Squishy, Yet Satisfying: Exploring Deformable Shapes' Cross-Modal Correspondences with Colours and Emotions

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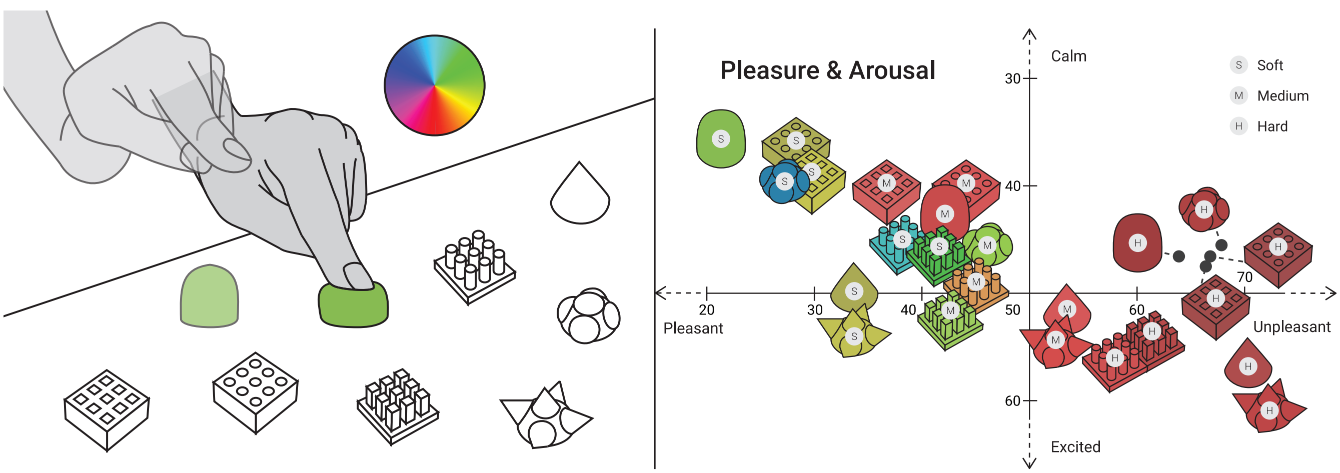

Figure 1: We explored how people associate colours and emotions with deformable shapes of various stiffness (soft, medium, and hard) and angularity (Bouba, Kiki) (left). Results from the study (right) show crossmodal correspondences between the deformable shapes for colours (hue and brightness) and emotions (positions along the axes from 0-100).

ABSTRACT

Surfaces with deformable and shape-changing properties seek to enhance and diversify tangible interactions with computing systems. However, we currently lack fundamental knowledge and user interface design principles that connect the inherent properties of deformable shapes with our human senses and cognitive associations. To address this knowledge gap, we systematically explored deformable shapes' cross-modal correspondences (CC) with colours and emotions. In our CC study, 52 participants were presented with deformable shape stimuli that varied in stiffness and angularity. They were asked to associate these stimuli with colours and emotions under (i) visuo-tactile and; (ii) tactile-only conditions. For the first time, our findings reveal (1) how stiffness level primarily influences the CC associations and; (2) that stiffness and angularity play a significant role in CC associations over the visibility of the shapes. The results were distilled into design guidelines for future deformable, shape-changing interfaces that engage specific human senses and responses.

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CCS CONCEPTS

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

KEYWORDS

Deformable, Shape, Colour, Emotion, Crossmodal Correspondences, Force, Touch, Visuo-tactile, Tactile-only

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1 INTRODUCTION

Shape-changing and deformable interfaces offer the unique potential for physical manipulation as a communication medium [2, 5, 24, 55]. They can provide users with compliant screens that enable variations in stiffness [31, 75] and the ability to morph into different shapes for both dynamic physical feedback and dynamic affordances [48]. Recent efforts in this space are largely technology-focused, with researchers seeking to develop new construction approaches for deformable and shape-changing interfaces [2, 5]. However, as the field matures, there is a growing need to develop fundamental design principles [2] on the user perception of these devices. This will enable designers to leverage deformation and shape to create intuitive mappings for interface signifiers and multi-sensory experiences that combine visual and tactile modalities with user affect.

To address this need, we draw on the Crossmodal Correspondence (CC) phenomenon, and its role in understanding how the human brain integrates information from multiple senses [39]. There is robust evidence, ranging from neuroscience [17, 67] to psychology [6, 51, 63] and HCI [56], that multi-sensory harmony allows efficient processing [41]. Research in cognitive science describes how external physical representations can aid in cognitive tasks such as encoding explicit information or coordinating thoughts [38]. CCs stretch across cultures [13], and even across generations [46], and thus provide reliable, inclusive design solutions. This makes the study of CCs involving deformability and shapes a clear avenue to inform design guidelines of such novel interfaces. Emotional responses to interfaces are known to impact whether someone will buy a device or use it regularly, thus the links between the senses and affect are crucial design considerations [34].

Work has begun to map out these fundamental principles for shapes, particularly CC of tactile static shapes [40] and dynamic shapes [21] to colour and emotions. This work includes guidelines based on studying visual-tactile CCs across deformable surfaces and their correspondences with shapes and colour [65], providing insights into the interplay between flat deformable surfaces and visual interface elements. We advance this growing area of research by studying the combinations of *deformable shapes* and their correspondences to *colours* and *emotions*. We seek to answer the following questions:

RQ1 How do people interact with, and assign emotions and colours to various deformable shapes of different stiffness?

RQ2 Do emotions and colour associations differ based on whether deformable shapes are visible during tactile interaction?

We address our research questions through a within-participants user study with 52 participants. We used a set of shapes as stimuli (see Figure 1), of which we varied the shape (Curve, Sinuous, Emerge, and Porous), angularity (Bouba, Kiki), and stiffness (softer than skin, equal to skin, harder than skin). For example, a hard Bouba-Curve represents a round cylindrical shape with little compliance, whereas a soft Kiki-Sinuous consists of multiple squishable spiky shapes (see Figures 2 & 3). The participants explored the different deformable shape stimuli and were subsequently tasked with associating them with emotions (Pleasure-Arousal-Dominance (PAD) Emotional-State Mode) and colours. These associations were performed in visuo-tactile and tactile-only conditions to investigate the influence of visual context on participants' perceptions.

The results of our study identified six key takeaways: (1) shape and stiffness consistently influence users' colour and emotional associations across both visuo-tactile and tactile-only modalities; (2) soft shapes are associated with cooler colours and harder shapes with warmer colours; (3) high brightness is associated with combinations of soft-rounded, or spiky shapes while darker colours are associated with harder-rounded shapes; (4) soft-rounded shapes are associated with pleasant feelings, while harder, spiky shapes tend to evoke unpleasantness; (5) spiky shapes are associated with excitement, while rounder shapes with calmer designs; and (6) rounder protruding shapes convey a sense of high control and making them softer can enhance this feeling.

These results have the potential for a lasting impact on the shape-change and deformable user interface field through our synthesis of the results into implementable design implications. For example, we envision UI designers of variable stiffness devices [28, 76, 80] can apply finding (2) to set user expectations of the softness/stiffness of a widget or surface *before* and interaction begins, resulting in more efficient and desirable interaction experiences.

Our study contributes evidence of cross-modal correspondences between the sensory haptics of physical shape and stiffness, with colours and emotions. The findings further advance the knowledge of designing effective affordances and signifiers for physical interfaces, with particular implications for deformable and shape-changing interfaces, eyes-free interaction, and multi-sensory experiences in HCI. We make the following contributions:

- Empirical evidence demonstrating how different shape features, stiffnesses, and user-applied force interact to determine associations with colour and emotions during tactile exploration (see Figure 1).
- We show that the visual modality has little influence over user associations with colour and emotions when exploring deformable shapes.
- Guidelines for the design of physical user interfaces that combine the visual-tactile modalities, as well as user affect.

2 RELATED WORK

We summarise related work on deformable and shape-changing interfaces and the use of Cross-modal correspondences in HCI.

2.1 Deformable & Shape-Changing Interfaces

Ishii et al. [29] outlines a defining vision for the future of physical interfaces with Radical Atoms. It envisions a world that goes beyond existing flat, static forms of interfaces and towards one with transformable materials. Since then, the way in which interfaces can change [2, 55] and deform [5] has been explored in a multitude of approaches.

A wide range of research has explored how to develop deformable non-rigid User Interfaces (UIs) elements that incorporate dynamic stiffness elements. Parkes and Ishii [52] demonstrate Bosu as a design tool for soft mechanics that can record and playback 3D motion. Similarly, Materiable imitates dynamic properties, such as flexibility, elasticity, and viscosity, again using 3D motion [49]. Such prototypes enable a richer embodied interaction and perceptions of rendered materials. Dynamic stiffness is also explored through pneumatics [28, 76, 80], including for tactile response related to levels of force input [76].

Smart materials and fluids offer new routes for implementing haptic and deformable displays. Ferrofluids, triggered by magnetic fields, can set areas of 'hardness' that also allow users to push into the interface [31, 32, 74]. Microfluidics presents an opportunity to down-scale the form factor of such devices [78]. Miruchna et al. [47] introduces temperature-actuated hydrogels, which provide an alternative method for adding actuated deformable elements to touch surfaces. Due to this combination of actuation and deformability, it has also been used in the context of wearable technologies [33] and the simulation of the feeling of paints on mobile devices [66].

The space of the deformable surfaces has also seen fabric used in devices, for example, TableHop [60]. Here, the fabric is used as a display alongside transparent electrodes to provide haptic feedback and deformable cues to the user [60]. Other non-rigid deformable interfaces include examples of foldable displays [36], elastic displays [73], thin-film touch-displays, and stretchable on-body displays [77].

2.2 The Human Side of Deformable & Shape-Changing Interfaces

While significant work has focused on technological advances in deformable and shape-changing interfaces, there is a need for a deeper understanding of user experiences with these novel devices [2]. To advance this understanding, we can look at key framework papers in the field. Morphees [59] presents a framework for the resolution of actuated mobiles; this framework was further evaluated and expanded by the authors in workshops that created taxonomies of everyday re-configurable objects [37]. Resolution change was then further explored by [53], but then in relation to people's feelings and perceptions via a large-scale video study where users watched handheld devices change shape. Similarly, the feelings and perceptions of users were studied in 'Imagined Physics' [45, 50]. This work reviewed examples of shape-changing interfaces and analysed human responses to the changes.

Sturdee and Alexander [68] classified different forms of shape change, this time on an application level, providing insights into end-use cases. We also see work focusing on understanding affordances and their role in shaping users' mental models [71]. Similarly, Follmer et al. [24] outline frameworks for dynamic affordances and constraints, shedding light on the design possibilities in shape-changing interfaces. Extending this, other work has proposed a design space for shape-changing widget controls and applications in eyes-free scenarios again, focusing on shape resolutions [57].

We also see work that seeks to understand the impact of deformations on usability for force input tasks [25, 61]. Fan's JND (Just Noticeable Difference) study [19] explores the detection of surface shapes under varying stiffness conditions, contributing to our understanding of deformable interactions with shape-changing displays.

Collectively, these studies showcase the diverse technical and interaction possibilities within the design space of deformable and shape-changing displays, emphasising the importance of understanding user experiences and perceptions when developing future prototypes and applications. Furthermore, there is a large body of work that explores the haptic perception of deformable material [3, 10, 14, 64]. This paper expands on these perception studies and framework papers by studying Crossmodal Correspondences (CC), and the pairing of deformation and shape.

2.3 Crossmodal Correspondences in HCI

Crossmodal correspondences (CC) pertain to the non-arbitrary perceptual mapping of stimulus features, both within and across different sensory modalities. One of the most widely-known CC phenomena is known as the "Bouba/Kiki" effect [54], which dates back to the 1970s. The results consistently demonstrated that the majority of participants associated the round shape with "baluma" and the angular shape with "takete" [39]. Subsequent studies replaced these names with "bouba" and "kiki", yielding similar outcomes. This work demonstrated that our affective or emotional response to objects can impact our aesthetic experience of them and judgments of appreciation [34].

Human-Computer Interaction (HCI) inherently involves multiple sensory modalities [35]. Common computer interfaces seamlessly integrate visual elements (e.g. monitors) with tactile components (e.g. touchscreens, keyboards, or mice). The use of CCs presents numerous advantages for novel HCI research, where the interplay between sensory modalities during presentation or input plays a central role. These benefits include gaining insights into which cues evoke specific human responses, learning how to harness these cues effectively, and identifying those that should be avoided. An intriguing characteristic of CCs is their universal presence across various languages, cultures [12], and age groups, which underscores their potential to yield reliable and inclusive design [43, 46].

As a result, there is a growing trend of incorporating CCs into HCI research and design [23, 40, 46]. This trend encompasses investigations into colour associations with tangible objects [40], shape-changing [22], and deformable surfaces [65]. Along with colour, Lin et al. [40] highlights the need to fill the gap in our understanding of how sensory modalities combine to convey and interpret emotional content. However, prior work that maps emotion associations to physical interface properties has so far only focused on haptics [79], solid, tangible shapes [40], or dynamic angularity change [22, 70]. Therefore, we contribute results on emotional associations for compliant shapes, combining shape and stiffness factors.

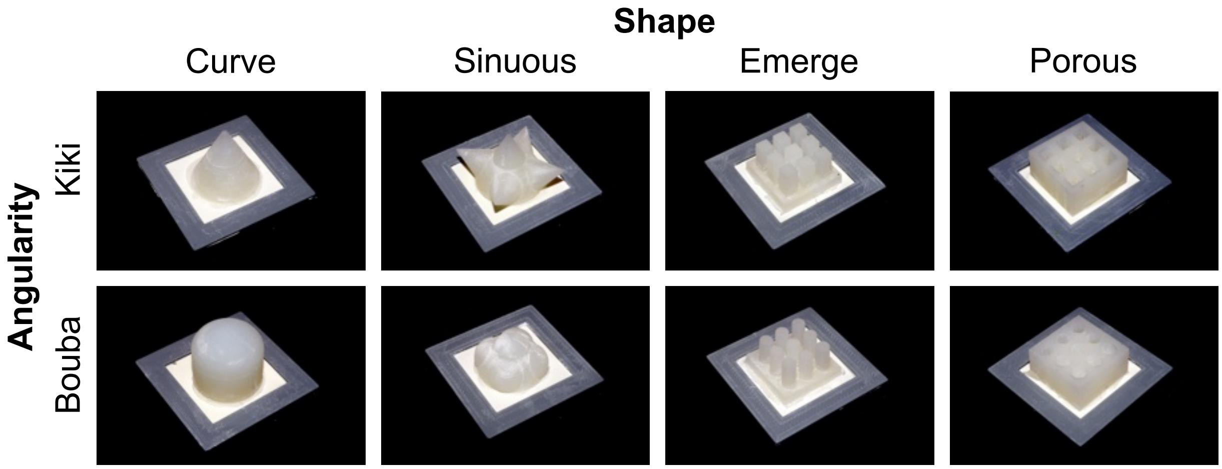

Figure 2: The four *Shapes* used in the study (Left to right: Curve, Sinuous, Emerge, and Porous) for each of their *Angularity's* (Top: Kiki, Bottom: Bouba). Each shape was cast three times at the three *Stiffness* levels. The image shows the Medium stiffness versions of the shapes.

Our work extends this by studying the CCs of deformable shapes with colours and emotions in the context of HCI. To the best of our knowledge, our work is the first to focus on cross-modal correspondence combinations of variable shape and stiffness stimuli in the context of HCI.

3 METHODOLOGY

This study aims to understand the crossmodal correspondence between tangible, deformable shapes of different stiffness, with colours, emotions, and user-applied force. These associations were measured in both visuo-tactile and tactile-only conditions. The study followed a within-subjects design.

3.1 Deformable Shape Stimuli

We developed a range of physical shapes, created with different *Stiffness* levels and *Angularity*, as stimuli for the study. This section describes these materials, the measures used in the study, and the rationale behind our choices. We primarily focused on touch and finger-based input scenarios when designing the stimuli. These encompassed activities such as pressing deformable buttons [1, 28, 62], applying pressure to various sections of the screen [31, 75], and interacting with shape displays [24, 30, 48].

3.1.1 Shapes. The variable properties for shapes are drawn from past literature on cross-modal correspondences [40, 65] and shape-changing interfaces [59] research. They were chosen based on a subset of 3D shape features that showed cross-modal correspondence between 3D shapes and stiffness [65]. They are summarised in Figure 2 and documented below:

Curve: A Morphees shape feature [59]. The curvature is determined by calculating the angle between three successive control points, naturally defining the degree of roundness in the shape instead of its sharpness.

Sinuous: 3D versions of Bouba/Kiki shapes based on Lin et al. [40]. Given their extensive background in cross-modal correspondence studies in psychology literature, these act as foundation shapes.

Emerge: Shapes based on pin array shape-changing interfaces [24, 30, 57]. This shape acts as an inverse for porosity and incorporates elements of the amplitude Morphees feature [59].

Porous: Morphees shape feature porosity [59]. Refers to the presence of discontinuities or perforations within a shape. Porosity quantifies the proportion of the perforated sections relative to the total area of the shape.

3.1.2 Shape Angularity. The angularity for these stimuli was determined by the mathematical formulas successfully used in previous studies [40, 42]. For each shape feature, we designed a rounded "Bouba" version of the shapes, and a pointy "Kiki" version. The 3D shapes were designed via a combination of Fusion 360 for digital modelling and Python scripts to generate and calculate the exact curvature and angularity of the shapes. All shapes were modelled via the same process of 3D-printed moulds and pouring three different types of silicone to cast the stiffness levels. For consistency, all shapes were modelled to a 20mm × 20mm × 20mm footprint and height.

3.1.3 Shape Stiffness. To investigate the impact of surface stiffness on the cross-modal correspondences, each tactile shape stimulus was moulded at three distinct stiffness levels (soft, medium, and hard). The decision to use three levels was informed by the stiffness-to-shape correspondence results of Steer et al. [65]. The stiffness levels were selected based on past studies investigating the impact of stiffness on user perceptions of deformation and shape [18, 19]. These are based on the reference point of the index finger pad, and the three levels of stiffness (See Figure 3) are as follows:

Soft (Softer than a finger pad): The softest level of stiffness was designed to be softer than the typical index finger pad, with a Shore hardness rating of 00-10.

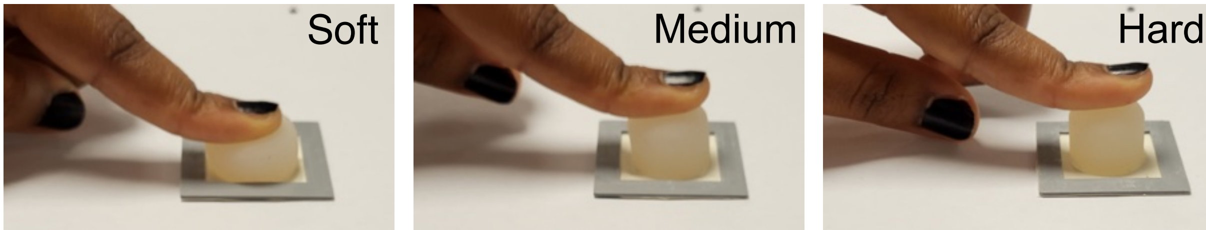

Figure 3: The three *Stiffnesses* used in the study (Left to right: Soft, Medium, and Hard), when pressed with 500g by the index finger of force on the Curved shape set.

Medium (As soft as a finger pad): This level of stiffness was calibrated to be similar to the typical index finger pad, with a Shore hardness rating of 00-50.

Hard (Harder than a finger pad): The hardest level of stiffness was designed to be harder than the index finger pad, with a Shore A-30 (approximately equivalent to Shore 00-80) hardness rating.

As is commonly used in other deformable perceptions studies, we used Ecoflex Silicone[1] for the silicone [19, 65]. To reduce surface texture's impact, each of the stimuli was dusted in calcium carbonate (chalk) [19, 26]. This chalk was also available for participants to dust their fingers with throughout the study.

3.2 Measures

3.2.1 Colours. Participants were presented with 10 distinct colours to choose from. The colours and their presentation in the interfaces were chosen based on the approaches used in previous CC studies [15, 40]. Doing this allows us to maintain continuity for our results with passed colour-based CC studies. Participants could refine their selection via a brightness bar (see Figure 4). Alongside each colour, examples of the minimum and maximum brightness versions of that colour were presented. The 10 colours and corresponding hexadecimal codes were red (ED3020), yellow (FFFF55), blue (3A5AC2), pink (ED3269), grey (7F7F7F), orange (F06E2B), lime green (91FB4D), sky blue (6FFCFE), purple (6323F7), and brown (AF7B51). All of the colours were displayed on the tablet screen over the top of a neutral grey (BCBCBC) background.

3.2.2 Emotions. To measure the emotions associated with the shapes, we used the Pleasure-Arousal-Dominance (PAD) Emotional-State Model [44], as this model is commonly used in CC studies within HCI [22, 40]. We asked participants to focus on subjectively experienced emotions induced by the sensory stimuli, rather than as a quality of the stimuli independent of an observer. In a similar manner to Lin et al. [40], we asked participants *"feeling the object with my hands gives me a sense of"* followed by three scales: pleasure (terms: Pleasant-Unpleasant), arousal (terms: Calm-Excited) and dominance (terms: Control-Lack of Control). Emotions were measured on an intuitive slider, which they dragged towards the word most fitting emotions on each of the scales of prevalence, arousal and dominance. E.g. sliding the cursor closer to pleasant compared to unpleasant for more pleasant associations. Because

[1]Ecoflex https://www.benam.co.uk/

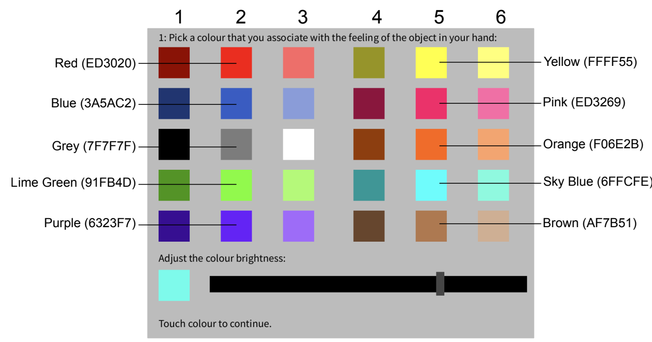

Figure 4: Colour selection interface used in the study. The colour columns (2, 5) were the primary selection columns, while adjacent columns (1, 3) and (4, 6), respectively, displayed the primary selection colour at its brightest (right) and darkest (left). The selected colour appears to the left of the slider, the brightness slider allows the participant to adjust the brightness before the final selection.

there was no conceptual absolute 0, it was not intended for participants to quantify their emotion perception as a number, so they did not see any values on the slider when making their input. The slider produced scores between 0 and 100 for increased granularity in scores and statistical convenience. Such input was preferred to a self-assessment manikin, since the latter is typically employed for measuring emotion excitation, or what users actually feel [7, 27], rather than just stimulus associations that are not meant to actually induce emotions.

3.2.3 User Force. For both tasks, the amount of force the user applies is recorded during their exploration of the stimuli. We used a widely available Force-Sensitive Resistor (FSR)[2] implemented with a Teensy4[3] microprocessor to read the sensor output, connected to serial and integrated with the study software. We followed other papers' hardware setup and calibration process using force sensors [19, 25]. Following this process ensured that we could map the voltage reading to grams and achieve nearly linear output. This involved amplifying the signal using the circuit seen in Figure 5.

[2]FSR: https://www.tangio.ca/force-sensing-resistors
[3]Teensy4: https://www.pjrc.com/store/teensy40.html

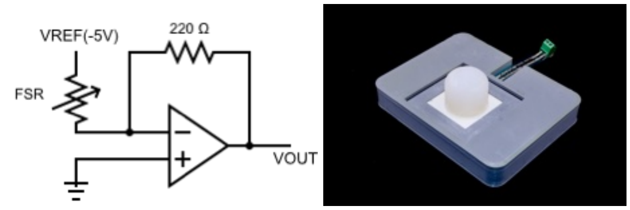

Figure 5: Left: Circuit diagram for FSR used in the study. Right: Force Platform used for each shape, with a Curve Bouba shape on it.

3.3 Study Setup & Apparatus

Our study setup consisted of (1) a force-sensing platform to place the stimuli, and (2) a touch screen monitor used to input answers depending on the task. In the tactile-only condition, a box covered the force-sensing platform and stimuli (see Figure 6). The study area was carefully controlled to minimise strong colour influences in the surrounding area of the participant's vision. Throughout the tasks, the participants sat on a chair at a desk and were told to rest their wrist on the table while touching the shapes.

3.3.1 Force-Sensor Platform. To capture force input, we mounted a force sensor inside a 3D-printed platform (see Figure 5). The platform ensured consistent placement of the stimuli for force sensing.

3.3.2 Cover for Tactile-only Conditions. A box was placed over the stimuli platform in the conditions where the shapes were hidden from view (See Figure 6). Participants used a single front opening to insert their hands to interact with the stimuli. The general placement and design allowed participants to rest their wrists flat on the table, as instructed by the researcher.

3.3.3 Selection Interface. To the left of the stimuli, we placed a touchscreen monitor. This was used to record the study's stiffness associations for colour and emotions. The system was coded using Java Processing[4] and integrated with the force sensor via serial communication (See Figure 6).

3.4 Procedure & Tasks

After obtaining participants' consent, they were asked to complete a demographic questionnaire. The experimental procedure comprised four main tasks: colour-tactile-only, colour-visuo-tactile, emotion-tactile-only, and emotion-visuo-tactile. In all tasks, participants pressed and matched 24 tactile stimuli (shape-stiffness) to either a colour or emotion scale (creating a total of 96 trials per participant). During these presses, the system recorded the force the participant's finger applied. In the visuo-tactile tasks, participants saw the stimulus before pressing it, while in the tactile-only tasks, the stimuli were hidden from view. Throughout the tasks, participants were reminded that there were no right or wrong answers. The task sequences were counterbalanced, and the order of presented stimuli was randomised to avoid ordering effects. The study concluded with a semi-structured interview, where participants were queried about their underlying rationales and strategies for forming associations for colour, emotion, and applied force across seen and unseen conditions. Each session took approximately 50 minutes (of which approximately 45 minutes tasks, and 5 minutes interview).

[4]Processing: https://processing.org/

Figure 6: Study setup from the participant's perspective during the colour tactile-only condition. The touchscreen monitor is used to answer questions (on the left), the box cover is used to hide the stimuli (right).

3.5 Participants

We recruited 52 participants, 26 identifying as female and 26 as male (Aged 18–60 years, Mean: 31.8, SD: 11.9). During the study, participants used their dominant hand to touch the stiffness stimuli. Of the participants, four were left-handed. All participants had normal or corrected-to-normal visual acuity and normal colour vision. All participants were compensated with a £10 gift voucher. An ethics review committee gave a favourable ethical opinion for this research project. This process involved submitting the study documentation, including procedures, questionnaires, interview scripts, consent forms, and information sheets for ethical review by two expert reviewers.

4 RESULTS

To answer our research questions, we analysed which properties of the deformable shapes affected colour and emotion associations, investigated how people interacted with the shapes, analysed what effect seeing the shape had on these associations, and summarised qualitative responses to understand participants' approaches and rationale for selections.

4.1 Data Analysis

Quantitative data was collected from the touch interface and force sensor. We elicited a total of 4992 responses from our 52 participants. These responses associated our deformable shapes with colours and emotions in visuo-tactile and tactile-only conditions. The forces users applied during the exploration of the shapes were collected and post-processed via coveting the voltages to grams based on our force sensor calibration process as mentioned in the Methodology. We calculated the average force over time for each shape interaction under each task for each condition.

For the quantitative data, we ran repeated measures analyses of variance (ANOVAs) investigating the effects of *Stiffness* (Soft, Medium, and Hard), *Angularity* (Bouba and Kiki), and *Visibility* (Visuo-Tactile and Tactile-Only) for each of the *Shape's* (Curve, Sinuous, Porous, and Emerge) associations with colour (Hue and Brightness) and emotion (Valence, Arousal, and Dominance). We used the same approach to test for effects on the force users applied during interaction.

Our analysis uses Holm-corrected post hoc pairwise comparisons where significant main effects and interactions were found. The assumption of sphericity was checked where necessary using Mauchly's test, and in cases where it was violated, results were reported with Huynh-Feldt corrections. We mark *p-values* with p^{*} for significant results where $p < .05$, p^{**} for significance of $p < .01$, and p^{***} for significance of $p < .001$. We also report η^2 effect size to show the magnitude of the observed differences for main effects and Cohen's d for post hoc tests.

Qualitative data was collected from the post-study interviews and audio-recorded with participants' consent. Recordings were transcribed, and 260 quotes were extracted. These were categorised through a deductive approach along three research themes: reflections in relation to (i) emotion associations, (ii) colour associations, and (iii) the force applied to the stimuli. Per research theme, a subset of the quotes was analysed using inductive thematic analysis [8, 9] to iteratively craft themes that comprised participants' most important reflections, after which all quotes were categorised accordingly.

4.2 Colour Associations

Overall, we observed that stiffness significantly affected colour associations for both Hue and Brightness across all *Shape* types. In most cases, this resulted in the softer version of the shapes being associated with lighter shades, and hues of yellows, greens, and blues (with exceptions for Porous shapes). A summary of colour selections is shown in Figure 7. In the remainder of this section, we provide a detailed analysis of the results. We used a repeated measures ANOVA followed by a post hoc pairwise comparison to investigate the effect of *Stiffness*, *Angularity*, and *Visibility* for the associated colour scales of Brightness (See Table 1) and Hue (See Table 2). We introduce the results individually for each *Shape*.

4.2.1 Brightness. **Curve Shapes:** Table 1 shows significant differences in *Angularity* (Line 1), *Stiffness* (Line 2), and an interaction between *Angularity* × *Stiffness* (Line 3). A post hoc analysis for *Angularity* showed a difference between Bouba and Kiki ($t(51) = -2.79, p = .007^{**}, d = -.261$), where Kiki shapes were associated with brighter colours. A post hoc analysis revealed a significant difference between all *Stiffnesses*, Soft-Medium ($t(51) = 4.24, p < .001^{***}, d = .467$), Soft-Hard ($t(51) = 10.62, p < .001^{***}, d = 1.170$), and Medium-Hard ($t(51) = 6.39, p < .001^{***}, d = .703$), where softer shapes were associated with brighter colours, and harder shapes with darker colours. A further post hoc analysis of the *Angularity* × *Stiffness* interaction saw a significant difference between Bouba-Hard and Kiki-Hard ($t(51) = -4.25, p < .001^{**}, d = -.562$), where Kiki-Hard curve shapes were associated with brighter colours than Bouba-Hard.

Sinuous Shapes: Table 1 shows significant differences for *Stiffness* (Line 4), *Visibility* × *Stiffness* (Line 5), and *Angularity* × *Stiffness* (Line 6). A post hoc analysis revealed a significant difference between all *Stiffnesses*, Soft-Medium ($t(51) = 4.89, p < .001^{***}, d = .496$), Soft-Hard ($t(51) = 8.57, p < .001^{***}, d = .870$), and Medium-Hard ($t(51) = 3.68, p < .001^{***}, d = .374$), where softer shapes where associated with brighter colours and harder shapes with darker colours. When analysing the *Visibility* × *Stiffness* interaction, we saw a significant difference between Visuo-Tactile-Hard and Tactile-Only-Hard ($t(51) = 4.93, p < .001^{***}, d = .671$), where the harder Visuo-Tactile shapes were associated with brighter colours. For *Angularity* × *Stiffness*, we saw a significant difference between Bouba-Hard and Kiki-Hard ($t(51) = -5.67, p < .001^{***}, d = -.726$), where Kiki-Hard was associated with brighter colours.

Emerge Shape: In Table 1, we see significant differences across *Angularity* (Line 7), *Stiffness* (Line 8) and *Angularity* × *Stiffness* (Line 9). A post hoc analysis on *Angularity* showed Kiki versions of Emerge shapes were associated with higher brightnesses ($t(51) = -2.79, p < .007^{**}, d = -.261$). The post-doc analysis of *Stiffness* revealed a significant difference between all *Stiffness* levels: Soft-Medium ($t(51) = 4.23, p < .001^{***}, d = .467$), Soft-Hard ($t(51) = 10.62, p < .001^{***}, d = 1.170$), and Medium-Hard ($t(51) = 6.39, p < .001^{***}, d = .703$), where softer shapes where associated with brighter colours and harder shapes with darker colours. A post hoc analysis of *Angularity* × *Stiffness* saw a significant difference between Bouba-Hard and Kiki-Hard ($t(51) = -4.25, p < .001^{***}, d = -.562$), where Bouba-Hard shapes were associated with significantly darker colours.

Porous Shapes: Table 1 shows the only significant differences in *Stiffness* (Line 10) for Porous shapes' colour associations. A post hoc analysis revealed a significant difference between all *Stiffnesses*: Soft-Medium ($t(51) = -13.95, p < .001^{***}, d = -1.605$), Soft-Hard ($t(51) = -9.91, p < .001^{***}, d = -1.140$), and Medium-Hard ($t(51) = 4.04, p < .001^{***}, d = .465$). The Soft shapes were associated with darker brightness values and the Medium stiffness with lighter brightness values. The Hard stiffness sat in between the two.

4.2.2 Hues. **Curve Shapes:** Table 2 shows significant differences based on *Angularity* (Line 1) and *Stiffness* (Line 2). A post hoc analysis of *Angularity* showed a difference between Bouba and Kiki ($t(51) = 2.23, p = .030^{*}, d = .218$) where Bouba is associated with higher hue values (Green hues) than Kiki (Red hues). A post hoc analysis of *Stiffness* showed a difference between Soft and Hard ($t(51) = 3.44, p = .003^{**}, d = .345$), where hues picked for Soft were higher than hues picked for Hard.

Sinuous Shapes: Table 2 shows significant differences based on *Angularity* (Line 3) and *Stiffness* (Line 4). A post hoc analysis of *Angularity* showed a significant difference between Bouba and Kiki ($t(51) = 2.43, p = .019^{*}, d = .273$) where Bouba is associated with higher hue values (Blues) than Kiki (Reds). A post hoc analysis of *Stiffness* showed a significant difference between Soft-Hard ($t(51) = 3.60, p < .001^{***}, d = .323$), where Soft was associated with higher hues (Blues) than Hard (Reds), and between Medium-Hard ($t(51) = 3.05, p = .006^{*}, d = .274$), where Medium is associated with higher hues (Greens) than Hard (Reds).

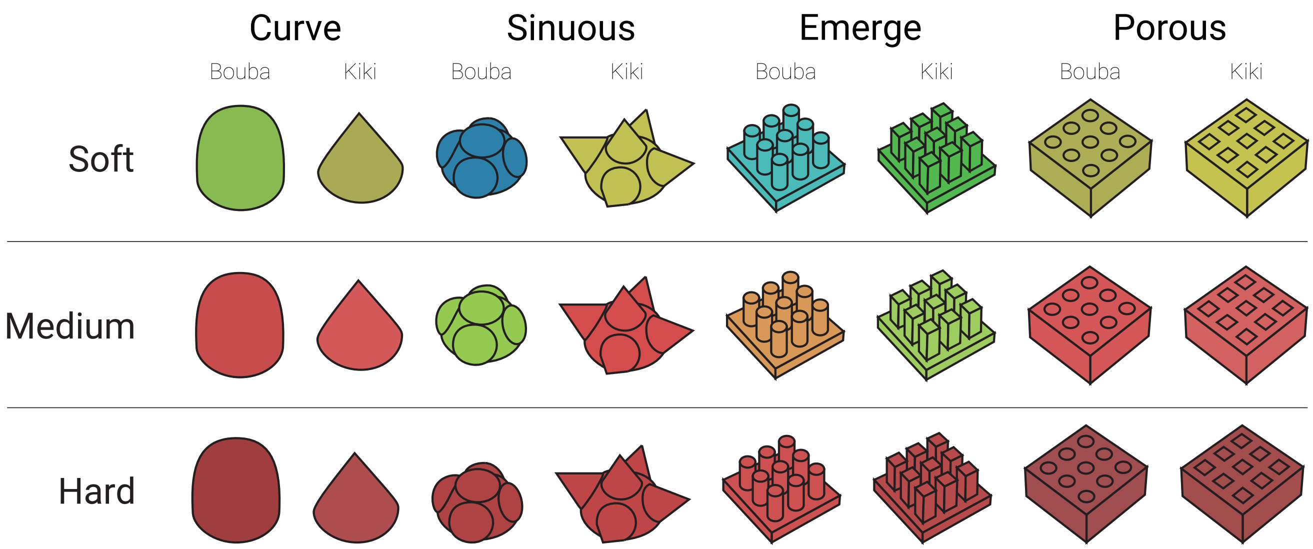

Figure 7: Overview of Shapes for each *Angularity* (Columns: Bouba, Kiki), and *Stiffness* (Rows: Soft, Medium, Hard) and associated colour values (for median Hue and average Brightness value) selected by the participants.

Table 1: Significant effects from the ANOVA of *Stiffness*, *Angularity*, and *Visibility* on Brightness for colour associations. * indicates significant results where $p < .05$, ** significant results where $p < .01$, and *** significant results where $p < .001$.

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Curve	*Angularity*	1.00	51.00	7.76	$.007^{**}$	.017
2		*Stiffness*	1.41	71.85	57.19	$< .001^{***}$	.227
3		*Angularity* × *Stiffness*	2.00	88.17	5.43	$.008^{**}$	.012
4	Sinuous	*Stiffness*	1.73	88.09	36.96	$< .001^{***}$	.114
5		*Visibility* × *Stiffness*	1.83	93.06	16.19	$< .001^{***}$	.041
6		*Angularity* × *Stiffness*	1.76	89.81	19.26	$< .001^{***}$	.041
7	Emerge	*Angularity*	1.00	51.00	7.76	$.007^{*}$	.017
8		*Stiffness*	1.41	71.85	57.19	$< .001^{***}$	.227
9		*Angularity* × *Stiffness*	1.73	88.17	5.43	$.008^{**}$	.012
10	Porous	*Stiffness*	1.56	79.32	103.04	$< .001^{***}$	.356

Table 2: Significant effects from ANOVA test of *Stiffness*, *Angularity*, and *Visibility* on Hue for colour associations. * indicates significant results where $p < .05$, ** significant results where $p < .01$, and *** significant results where $p < .001$.

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Curve	*Angularity*	1.00	51.00	4.98	$.030^{*}$	.013
2		*Stiffness*	1.83	93.40	5.95	$.005^{**}$	.022
3	Sinuous	*Angularity*	1.00	51.00	5.91	$.019^{*}$	.022
4		*Stiffness*	2.07	105.71	7.53	$< .001^{***}$	.024
5	Emerge	*Stiffness*	1.92	98.04	4.23	$.017^{*}$	.013
6		*Visibility*	1.00	51.00	38.23	$< .001^{***}$	.137
7		*Visibility* × *Stiffness*	2.03	103.40	4.39	$.014^{*}$	.013
8	Porous	*Stiffness*	1.77	90.09	7.658	$.001^{**}$	.036

Emerge Shapes: In Table 2, we see significant differences for *Stiffness* (Line 5), *Visibility* (Line 6) and *Visibility* × *Stiffness* (Line 7). A post hoc analysis of *Stiffness* showed a significant difference between Soft-Hard ($t(51) = 2.88, p = .015^{*}, d = .271$), where Soft was associated with higher hues of greens and blues, while Hard was associated with hues of red. A post hoc analysis of *Visibility* showed a significant difference between Visuo-Tactile and Tactile-Only ($t(51) = 6.18, p < .001^{***}, d = .716$). Further inspection of the *Visibility* × *Stiffness* interaction through post hoc analysis showed that Visuo-Tactile-Soft is significantly different from both Tactile-Only-Hard and Visuo-Tactile-Hard (both: $p < .001^{***}, d > .543$), where Visuo-Tactile-Soft is associated with higher hues of blues.

Porous Shapes: Table 2 shows significant differences in *Stiffness* (Line 8). A post hoc analysis on *Stiffness* showed a significant difference between Soft-Hard ($t(51) = 3.84, p < .001^{***}, d = .394$), where Soft was associated with yellow hues and Hard associated with red hues. There was also a significant difference between Soft-Medium ($t(51) = 2.56, p = .024^{*}, d = .262$), where Soft was associated with yellow hues and Medium with red hues.

4.2.3 Colour Associations Summary. Our results show that stiffness significantly affects colour associations for both Hue and Brightness, regardless of *Shape*. Softer versions of the shapes were usually associated with lighter shades, and hues of yellows, greens and blues. The exception was Porous shapes, whose softer versions were associated with dark shades (instead of light shades). In addition, harder Porous shapes were associated with even darker shades and mostly reds. Where *Angularity* had effects, Kiki shapes were more associated with high brightness. *Visibility* played little role in participants' shape-colour associations, the exceptions being the Brightness of Hard-Sinous shapes and Hue associations for Hard-Emerge shapes.

4.3 Emotion Associations

Overall, we observed Soft shapes were associated with higher pleasantness, while Hard shapes were associated with lower pleasantness. For arousal, Soft versions of Curve, Emerge, and Porous shapes were calmer and Hard *Stiffnesses* were more exciting. Dominance measures were less well defined, with Bouba-Sinuous, Bouba-Curves, and Kiki-Emerge-Hard rated with higher control. *Visibility* only saw a few specific instances of significant effect. A summary of the emotion associations is shown in Figure 8.

We used a repeated measures ANOVA followed by a post hoc pairwise comparison to investigate the effect of *Stiffness*, *Angularity*, and *Visibility* for the associated emotion scales of Pleasure (See Table 3), Arousal (See Table 4), and Dominance (Table 5). The discuss the emotion results in more detail in the following sections.

4.3.1 Pleasure. **Curved Shapes:** Table 3 shows significant differences across *Angularity* (Line 1), *Stiffness* (Line 2), and *Visibility* (Line 3). A post hoc analysis revealed a significant difference across all *Stiffnesses*, Soft-Medium ($t(51) = -7.83, p < .001^{***}, d = -1.008$), Soft-Hard ($t(51) = -15.27, p < .001^{***}, d = -1.965$), and Medium-Hard ($t(51) = -7.44, p < .001^{***}, d = -.957$) where the softer version was associated with greater pleasantness. The *Angularity* post hoc analysis showed Bouba was associated with greater pleasantness than Kiki. ($t(51) = -5.61, p < .001^{***}, d = -.466$). The *Visibility* post hoc analysis showed that Visuo-Tactile was associated with greater pleasantness than Tactile-Only ($t(51) = -2.211, p < .032^{*}, d = -.150$).

Sinuous Shapes: Table 3 shows significant differences across *Angularity* (Line 4) and *Stiffness* (Line 5). A post hoc analysis revealed a significant difference between all *Stiffnesses*, Soft-Medium ($t(51) = -6.40, p < .001^{***}, d = -.884$), Soft-Hard ($t(51) = -14.06, p < .001^{***}, d = -1.912$), and Medium-hard ($t(51) = -7.56, p < .001^{***}, d = -1.028$), where softer shapes are associated with greater pleasantness. A post hoc analysis between Bouba and Kiki showed Bouba was more pleasant ($t(51) = -3.03, p = .004^{**}, d = -.262$).

Emerge Shapes: Table 3 shows significant differences for *Stiffness* (Line 6), *Visibility* (Line 7), *Visibility* × *Stiffness* (Line 8), and *Angularity* × *Stiffness* (Line 9). A post hoc analysis on *Stiffness* shows Soft was significantly more pleasant than Hard ($t(51) = -7.16, p < .001^{***}, d = -.871$) and Medium significantly more pleasant than Hard ($t(51) = -5.65, p < .001^{***}, d = -.687$).

A post hoc analysis of the *Visibility* × *Stiffness* interaction showed only pleasantness associations for Soft were significantly different between the two visual conditions. In the Visuo-Tactile condition, Soft-Emerged shapes were significantly more pleasant ($t(51) = -4.85, p < .001^{***}, d = -.493$). A post hoc analysis of *Angularity* × *Stiffness* only showed significant differences where either *Angularity* or *Stiffness* combinations were different, already highlighted in the *Stiffness* post hoc results.

Porous Shapes: Table 3 shows significant differences in the shape's *Angularity* (Line 10), *Stiffness* (Line 11), and interaction of the *Stiffness* × *Angularity* (Line 12). A post hoc analysis revealed a significant difference between all *Stiffness* levels, Soft-Medium ($t(51) = -3.57, p < .001^{***}, d = -.556$), Soft-Hard ($t(51) = -11.85, p < .001^{***}, d = -1.844$), and Medium-Hard ($t(51) = -8.28, p < .001^{***}, d = -1.288$). A post hoc analysis on *Angularity* showed differences between Bouba and Kiki ($t(51) = 2.32, p = .024^{*}, d = 0.129$) where Kiki was more pleasant than Bouba. In the post hoc analysis of of *Stiffness* × *Angularity*, showed Medium-Kiki was more pleasant than Medium-Bouba ($t(51) = 4.98, p < .001^{***}, d = 0.419$).

4.3.2 Arousal. **Curved Shapes:** Table 4 shows significant differences in *Angularity* (Line 1), *Stiffness* (Line 2), *Visibility* (Line 3), and *Visibility* × *Stiffness* (Line 4). A post hoc analysis revealed a significant difference between Soft-Hard ($t(51) = -3.141, p = .007^{*}, d = -.423$) and Bouba-Kiki ($t(51) = -5.502, p < .001^{**}, d = -.497$). A post hoc analysis of *Visibility* revealed a significant difference between Visuo-Tactile and Tactile-Only ($t(51) = -2.334, p = .024^{*}, d = -.117$) where Visuo-Tactile was more calm than Tactile-Only. A post hoc analysis of the *Visibility* × *Stiffness* interaction revealed a Soft-Visuo-Tactile was more calm than Hard-Tactile-Only ($t(51) = -3.197, p = .024^{*}, d = -.478$)

Sinuous Shapes: Table 4 shows significant differences in the shape's *Angularity* (Line 5) and *Angle* × *Stiffness* (Line 6). A post hoc analysis of *Angularity* revealed Bouba shapes to be significantly less arousing ($t(51) = -6.38, p < .001^{***}, d = -.644$). A further post hoc analysis of the interaction between *Angle* × *Stiffness* showed us that even for the same *Stiffness*, Bouba shapes were rated less arousing and Kiki more arousing (Soft-Bouba and Soft-Kiki ($t(51) = -5.63, p < .001^{***}, d = -.720$), Medium-Bouba and Medium-Kiki

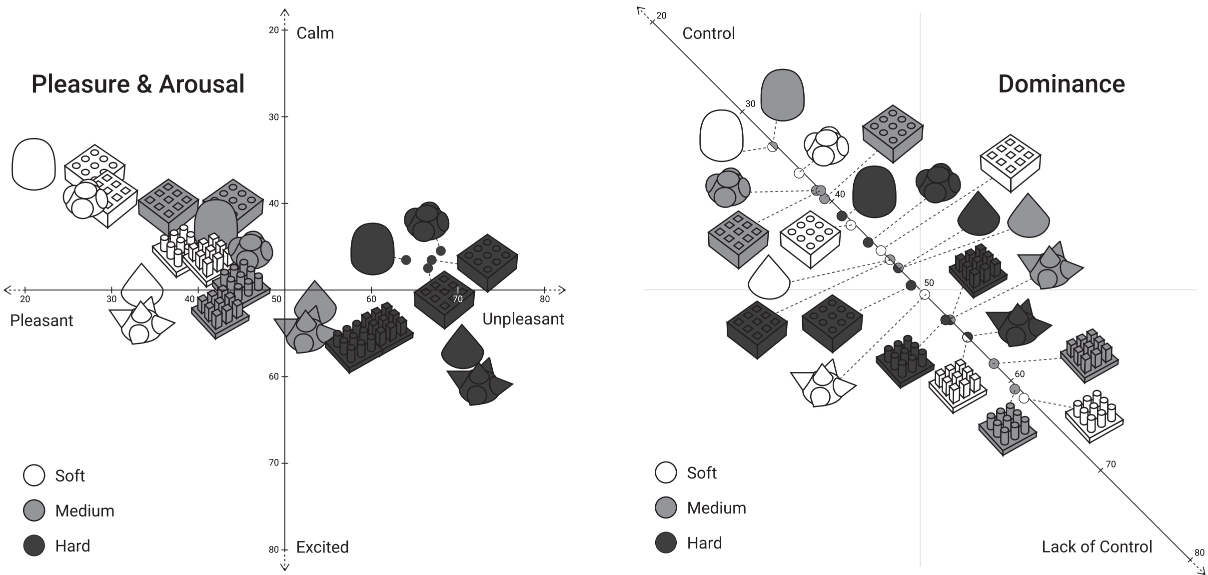

Figure 8: Overview distribution of emotion associations with deformable shapes across both *Visibility* conditions. Each of the emotions is plotted on axes from 0 to 100. Left: the shapes plotted for pleasure and arousal. Right: the shapes plotted for the dominance scale. The emotions value positions along the axes from 0-100.

Table 3: Significant effects from ANOVA test of *Stiffness*, *Angularity*, and *Visibility* on Pleasure for emotion associations. * **indicates significant results where** $p < .05$, ** **significant results where** $p < .01$, **and** *** **significant results where** $p < .001$.

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Curve	*Angularity*	1.26	64.05	116.59	$< .001^{***}$	.451
2		*Stiffness*	1.00	51.00	31.49	$< .001^{***}$	.038
3		*Visibility*	1.00	51.00	4.89	$.032^{*}$	.004
4	Sinuous	*Angularity*	1.00	51.0	38.53	$<.001^{***}$	.084
5		*Stiffness*	1.6	76.26	7.15	$.004^{**}$	.017
6	Emerge	*Stiffness*	1.48	75.69	28.45	$< .001^{***}$	.181
7		$Visibility$	1.00	51.00	7.20	$.010^{*}$	.010
8		*Visibility* × *Stiffness*	2.00	102.00	8.73	$< .001^{***}$	.017
9		*Angularity* × *Stiffness*	2.00	102.00	8.73	$.039^{*}$	.006
10	Porous	*Angularity*	1.00	51	5.39	$.024^{*}$	.003
11		*Stiffness*	1.54	78.63	73.91	$< .001^{***}$	.431
12		*Angularity* × *Stiffness*	2.06	104.78	10.57	$< .001^{***}$	.008

($t(51) = -3.48, p = .007^{**}, d = -.446$), and Hard-Bouba and Hard-Kiki ($t(51) = -5.98, p < .001^{***}, d = -.765$)).

Emerge Shapes: Table 4 shows significant differences in the shape's *Stiffness* (Line 7). A post hoc analysis on *Stiffness* shows Soft was significantly less arousing than Hard ($t(51) = -3.89, p < .001^{***}, d = -.476$).

Porous Shapes: Table 4 shows significant differences in the shape's *Stiffness* (Line 8). A post hoc analysis revealed a significant difference between Soft and Hard ($t(51) = -2.89, p = .014^{*}, d = -.448$), where soft is less arousing than Hard.

4.3.3 Dominance. **Curved Shapes:** Table 5 shows significant difference for the *Angularity* (Line 1) and *Angularity* × *Stiffness* (Line 2). The post hoc analysis revealed significant differences between Bouba and Kiki shapes ($t(51) = -6.20, p < .001^{***}, d = -.475$), where Bouba curves were rated to have higher control. Further, on inspection of the *Angularity* × *Stiffness* interaction, we see the significant difference comes Soft-Kiki having significantly more control than Soft-Bouba ($t(51) = -4.88, p < .001^{***}, d = -.540$).

Sinuous Shapes Table 5 shows significant differences in the shape's *Angularity* (Line 3) where the post hoc analysis revealed Bouba shapes to have significantly more control ($t(51) = -6.57, p < .001^{***}, d = -.590$).

Emerge Shapes Table 5 shows significant differences in the shape's *Angularity* (Line 4), *Stiffness* (Line 5), and *Visual* × *Stiffness* (Line 6). In a post hoc analysis of *Angularity*, we observed significantly higher lack of control ($t(51) = -3.89, p < .001^{***}, d =$

Table 4: Significant effects from ANOVA test of *Stiffness*, *Angularity*, and *Visibility* on Arousal for emotion associations. p value are marked with $*$ for significant results where $p < .05$, $**$ significance of $p < .01$, and $***$ for significance of $p < .001$.

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Curve	*Angularity*	1.00	51.00	30.28	$< .001^{***}$	.070
2		*Stiffness*	1.21	64.05	4.93	$.024^{*}$	.034
3		*Visibility*	1.00	51.00	5.45	$.024^{*}$	.004
4		*Visibility* × *Stiffness*	2.00	102.24	3.28	$.041^{*}$	.006
5	Sinuous	*Angularity*	1.00	51.0	40.67	$<.001^{***}$	.109
6		*Angularity* × *Stiffness*	1.90	96.65	3.23	$.047^{*}$	.005
7	Emerge	*Stiffness*	1.36	69.21	7.58	$.004^{**}$	.051
8	Porous	*Stiffness*	1.25	63.95	4.408	$.031^{*}$	.043

Table 5: Significant effects from ANOVA test of *Stiffness*, *Angularity*, and *Visibility* on Dominance for emotion associations. p value are marked with $*$ for significant results where $p < .05$, $**$ significance of $p < .01$, and $***$ for significance of $p < .001$.

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Curve	*Angularity*	1.00	51.00	38.49	$< .001^{***}$	.075
2		*Angularity* × *Stiffness*	1.99	101.56	3.41	$.037^{*}$	.007
3	Sinuous	*Angularity*	1.00	51.0	43.11	$<.001^{***}$	.109
4	Emerge	*Angularity*	1.00	51.00	5.47	$.023^{*}$	.007
5		*Stiffness*	1.46	74.61	4.73	$.020^{*}$	.026
6		*Visibility* × *Stiffness*	1.80	91.89	3.78	$.030^{*}$	.011

−.476) for Bouba over Kiki. For *Stiffness* a post hoc analysis showed Hard was associated with a significantly higher control than Soft ($t(51) = 2.21, p < .029^{*}, d = .233$), and Hard had a higher control over Medium ($t(51) = 2.81, p < .018^{*}, d = .262$). In the *Visual* × *Stiffness* post hoc analysis, stiffness was influenced by visual in cases of Hard-Visuo-Tactile having higher control than Soft-Tactile-Only ($t(51) = -3.02, p < .041^{*}, d = .349$) and Hard-Visuo-Tactile having higher control than Medium-Visuo-Tactile being ($t(51) = 3.770, p < .003^{**}, d = .435$).

Porous: We found no significant differences for dominance in porous shapes.

4.3.4 Emotions Summary. Overall we observed Soft shapes associated with higher levels of pleasantness, while Hard shapes were associated with lower levels of pleasantness. Specifically for Curve and Sinuous shapes, Bouba *Angularity* contributed to higher pleasantness and Kiki to lower pleasantness. For arousal, the Soft Curve, Emerge, and Porous shapes were calmer and Hard *Stiffness* more exciting. Additionally, Bouba versions of Curve and Sinuous shapes contributed to calmness and Kiki to more excitement. For dominance, both Bouba-Sinuous and Bouba-Curve were rated with higher control compared to Kiki. For Emerge shapes, *Stiffness* played an additional role, where higher control was associated with harder shapes with Kiki *Angularity*. Finally, we only observed a few effects for *Visibility*. Visual-Tactile Soft-Emerge shapes were associated with more pleasantness and seeing Curves only influenced higher differences between Soft-Visuo-Tactile and Hard-Tactile-Only for arousal.

4.4 Force Applied during Interaction

Overall, Curve, Sinous, and Porous *Shapes*, yielded higher forces on Bouba *Angularity* and lower forces on the Kiki versions. In contrast, Emerge shapes yielded lower forces on Bouba *Angularity* and higher forces on the Kiki versions. A full overview of the average force applied in each colour and emotion task can be seen in Table 7 and 9, respectively. The remainder of this section analyses the forces applied during interaction more deeply. We used a repeated measures ANOVA followed by a post hoc pairwise comparison to investigate the effect of *Stiffness*, *Angularity*, and *Visibility* for the force users applied during each the Colour Tasks (see Table 6) and Emotion Tasks (see Table 8).

4.4.1 Colour Task. **Curve:** Table 6 shows a significant difference in the shape's *Angularity* (Line 1), where post hoc analysis revealed there were higher forces on the Bouba versions of Curve ($t(51) = 6.183, p < .001^{**}, d = 0.390$).

Sinuous: Table 6 shows significant differences in the shape's *Angularity* (Line 2). A post hoc test showed there were higher forces applied to Bouba shapes ($t(51) = 6.08, p < .001^{***}, d = .378$).

Emerge: Table 6 shows significant differences in the shape's *Angularity* (Line 3), and *Stiffness* (Line 4). A post hoc analysis of *Angularity* showed higher forces on the Kiki versions of Emerge ($t(51) = -3.25, p = .002^{**}, d = -.227$). A post hoc analysis of *Stiffness* showed a significant difference in each of the *Stiffness* combinations: Soft-Medium ($t(51) = -3.53, p < .001^{***}, d = -0.233$), Soft-Hard ($t(51) = -10.69, p < .001^{***}, d = -0.706$) and Medium-Hard ($t(51) = -7.17, p < .001^{***}, d = -0.474$). In all cases, participants applied more force to the harder shapes.

Table 6: Significant effects from ANOVA test of *Stiffness*, *Angularity*, and *Visibility* on force participants applied during the colour associations tasks. p value are marked with $*$ for significant results where $p < .05$, $**$ significance of $p < .01$, and $***$ for significance of $p < .001$.

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Curve	*Angularity*	1.00	51.00	38.23	<.001***	.114
2	Sinuous	*Angularity*	1.00	51.00	36.90	<.001***	.081
3	Emerge	*Angularity*	1.00	51.00	10.56	.002**	.023
4		*Stiffness*	1.60	81.66	59.38	<.001***	.151
5	Porous	*Angularity*	1.00	51.00	14.53	<.001***	.014
6		*Stiffness*	1.65	84.31	5.93	.006**	.026
7		*Visibility*	1.00	51.00	4.069	.049*	.017

Table 7: Overview of force values (grams) applied by the participants for associations made during the colour tasks averaged across task *Visibility* conditions.

	Curve		Sinuous		Emerge		Porous	
	Bouba	Kiki	Bouba	Kiki	Bouba	Kiki	Bouba	Kiki
Soft	101.4	78.2	92.7	76.0	58.0	65.8	97.7	89.8
Medium	105.3	85.5	101.5	80.6	66.1	79.3	114.4	101.0
Hard	103.6	81.6	95.3	74.1	88.5	98.7	107.5	102.5

Porous: Table 6 shows significant differences in the shape's *Angularity* (Line 5), *Stiffness* (Line 6), and *Visibility* (Line 7). An *Angularity* post hoc analysis showed higher forces applied on the Bouba versions of Porous shapes ($t(51) = 3.813, p < .001^{**}, d = .157$). The *Stiffness* post hoc analysis revealed a significant difference between Soft-Medium ($t(51) = -3.246, p = .005^{*}, d = -.250$) and Soft-Hard ($t(51) = -2.62, p = .020^{*}, d = -0.202$), where the Softer shapes yielded lower force values. A post hoc analysis of *Visibility* showed higher forces were applied in the Tactile-Only condition: $t(51) = -2.02, p = .049^{*}, d = -.174$.

4.4.2 Emotions Task. **Curve:** Table 8 shows significant differences in the shape's *Angularity* (Line 1), where Bouba yields significantly higher forces than Kiki ($t(51) = 6.757, p < .001^{**}, d = .457$).

Sinuous: Table 8 shows significant differences in the shape's *Angularity* (Line 2), and *Stiffness* (Line 3). A post hoc analysis for *Angularity* shows Bouba yields significantly higher forces than Kiki ($t(51) = 6.21, p < .001^{***}, d = 0.353$). A post hoc analysis for *Stiffness* showed higher forces for Medium stiffnesses over the Soft ($t(51) = -3.47, p = .002^{**}, d = -.181$) and Hard stiffnesses ($t(51) = 3.03, p = .006^{**}, d = .158$).

Emerge: Table 8 shows significant differences in the shape's *Angularity* (Line 4) and *Stiffness* (Line 5). Post hoc tests for *Angularity* showed Kiki yielded significantly higher forces than Bouba ($t(51) = -4.64, p < .001^{***}, d = -.226$). For the *Stiffness* post hoc analysis, Hard elicited higher forces than Medium ($t(51) = -6.62, p < .001^{***}, d = -.409$), and Soft ($t(51) = -11.19, p < .001^{***}, d = -.691$), while Medium was higher than Soft ($t(51) = -4.57, p < .001^{***}, d = -.282$).

Porous: Table 8 shows significant differences in the shape's *Stiffness* (Line 6). In the post hoc comparison, Soft was significantly lower than Medium ($t(51) = -3.82, p < .001^{***}, d = -.273$), and Soft was significantly lower than Hard ($t(51) = -3.43, p = .002^{**}, d = -.245$).

4.4.3 Force Applied Summary. Overall, the *Shapes* Curve, Sinous and Porous, yielded higher forces on Bouba *Angularity* and lower forces on the Kiki versions. In contrast, Emerge shapes yielded lower forces on Bouba *Angularity* and higher forces on the Kiki versions. Additionally, in colour tasks, Emerge, Porous and Sinuous Hard *Stiffnesses* yielded higher forces, with lower forces on the Soft *Stiffness* versions. For *Visibility* effects, we only saw different force interactions for Porous in colour tasks where higher forces were applied in the Tactile-Only condition.

4.5 Qualitative Results

In this section, we present participants' reasoning behind assigning colours and emotions to different stimuli, and whether their interactions with the objects changed across conditions. Throughout this section, participant reflections will be in relation to the stimuli as shown in Figure 7 and Figure 8.

4.5.1 Colour Associations. We observed a diversity of approaches when associating colours with shapes and stiffnesses. These encompassed both rational reflections grounded in the inherent properties of the stimuli and personal strategies unique to each individual. Participants articulated their associations through several similes and the use of positive and/or negative mappings. Finally, a minority of participants relied on the colours shown in the interface to inform their colour choices.

Rationale for Object-Colour Associations: When participants were asked about their rationale for associating colour with objects, more than half made specific references to choosing colours

Table 8: Significant effects from ANOVA test of *Stiffness*, *Angularity*, and *Visibility* on force participants applied during the Emotion association tasks. p value are marked with $*$ for significant results where $p < .05$, $**$ significance of $p < .01$, and $***$ for significance of $p < .001$.

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Curve	*Angularity*	1.00	51.00	45.659	<.001***	.122
2	Sinuous	*Angularity*	1.00	51.00	38.53	<.001***	.084
3		*Stiffness*	1.60	81.70	7.146	.003**	.017
4	Emerge	*Angularity*	1.00	51.00	21.55	<.001***	.026
5		*Stiffness*	1.55	79.03	63.26	<.001***	.164
6	Porous	*Stiffness*	1.93	98.52	8.85	<.001***	.046

Table 9: Overview of force values (Grams) applied by the participants for associations made during the emotions averaged across task *Visibility* conditions.

	Curve		Sinuous		Emerge		Porous	
	Bouba	**Kiki**	**Bouba**	**Kiki**	**Bouba**	**Kiki**	**Bouba**	**Kiki**
Soft	58.8	68.9	106.0	83.9	111.9	84.5	106.3	100.4
Medium	71.5	85.9	116.7	96.0	117.4	83.7	123.0	120.3
Hard	94.6	105.8	108.5	84.36	110.6	80.7	120.0	119.6

based on both shape and stiffness (n = 31). These participants conflated the two concepts when describing their strategies (e.g. juxtaposing 'soft' with 'spiky' or 'sharp'). For example, P46: *"A pointy hard shape was a very cold colour. A soft rounded shape was a more warm colour"*. In contrast, some participants solely referenced shape (n = 11) or stiffness (n = 9). For instance, a shape mapping by P48: *"The [Kiki-Sinuous] ones, they kind of look like stars, so I picked yellow a couple of times"* (see Figure 7).

Strategies for Colour Associations: Participants highlighted different overarching strategies for colour associations. First, 20 participants did not indicate a clear rationale for their colour choice, but described it as a decision based on their feelings or intuition (e.g. P37: *"On the first touch of something, a colour just sprung to mind from the palette available and for the softer squishier shapes I tended to go for brighter colours, dull or unresponsive shapes I went for more matte, less vibrant colours"*). Second, participants used their visual imagination (n = 19), such as P26: *"When I couldn't see what they were, I kind of like imagined what they would be [...] I think [Porous] reminded me of cheese, which is why I put them as yellow"* (see Figure 7). Third, participants commented specifically on the tactile properties of the objects to determine colour (n = 18), such as P8: *"The softer the object for me the more pleasant the sensation, so I went to brighter colours between green and yellow"*. Fourth, participants would refer to personal preferences (n = 9) such as their favourite colour for their mapping: *"Anything that I didn't like, especially shapes with gaps or shapes that aren't uniform in a sense, I linked them to colours that I don't like, like orange and darker brown shades"* (P21). Lastly, participants would describe their expectations regarding the visual and/or tactile properties of the object (n = 8), and choose a colour based on whether these expectations were met: *"From looking at it I assumed how stiff it was, and then based on how stiff it actually was, I changed my mood about it. So if it looked like it was gonna be soft and it wasn't soft, I put a darker colour"* (P1).

Use of Similes to Describe Colour Choices: More than half of the participants (n = 29) made use of similes when describing colour choices. The majority would compare the stimuli to everyday objects, such as buttons (Bouba-Curve), buildings (Emerge), brushes (Bouba-Emerge), game controllers (Bouba-Curve), pyramids (Kiki-Curve), Lego (Emerge), and keyboard keys (Porous); see Figure 7. Another common simile was nature and seasons, for instance, participants associated Kiki-Sinuous shapes with sea creatures, and Emerge shapes with seaweed or coral. Others would associate stiffness with concepts such as moss, leaves flowers, or grass: *"For [Bouba-Sinuous], if it was really sturdy, I went for a grey, like a stone. But if it was really soft, I chose green because it gave me ideas of leaves or moss or something like that"* (P28). Participants would also reference food items to decide on colours, for instance, Bouba-Sinuous shapes were associated with blancmange or soft sweets (e.g. gummy bears). Comparisons to pop culture were made, such as Pokemon and Mario for Kiki-Sinuous shapes (Figure 7). At times the similes for a singular shape would be different across stiffnesses, for instance, P30: *"[Porous] kind of reminded me more of bricks, whereas some of the softer ones more of sponges"*. Others made positive and/or negative associations, either based on shape, such as P50: *"The pointy shapes to me, they were always red because it signified danger"*; or stiffness, such as P12: *"The ones that are more spiky and hard to press are more like red so like danger, and then things that are more squidgy were safer"*.

4.5.2 Emotion Associations. We observed different approaches by participants when connecting emotions to shapes and stiffness. These approaches involved rational reflections rooted in the inherent properties of the stimuli, particularly the tactile interactions with them. Further, participants assigned emotions based on their immediate emotional response to the stimuli, and adjusted their emotional associations based on the visibility of the stimuli.

Rationale for Object-Emotion Associations: When participants were asked about their rationale for associating colour with pleasure, arousal, and dominance, the majority (n = 46) made specific references to selecting emotions based on shape as well as stiffness: *"The softer it was the more control I felt, the softer it was the more pleasant it was, the spikier it was the more excitement or lack of calmness"* (P31).

Emotions based on Tactile Feedback: Almost half of the participants (n = 25) based their emotions on the tactile feedback of the objects, for example, P6 describes the following for control: *"The things that were like the grid type [Emerge], I felt particularly at the harder end of the spectrum [hard Emerge], I felt very in control with those. Whereas with the ones that are a bit like toothbrushes [soft Emerge], because they're kind of flopping around your fingers, they didn't feel so much like I was in control of them"* (Figure 2). In contrast, only 8 participants described visual feedback to be of influence.

Evoking Emotions: Some participants (n = 17) expressed feeling a particular emotion because of the stimuli, which could be either a positive experience, for example, P5 regarding the shape of the object: *"I think when the shape looks extravagant, like a star [Kiki-Sinuous] or anything like that. When it's more complex, then obviously it's more exciting for me"* (Figure 2). Additionally, it could also elicit negative emotions, especially in relation to the stiffness of the stimuli: *"Touching the soft ones was really gross, the stiffer and spiky ones, I liked those more"* (P29).

Revision of Emotions based on Visibility: Participants also expressed the change in feelings based on the visibility of the stimuli (n = 12), attributing more importance to different emotions: *"I think when I couldn't see them, I was focusing more on control of being able to move them around. I instantly didn't like any of the spiky ones when I couldn't see them, they just creeped me out a little bit"* (P7). Further, differences in stiffness of the stimuli became more prominent, as explained by P35: *"Especially when I can't see it, the stiffness level makes more difference. I would say just in general, that it's the softest touch and stiffness that makes big differences, rather than the shape, the visual".*

4.5.3 Force Applied. More than half of the participants (n = 33) indicated that the visibility of the stimuli played a major role in the level of force they applied, two participants attributed it to stiffness, only one to both visibility and stiffness, and 16 did not indicate any influence at all. More specifically, 20 participants expressed pressing harder and/or for a more prolonged time when they could not see the stimuli, primarily to explore the shape. For instance, P9: *"I think when you can't see it, it's weird. You have to kind of wiggle a bit harder. But when you can see it, you can gauge more what the texture is going to be like".* In contrast, 9 participants would press harder when seeing the stimuli because of familiarity with the shapes or to explore the visual deformation: *"When I could see them I pressed a bit harder maybe just because I could see it deforming under my touch. So I could also see the limit of the material"* (P4). Two participants pressed more softly when they could not see the stimuli, as they wanted to be more careful or were apprehensive to touch them: *"I did not like pressing the spiky ones when I couldn't see the objects, I have a bit of a fear of needles. So I think that was kind of playing into that"* (P7). Finally, of the two participants who described the stiffness of the stimuli as an influence on their applied force, one expressed pressing harder when firm, whereas the other pressed harder when soft because of the physical deformation: *"I probably ended up pressing firmer into the soft ones just because they were squidgy, it felt nice to press into* (P1).

4.5.4 Summary. To summarize, our qualitative results provide further insights into how participants associate colour, emotions, and tactile experiences with shapes and stiffness. When associating colour with shape and stiffness, over half of the participants made specific references to the stimuli's physical characteristics and used vivid similes to elucidate their choices. Additionally, they described a myriad of strategies, including intuition, visual imagination, tactile sensations, personal preferences, and expectations to support their colour associations. The majority of participants linked emotions to the stimuli's shape and stiffness, drawing on tactile feedback and emotional responses evoked by the stimuli, and occasionally revised their associated emotions based on the stimulus' visibility. Furthermore, more than half of the participants acknowledged the substantial impact of stimulus visibility on their interactions, as they reported altering their engagement patterns, such as pressing harder or exploring the object more thoroughly when the stimulus was not visible. These findings collectively illustrate the intricate interplay between sensory perceptions, cognitive strategies, and stimulus characteristics in shaping individuals' colour and emotion associations, as well as their tactile interactions.

5 DISCUSSION

This paper explored cross-modal correspondences of deformable shapes with colours and emotions. More specifically, our RQs focused on investigating the possible relation between angularity and stiffness for colour and emotion associations (RQ1), and the possible influence of visibility on these associations (RQ2). The results of our study revealed (i) the cross-modal correspondences between angularity and stiffness for colour and emotions, (ii) the differences in applied and perceived force, and (iii) the lack of effect visibility has on tactile associations. Below, we discuss the trends and extrapolate their implications for the future design of physical user interfaces in more detail.

5.1 Colour Associations

We noticed distinctive trends in the relationships between brightness and hue for collections of shapes and stiffnesses. The angularity of protruding shapes (Curve, Sinuous, and Emerge) compared to permeable ones interact with brightness, resulting in clear mapping of associations between brightness and stiffness for protruding shapes, whereas permeable shapes show a non-linear mapping. We observed a pronounced influence of stiffness on hue, with stiffness playing a more dominant role than angularity. Specifically, harder shapes are predominantly associated with red, while softer shapes are yellows, blues, and greens (See Figure 7).

5.1.1 Brightness of Protruding Shapes. For Curve, Sinuous, and Emerge, softer shapes were more closely associated with higher brightness and harder shapes with lower brightness. In other words, for any of the protruding shapes, regardless of their Kiki or Bouba equivalent, the overall stiffness seemed to be a stronger indicator for colour associations than angularity. Our findings on stiffness levels align with [65], where soft, flat surfaces were associated with higher brightness. However, we contrast with previous work where Bouba-Sinuous shapes were associated with a higher brightness level, and Kiki-Sinuous shapes with dark colours [40]. This suggests that adding deformation to protruding shapes (Curve/Sinuous/Emerge) changes their cross-modal associations, even compared to studies exploring CCs with rigid shapes [40]. This could be explained by the unique interplay of shape and stiffness for determining colour. For our study conditions, whenever participants were asked to associate a colour, more than half of them referenced similes, and described the visible (angularity) and/or tangible (stiffness) properties that motivated their choices. We observed that participants created concept pairings between hard and soft objects of the same shape type (e.g., sponge vs. brick for Porous, moss vs. stone for Sinuous), illustrating how different combinations of stiffness and angularity result in different associations.

5.1.2 *Brightness of Permeable Shapes.*

In contrast to protruding shapes, the Porous soft shapes were associated with lower brightness, medium stiffness with higher brightness, and hard stiffness in between. Previous research [65] investigated associations between stiffnesses and visual shapes. It found that high porosity was linked to soft surfaces, as well as a connection between high brightness and soft surfaces. However, our study suggests that examining these properties in isolation may not reflect their combined effects, in this case, showing that porosity is associated with low brightness. Again, this could be explained by the unique interplay of shape and stiffness when determining colour, but with the difference that the results for permeable shapes suggest that the relation between brightness and stiffness is not a straightforward, linear one, but rather follows a more complex pattern than protruding shapes.

5.1.3 *Hue for Soft and Hard Shapes.*

Our qualitative results highlighted the unique nature of hue associations, which can vary from person to person due to factors such as personal preferences, similes, and positive or negative associations. Regardless of that, we observed significant effects of stiffness for hue, in which soft shapes were consistently associated with cold (blue/green) and warm colours (yellow), while hard shapes were predominantly linked to warm colours (shades of red). This connection between red and hardness aligns with our qualitative findings, where participants associated Kiki-Curve and Kiki-Sinuous shapes with 'danger', hence signifying the colour red. This resonates with prior research on CC [40], which showed that Kiki shapes were associated with red and Bouba shapes with blue. However, our study introduces a novel perspective by incorporating stiffness properties. We observed that in the context of stiffness, the soft Sinuous-Bouba shape is associated with blue, while the hard Sinuous-Bouba is linked to red. This result suggests that when considering the interaction of stiffness and angularity, stiffness takes precedence over angularity in influencing colour perception when the shapes become harder.

5.2 Emotion Associations

Overall, for aesthetic experience (e.g. pleasure, arousal), stiffness played more of a role than for pragmatic experience (e.g. dominance). This showed a more intricate interplay between angularity and stiffness, dependent on the shape. It became evident that the various emotional responses, both across and within different emotions, can be traced back to individual differences among the participants. This diversity in emotional associations underscores the presence of unique mappings between emotions, stiffness, and shape characteristics. For instance, our findings reveal distinct mappings where *stiffness*, coupled with specific shapes (Emerge), influences control perception, while *angularity* in conjunction with other shapes (Curve/Sinuous) is also linked to control perception. Further, we observed that these mappings can be inherently variable, with some individuals associating softness with pleasantness and others attributing softness to unpleasantness. In essence, our study highlights the nuanced nature of emotional and perceptual responses, suggesting that users' assessment of UIs encompasses both unique individual mappings and potentially opposing associations, as well as overarching properties that could strategically inform the elicitation of emotions when interacting with future UIs.

5.2.1 *Dominance in Relation to Angularity and Stiffness.*

In general, it seems that participants assigned dominance to the perceived level of stability of the stimuli, which was intricately tied to the shared result of specific characteristics of angularity and stiffness within each shape. This resonates with the qualitative observation of emotions based on tactile feedback of the stimuli, as this can give more or less a sense of agency during interaction.For both Curve and Sinuous shapes, we observed a correlation between angularity and the perception of control. Hence, the Bouba shapes consistently instilled a heightened sense of control, while the Kiki shapes evoked feelings of less control. This observation can be attributed to the inherent disparities in the ease of manipulation between spikier and rounded shapes. For instance, attempting to press the pointed tip of a Kiki-Curve shape, in contrast to a Bouba-Curve, often led to greater instability, thus contributing to a reduced sense of control (See Figure 8).

In the case of Emerge shapes, angularity played a less prominent role in dominance. Instead, we identified a correlation between stiffness and the perception of control. Here, the harder variants consistently elicited an elevated sense of control, while the softer versions gave a perception of reduced control. In contrast to the Curve and Sinuous shapes, where angularity played an important role in shaping stability and control perceptions, for the Emerge shapes this was hinged on the stiffness. For example, applying force to firmer pillars, whether cylindrical or square in shape, conveyed a heightened sense of control. In contrast, attempting to manipulate soft pillars, showed greater compliance and less predictability, thus diminishing the perceived sense of control.

5.2.2 *Pleasure and Arousal in Relation to Stiffness.*

Conversely, our findings on the dimensions of arousal and pleasure show a more uniform trend. Across the majority of stimuli, stiffness emerges as a key factor, where softer shapes are associated with higher levels of calmness and pleasantness, and harder shapes were more frequently linked to feelings of excitement and unpleasantness. This resonates with the qualitative insights on the elicitation of emotions when touching particular stimuli, either creating positive or negative reactions that contributed to participants' perception of aesthetic or hedonic properties. Specifically, the Bouba versions of Curve, Sinuous, and Emerge shapes were associated with a higher degree of pleasantness, while the Kiki shapes elicited a greater sense of unpleasantness, which aligns with prior research [40]. However, our results show a large effect size for the impact of stiffness, highlighting that deformation elicits stronger associations to certain levels of pleasure (i.e., soft is more pleasant and hard is less pleasant).

5.3 Visibility & Force Applied

RQ2 investigated whether emotions and colour associations differ based on whether deformable shapes are visible during tactile interaction. Our analysis showed few significant differences between the visual conditions for each shape type, highlighting that seeing the stimuli had little impact on the resulting associations. As these CCs demonstrate, stiffness and shape design factors can be employed across visuo-tactile and tactile-only modalities for successful multi-sensory experiences. This implies that when touching interface elements, people's assigned qualities, such as emotions and colour, do not change based on whether they can see these interface elements or how their touch deforms them. In real-world applications, this would mean that interface elements will sustain their qualities (e.g. a calming button in a medical context), so a designer can implement these interface elements, knowing that a user will interact with it consistently across different visibility conditions and can switch between them. This provides further motivation for deploying deformable and shape-changing UIs in both eyes-free and eyes-on contexts [11, 57, 58].

Interestingly, the quantitative results only show a significant difference for Porous shapes across visibility conditions, whereas more than half of the participants expressed they altered their interactions based on whether they could see the stimuli. This implies that although the absolute forces applied are similar, people's perception of the amplitude and duration of applied force differs based on visibility.

6 DESIGN IMPLICATIONS

The successful design of multi-modal cues and signifiers requires an understanding of their perception by users—our study provides this insight for deformable user interfaces.

This paper contributes towards a growing set of CC study results [22, 40, 46, 65] that are building a picture of how people perceive and make associations with visual-haptic interface elements within HCI. This supports researchers and designers in the development of novel, but intuitive physical user interfaces.

Our findings are a pathway towards creating diverse multi-sensory interaction opportunities that combine deformation, shapes, emotions, and colours. We distill our findings into key design recommendations for creating diverse multi-sensory interactions, particularly for leveraging the haptic properties of deformation and shape in future physical UI design.

Our design implications support practitioners in navigating the broad range of shape and deformation possibilities [4, 37, 55, 59], and by doing so we begin to address one of the grand challenges within the field [2].

The guidelines are particularly relevant for physical UIs of personal devices (e.g., phones, smartwatches, tablets) and finger-based interactions with UI elements. Our recommendations provide a new design space to inform the next generation of physical signifiers (see Figure 9). We present our implications in three parts: implications for emotion associations, implications for colour associations, and implications for eyes-free interaction.

6.1 Implications for Emotion Association

Our recommendations related to emotions (Design Recommendations 1-3) are designed for creating interface elements that map to user associations with emotions of pleasantness, arousal, and dominance. Incorporating these recommendations into UI design can create interfaces that align with users' emotional expectations—creating a 'multimodal harmony'—and/or interfaces that target specific emotions to direct user experience and interaction.

Design Recommendation 1: Soft rounded shapes are best for eliciting pleasant associations. Harder, spiky shapes will elicit more unpleasant associations.

The combination of shape and stiffness can directly impact user feelings of pleasantness in future physical interfaces. For example, it could allow game designers to manipulate the shape and feel of deformable controllers based on interactions with the video game environment (e.g., an unpleasant spiky object in a horror game). Further, it could be an additional design factor when nudging particular user behaviours. For example, a phone display becoming stiffer as a motivator to reduce social media time or a softening display to promote reading time.

Design Recommendation 2: Spiky shapes are best for excitement, while rounder shapes are for calmer contexts.

Shape is the dictating property when considering arousal levels for user associations. For example, round UI elements could be used in a meditation app to convey calming associations or spiky shapes for a text message notification from a close friend inviting another friend to a party. This resonates with examples from prior research on shape-changing interfaces that aimed to calm users through an inflatable round (balloon-like) interface [20] or to visually alert people of phone notifications through a variety of shape resolutions [53].

Design Recommendation 3: Rounder protruding shapes are associated with high control, whereas spiky shapes can be used to associate less control. Making rounder shapes softer can increase this factor of control.

The shape of an object plays a significant role in the associated sense of control. Softening controls based on round shapes can elevate this sense of control. Compliant and shape-changing displays (e.g. [24, 48, 69, 75]) can modify their controls' shape and stiffness dynamically exert greater control. For example, in a graphic design tool, softer and more rounded controls could support the fine manipulation of graphics (and the opposite for courser, larger objects).

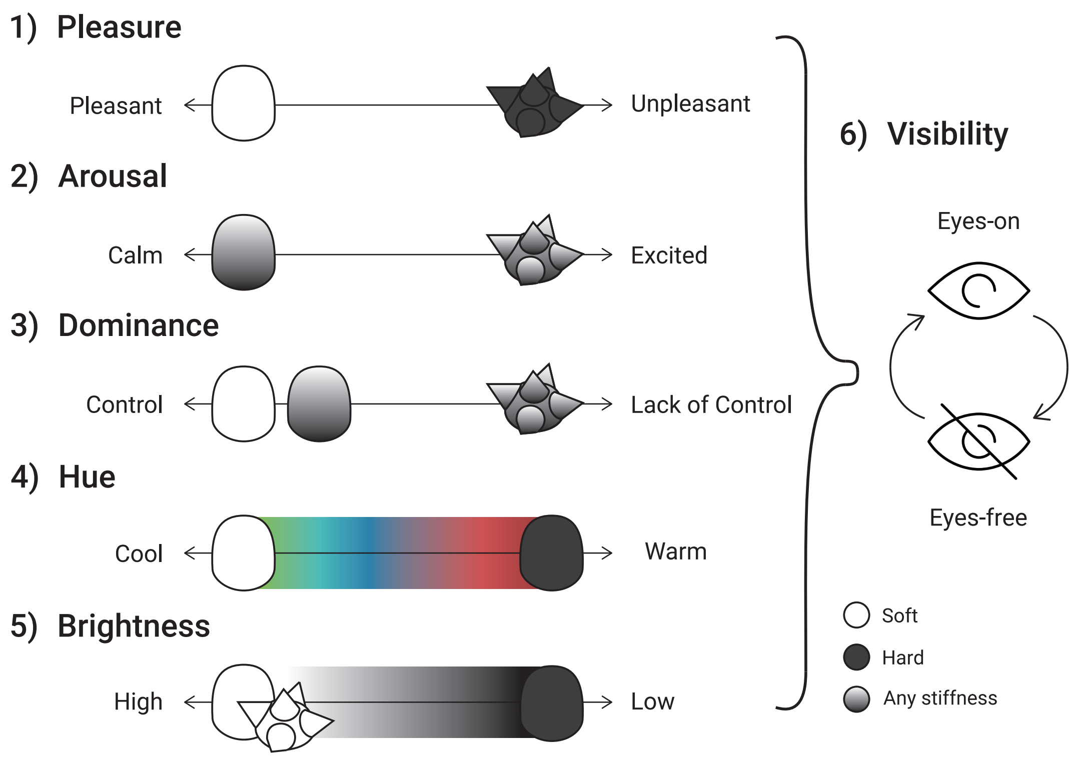

Figure 9: Visual overview of the design implications of using shape (exemplified by a Kiki and Bouba shape) and stiffness (soft, hard, or any stiffness) for association with emotion and colour. For example, (1) indicates soft rounded shapes (white Bouba) are best for eliciting pleasant associations (left), whereas harder spiky shapes (black Kiki) with more unpleasant associations (right). Design recommendation (6) demonstrates that associations and recommendations (1)–(5) can be used identically in eyes-free and eyes-on contexts.

This would enhance the sense of control, potentially leading to a more efficient user experience.

This recommendation could also be applied to interactions that extend beyond a display, where there are limited visual channels for emotional signifiers. For example, when a drone is gradually flying out of signal range of its controller, the joystick area can become spiky to create an intuitive haptic mapping to notify the user of a lack of control, which they can experience irrespective their eyes' position (on or off the controller).

6.2 Implications for Colour Association

Hue and brightness can be used together, or individually, to complement shape-changing and/or deformable properties on a physical UI. Design Recommendations 4 & 5 explain how to use colours in physical UI design to ensure intuitive visual and tactile mapping. When users see colours in conjunction with haptic sensations from the interface elements, colour can reinforce stiffness and shape signifiers, either confirming something previously felt or providing feedforward on what to expect to feel.

Design Recommendation 4: Soft shapes should be used in conjunction with cooler colours (e.g. green and blue). While harder shapes should be used with warmer colours (e.g., red).

Design Recommendation 5: Soft-rounded or spiky shapes should be used in conjunction with high brightness. While harder-rounded shapes should be used with darker colours.

When a UI designer has freedom of colour choice, they can use a specific colour to signify stiffness and shape and create sensory harmony (for example, a red button to indicate hardness), extending the work by Steer et al. [65] on colour and stiffness associations. Conversely, they can subvert expectations by choosing opposing combinations (e.g. a soft red button). However, not all interfaces have the freedom to pick any colour, as there may be specific requirements for branding, aesthetics, or application (e.g. simulating mixing of paint colours on a deformable display [66]). In such cases, designers can use brightness to associate different shapes and stiffnesses. Prior work on configurable platforms implementing shape-change and force [16, 48] often utilise projection or LED technologies to convey colour (e.g. on a pin-based grid or deformable LED spheres), and can therefore make use of these recommendations to match colours for a variety of applications.

6.3 Implications for Eyes-Free Interactions

In scenarios where users are switching between eyes-on and eyes-free, designers can maintain the continuity of the signifier. Regardless of whether someone is looking at their device (e.g. phone, tablet), the stiffness of the device can be associated with specific emotions and colours.

Design Recommendation 6: Properties of shape and stiffness can be used identically in both eyes-free and eyes-on contexts – users will make the same colour and emotional associations.

For example, recognising incoming phone calls from colleagues outside regular work hours becomes instinctive as the phone responds with a more pronounced spikiness upon being grasped, regardless of whether it is visible or in a pocket. This is particularly relevant to the field as several works have highlighted the benefits of using tangibility for eyes-free interactions [11, 57, 58].

6.4 Summary

Our design recommendations contribute to actionable knowledge of how people perceive and associate visual-haptic interface elements. As we add our findings to the growing repository of cross-modal study results, we pave the way for researchers and designers to develop multi-sensory interactions for shape-change and deformable interfaces confidently. By distilling our discoveries into actionable design recommendations, we envision a future where diverse tactile experiences, encompassing deformation, shapes, emotions, and colours, foster intuitive physical interfaces. Our work addresses grand challenges within the field and provides findings for shaping the next generation of physical signifiers. We envision these principles being utilised across conventional UI components like buttons and innovative applications of deformable surfaces, including video games and entertainment experiences.

7 LIMITATIONS & FUTURE WORK

This study continues the investigation of CCs in physical user interfaces. In this work, we did not intentionally *elicit* emotions in the participants through the stimuli. We focused on the *associations* of deformable shapes with emotions (e.g. 'this shape is pleasant'). However, during interviews, some participants described experiencing emotions as well (e.g. 'this shape makes me feel pleasant'). In future research, it may be valuable to incorporate bio-measures to understand better whether this study's results align with direct emotional elicitation. Further, while our study collected qualitative data on participant association strategies, future studies could focus on people's expectations based on how the stimuli looked. This would provide insight into how associations with colour and emotion relate to current findings [65] when people could only see the stimuli. This would build a better understanding of user anticipations and expectations before interaction occurs, similar to work on shape-changing affordances from Tiab and Hornbæk [72]. The next logical step in our research trajectory involves the exploration of dynamic shapes and dynamic stiffnesses. Dynamicity may shed light on the evolving nature of cross-modal correspondences, providing insights into how users perceive and respond to changing shapes and stiffness levels over time. Additionally, delving into dynamic shapes and stiffness could have practical implications for developing interactive technologies, such as deformable interfaces in gaming, virtual reality, and other interactive applications. The shapes, and resulting design recommendations, have not yet been employed within "real-world" scenarios. It is therefore important for future work to investigate how this controlled understanding of shapes applies in real-world contexts to assess the ecological validity of the results, practical implications, and potential benefits and drawbacks.

8 CONCLUSION

This paper advanced our understanding of cross-modal correspondences for deformable shape interactions. More specifically, it explored CCs between physical shape, stiffness, colours, and emotions. Our research outcomes uncover a series of key takeaways: (1) shape and stiffness properties consistently influence users' colour and emotional associations across both visuo-tactile and tactile-only modalities; (2) soft shapes are associated with cooler colours and harder shapes with warmer colours; (3) high brightness is associated with combinations of soft-rounded, or spiky shapes while darker colours are associated with harder-rounded shapes; (4) soft-rounded shapes are associated with pleasant feelings, while harder, spiky shapes tend to evoke unpleasantness; (5) for creating excitement, spiky shapes are effective, while rounder shapes are suitable for calmer design; and (6) rounder protruding shapes convey a sense of high control and making them softer can enhance this feeling. These conclusions and their accompanying design guidelines aim to support designers and researchers in effectively engaging specific human senses in the next generation of physical user interfaces.

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