties which need to be clarified by future work, there are some clear high level patterns we can point to:

- Where Bouba-like features dominated in the static shape and shape-change, shape-change induced higher arousal than the static shape.
- Tactile perception on shape-change motion features (without visual access) has positive associations with arousal, while with both visual and tactile perception [66], affective associations can be observed in both valence and arousal.
- Higher frequency was observed to increase arousal across all shape-changes, regardless of whether Bouba or Kiki features dominated in the shape-change.
- For shape-changes in which Bouba features dominated, a reduction in shape-change frequency was associated with an increase in valence.
- Certainty in assigning affect seemed to be increased by shape-change, relative to static shapes.
- Certainty in touch-affect associations often seems to be linked to the congruence of shape-change features and shape-change motions. Where features with opposite associations are mixed - (e.g. bouba-dominant changes with high-frequencies) then the level of certainty can be reduced.

8.3 Understanding perception of shape-change as it unfolds

One important outstanding issue in shape-change research is to understand experience over the course of shape-change, as it unfolds [2]. However, among established measurement instruments, there seems to be a lack of effective approaches to help to penetrate into the process. Many approaches to measuring affect are slow and not suited to understanding experiences as they unfold. For example, SAM requires three steps reflection on valence, arousal and dominance one after another [8]. This makes it effective for understanding the final product of shape-change, but not intuitive or efficient to dip into the process. User report via Likert scales force people to reduce the granularity of their affects and categorise into a scale with seven or nine chunks. This may reduce resolution in understanding emotional responses.

In this paper we take a small first step towards understanding the dynamics of user responses to shape-change as it unfolds, by making use of methodologies from dynamical theories of cognition which open a window on unfolding processes of decision and attribution. We used kinematic analysis of the user's movement to understand uncertainty in their experience of shape-change. A limitation in many current methods in shape-change research is the need for users to narrate their subjective experiences effectively. This process can be slow and at odds with in-the-moment affective experience. Analysis of users' movement, using kinematic approaches like those we apply here, seems a promising way forwards. Beyond our use here to understand certainty, recent research has begun to apply the approach to understand affect more directly [70, 71]. We suggest that future work can help understand shape-change as it unfolds by augmenting user-report measures with validated objective measures of experience, including perhaps kinematic approaches, which can help understand user experience. Such metrics should be able to be captured quickly, often, and without disrupting the experience. A simple next step, which might be explored could be built on the approach described in this paper, by extending the shape-change duration, and allowing participants to mark out their subjective experience on the circumplex interface in moment-by-moment reaction to the shape change as it unfolds. The literature we discuss in our background section offers ample resources for grounding and developing such an approach.

ACKNOWLEDGMENTS

...

REFERENCES

[1] Harini Alagarai Sampath, Bipin Indurkhya, Eunhwa Lee, and Yudong Bae. 2015. Towards multimodal affective feedback: Interaction between visual and haptic modalities. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2043–2052.

[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*. 1–14.

[3] Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D Wilson. 2016. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1968–1979.

[4] Paul Bach-y Rita, Kurt A Kaczmarek, Mitchell E Tyler, Jorge Garcia-Lara, et al. 1998. Form perception with a 49-point electrotactile stimulus array on the tongue: a technical note. *Journal of rehabilitation research and development* 35 (1998), 427–430.

[5] Laura Barca and Giovanni Pezzulo. 2012. Unfolding Visual Lexical Decision in Time. *PLOS ONE* 7 (04 2012), 1–9. https://doi.org/10.1371/journal.pone.0035932

[6] Lisa Feldman Barrett and James A Russell. 1999. The structure of current affect: Controversies and emerging consensus. *Current directions in psychological science* 8, 1 (1999), 10–14.

[7] Elisheva Ben-Artzi and Lawrence E Marks. 1995. Visual-auditory interaction in speeded classification: Role of stimulus difference. *Perception & Psychophysics* 57, 8 (1995), 1151–1162.

[8] Margaret M Bradley and Peter J Lang. 1994. Measuring emotion: the self-assessment manikin and the semantic differential. *Journal of behavior therapy and experimental psychiatry* 25, 1 (1994), 49–59.

[9] Andrew J Bremner, Serge Caparos, Jules Davidoff, Jan de Fockert, Karina J Linnell, and Charles Spence. 2013. "Bouba" and "Kiki" in Namibia? A remote culture make similar shape–sound matches, but different shape–taste matches to Westerners. *Cognition* 126, 2 (2013), 165–172.

[10] Antonio Calcagnì, Luigi Lombardi, and Simone Sulpizio. 2017. Analyzing spatial data from mouse tracker methodology: An entropic approach. *Behavior research methods* 49, 6 (2017), 2012–2030.

[11] Franceli L Cibrian, Oscar Peña, Deysi Ortega, and Monica Tentori. 2017. BendableSound: An elastic multisensory surface using touch-based interactions to assist children with severe autism during music therapy. *International Journal of Human-Computer Studies* 107 (2017), 22–37.

[12] Francis B Colavita. 1974. Human sensory dominance. *Perception & Psychophysics* 16, 2 (1974), 409–412.

[13] Roddy Cowie, Ellen Douglas-Cowie, Nicolas Tsapatsoulis, George Votsis, Stefanos Kollias, Winfried Fellenz, and John G Taylor. 2001. Emotion recognition in human-computer interaction. *IEEE Signal processing magazine* 18, 1 (2001), 32–80.

[14] Clare Cullen and Oussama Metatla. 2018. Multisensory storytelling: a co-design study with children with mixed visual abilities. In *Proceedings of the 17th ACM Conference on Interaction Design and Children*. ACM, 557–562.

[15] Rick Dale, Jennifer Roche, Kristy Snyder, and Ryan McCall. 2008. Exploring Action Dynamics as an Index of Paired-Associate Learning. *PLOS ONE* 3, 3 (03 2008), 1–10. https://doi.org/10.1371/journal.pone.0001728

[16] Donald Degraen, André Zenner, and Antonio Krüger. 2019. Enhancing texture perception in virtual reality using 3D-printed hair structures. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–12.

[17] Nicholas D Duran, Rick Dale, and Danielle S McNamara. 2010. The action dynamics of overcoming the truth. *Psychonomic bulletin & review* 17, 4 (2010), 486–491.

[18] Paul Ekman. 1992. An argument for basic emotions. *Cognition & emotion* 6, 3-4 (1992), 169–200.

[19] Karla K Evans and Anne Treisman. 2009. Natural cross-modal mappings between visual and auditory features. *Journal of vision* 10, 1 (2009), 6–6.

[20] Behnaz Farahi. 2020. Emotional Intelligence: Affective Computing in Architecture and Design. In *Architectural Intelligence*. Springer, 235–251.

[21] Lisa Feldman Barrett and James A Russell. 1998. Independence and bipolarity in the structure of current affect. *Journal of personality and social psychology* 74, 4 (1998), 967.

[22] Daniel J Finnegan, Eamonn O'Neill, and Michael J Proulx. 2016. Compensating for distance compression in audiovisual virtual environments using incongruence. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 200–212.

[23] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: dynamic physical affordances and constraints through shape and object actuation.. In *Uist*, Vol. 13. 2501988–2502032.

[24] Jonathan Freeman, Rick Dale, and Thomas Farmer. 2011. Hand in Motion Reveals Mind in Motion. *Frontiers in Psychology* 2 (2011), 59. https://doi.org/10.3389/fpsyg.2011.00059

[25] Elia Gatti, Elena Calzolari, Emanuela Maggioni, and Marianna Obrist. 2018. Emotional ratings and skin conductance response to visual, auditory and haptic stimuli. *Scientific data* 5, 1 (2018), 1–12.

[26] Michael J. Gill and Nick D. Ungson. 2018. How much blame does he truly deserve? Historicist narratives engender uncertainty about blameworthiness, facilitating motivated cognition in moral judgment. *Journal of Experimental Social Psychology* 77 (2018), 11–23. https://doi.org/10.1016/j.jesp.2018.03.008

[27] Patrick Gomez and Brigitta Danuser. 2004. Affective and physiological responses to environmental noises and music. *International Journal of psychophysiology* 53, 2 (2004), 91–103.

[28] David Hecht and Miriam Reiner. 2009. Sensory dominance in combinations of audio, visual and haptic stimuli. *Experimental brain research* 193, 2 (2009), 307–314.

[29] Eric Hehman, Ryan M Stolier, and Jonathan B Freeman. 2015. Advanced mouse-tracking analytic techniques for enhancing psychological science. *Group Processes & Intergroup Relations* 18, 3 (2015), 384–401.

[30] Eve Hoggan, Andrew Crossan, Stephen A Brewster, and Topi Kaaresoja. 2009. Audio or tactile feedback: which modality when?. In *Proceedings of the SIGCHI conference on human factors in computing systems*. ACM, 2253–2256.

[31] Yuhan Hu and Guy Hoffman. 2019. Using skin texture change to design emotion expression in social robots. In *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 2–10.

[32] Alexandra Ion, Robert Kovacs, Oliver S Schneider, Pedro Lopes, and Patrick Baudisch. 2018. Metamaterial textures. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.

[33] Leslie M Kay. 2011. Olfactory coding: random scents make sense. *Current Biology* 21, 22 (2011), R928–R929.

[34] Wolfgang Köhler. 1967. Gestalt psychology. *Psychologische Forschung* 31, 1 (1967), XVIII–XXX.

[35] Peter Lang and Margaret M Bradley. 2007. The International Affective Picture System (IAPS) in the study of emotion and attention. *Handbook of emotion elicitation and assessment* 29 (2007), 70–73.

[36] Peter J Lang. 1995. The emotion probe: Studies of motivation and attention. *American psychologist* 50, 5 (1995), 372.

[37] Jung Min Lee, Jongsoo Baek, and Da Young Ju. 2018. Anthropomorphic Design: Emotional Perception for Deformable Object. *Frontiers in psychology* 9 (2018), 1829.

[38] Anan Lin, Meike Scheller, Feng Feng, Michael J Proulx, and Oussama Metatla. 2021. Feeling Colours: Crossmodal Correspondences Between Tangible 3D Objects, Colours and Emotions. In *Proceedings of the 2021 CHI Conference on Human*

Factors in Computing Systems. 1–12.
[39] Manuela M Marin, Bruno Gingras, and Joydeep Bhattacharya. 2012. Crossmodal transfer of arousal, but not pleasantness, from the musical to the visual domain. *Emotion* 12, 3 (2012), 618.
[40] Daphne Maurer, Thanujeni Pathman, and Catherine J Mondloch. 2006. The shape of boubas: Sound–shape correspondences in toddlers and adults. *Developmental science* 9, 3 (2006), 316–322.
[41] Oussama Metatla, Nuno N Correia, Fiore Martin, Nick Bryan-Kinns, and Tony Stockman. 2016. Tap the shapeTones: Exploring the effects of crossmodal congruence in an audio-visual interface. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1055–1066.
[42] Oussama Metatla, Emanuela Maggioni, Clare Cullen, and Marianna Obrist. 2019. " Like Popcorn" Crossmodal Correspondences Between Scents, 3D Shapes and Emotions in Children. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–13.
[43] Marianna Obrist, Sriram Subramanian, Elia Gatti, Benjamin Long, and Thomas Carter. 2015. Emotions mediated through mid-air haptics. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2053–2062.
[44] Andrew Ortony and Terence J Turner. 1990. What's basic about basic emotions? *Psychological review* 97, 3 (1990), 315.
[45] Sharon Oviatt, Björn Schuller, Philip Cohen, Daniel Sonntag, and Gerasimos Potamianos. 2017. *The handbook of multimodal-multisensor interfaces, volume 1: Foundations, user modeling, and common modality combinations*. Morgan & Claypool.
[46] Cesare Valerio Parise and Charles Spence. 2009. 'When birds of a feather flock together': Synesthetic correspondences modulate audiovisual integration in non-synesthetes. *PLoS One* 4, 5 (2009), e5664.
[47] Cesare V Parise and Charles Spence. 2012. Audiovisual crossmodal correspondences and sound symbolism: a study using the implicit association test. *Experimental Brain Research* 220, 3-4 (2012), 319–333.
[48] Esben W Pedersen, Sriram Subramanian, and Kasper Hornbæk. 2014. Is my phone alive? A large-scale study of shape change in handheld devices using videos. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2579–2588.
[49] Betina Piqueras-Fiszman, Jorge Alcaide, Elena Roura, and Charles Spence. 2012. Is it the plate or is it the food? Assessing the influence of the color (black or white) and shape of the plate on the perception of the food placed on it. *Food Quality and Preference* 24, 1 (2012), 205–208.
[50] Isabel PS 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*. 1–23.
[51] Vilayanur S Ramachandran and Edward M Hubbard. 2003. Hearing colors, tasting shapes. *Scientific American* 288, 5 (2003), 52–59.
[52] Nimesha Ranasinghe, Pravar Jain, Nguyen Thi Ngoc Tram, Koon Chuan Raymond Koh, David Tolley, Shienny Karwita, Lin Lien-Ya, Yan Liangkun, Kala Shamaiah, Chow Eason Wai Tung, et al. 2018. Season traveller: Multisensory narration for enhancing the virtual reality experience. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–13.
[53] 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*. 735–744.
[54] Kyle Rector, Roger Vilardaga, Leo Lansky, Kellie Lu, Cynthia L Bennett, Richard E Ladner, and Julie A Kientz. 2017. Design and real-world evaluation of Eyes-Free Yoga: An exergame for blind and low-vision exercise. *ACM Transactions on Accessible Computing (TACCESS)* 9, 4 (2017), 1–25.
[55] Jaime Redondo, Isabel Fraga, Isabel Padrón, and Ana Piñeiro. 2008. Affective ratings of sound stimuli. *Behavior Research Methods* 40, 3 (2008), 784–790.
[56] Luca Rinaldi, Emanuela Maggioni, Nadia Olivero, Angelo Maravita, and Luisa Girelli. 2018. Smelling the space around us: Odor pleasantness shifts visuospatial attention in humans. *Emotion* 18, 7 (2018), 971.
[57] James A Russell. 1980. A circumplex model of affect. *Journal of personality and social psychology* 39, 6 (1980), 1161.
[58] Lisa Skedung, Martin Arvidsson, Jun Young Chung, Christopher M Stafford, Birgitta Berglund, and Mark W Rutland. 2013. Feeling small: exploring the tactile perception limits. *Scientific reports* 3, 1 (2013), 1–6.
[59] Charles Spence. 2011. Crossmodal correspondences: A tutorial review. *Attention, Perception, & Psychophysics* 73, 4 (2011), 971–995.
[60] Charles Spence and Jon Driver. 1997. Audiovisual links in exogenous covert spatial orienting. *Perception & psychophysics* 59, 1 (1997), 1–22.
[61] Adam J Spiers and Aaron M Dollar. 2016. Design and evaluation of shape-changing haptic interfaces for pedestrian navigation assistance. *IEEE transactions on haptics* 10, 1 (2016), 17–28.
[62] Michael J Spivey and Rick Dale. 2004. On the continuity of mind: toward a dynamical account of cognition. (2004).
[63] Paul E. Stillman, Xi Shen, and Melissa J. Ferguson. 2018. How Mouse-tracking Can Advance Social Cognitive Theory. *Trends in Cognitive Sciences* 22, 6 (2018), 531–543. https://doi.org/10.1016/j.tics.2018.03.012
[64] Leland S Stone and Peter Thompson. 1992. Human speed perception is contrast dependent. *Vision research* 32, 8 (1992), 1535–1549.
[65] 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*. 3781–3792.
[66] 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*. 1282–1293.
[67] Anna Vallgårda, Morten Winther, Nina Mørch, and Edit E Vizer. 2015. Temporal form in interaction design. *International Journal of Design* 9, 3 (2015).
[68] Anke Van Oosterhout, Miguel Bruns Alonso, and Satu Jumisko-Pyykkö. 2018. Ripple thermostat: Affecting the emotional experience through interactive force feedback and shape change. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.
[69] Anke van Oosterhout and Eve Hoggan. 2021. Deformation Techniques for Shape Changing Interfaces. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–7.
[70] Takashi Yamauchi and Kunchen Xiao. 2017. Reading Emotion From Mouse Cursor Motions: Affective Computing Approach. *Cognitive Science* 42 (11 2017). https://doi.org/10.1111/cogs.12557
[71] Simin Yang, Courtney Nicole Reed, Elaine Chew, and Mathieu Barthet. 2021. Examining Emotion Perception Agreement in Live Music Performance. *IEEE Transactions on Affective Computing* (2021).
[72] Steve Yohanan and Karon E MacLean. 2011. Design and assessment of the haptic creature's affect display. In *2011 6th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 473–480.