Feel the Force, See the Force: Exploring Visual-tactile Associations of Deformable Surfaces with Colours and Shapes

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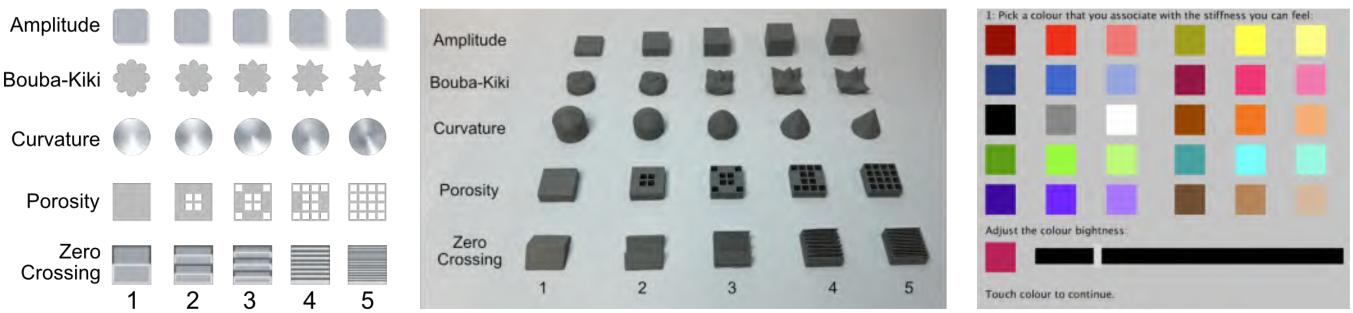

Figure 1: The 2D shapes (left), 3D shapes (centre), and colours (right) used in the crossmodal correspondences study.

ABSTRACT

Deformable interfaces provide unique interaction potential for force input, for example, when users physically push into a soft display surface. However, there remains limited understanding of which visual-tactile design elements signify the presence and stiffness of such deformable force-input components. In this paper, we explore how people correspond surface stiffness to colours, graphical shapes, and physical shapes. We conducted a cross-modal correspondence (CC) study, where 30 participants associated different surface stiffnesses with colours and shapes. Our findings evidence the CCs between stiffness levels for a subset of the 2D/3D shapes and colours used in the study. We distil our findings in three design recommendations: (1) lighter colours should be used to indicate soft surfaces, and darker colours should indicate stiff surfaces; (2) rounded shapes should be used to indicate soft surfaces, while less-curved shapes should be used to indicate stiffer surfaces, and; (3) longer 2D drop-shadows should be used to indicate softer surfaces, while shorter drop-shadows should be used to indicate stiffer surfaces.

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CCS CONCEPTS

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

KEYWORDS

Multisensory Interaction, Force, Crossmodal Correspondences, Colour, Touch

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1 INTRODUCTION

Recent hardware and software advances have enabled deformable screens to offer novel interaction possibilities to the user, such as deformable input, force feedback, and physical shape-change [2, 13, 48]. The addition of such elements enhances the interactive experience by offering both feedback via stiffness and an additional method of control [14, 38]. For example, when a user physically pushes into a soft display surface, they can provide a force input and concurrently feel stiffness as a force output.

However, such interactions are 'hidden', currently requiring explicit instruction from the interface (unlike, e.g. a UI button that visually affords pressing). In addition, deformable screen technology is still in its infancy, which means that there exist no conventions signifying how users should interact with them. This presents the unique opportunity to develop intuitive force signifiers that can unlock these 'hidden' deformable interactions. Alongside these growing interaction possibilities, there exists the use of shape-changing surfaces, as well as, new forms of affordances and signifiers that support novel methods of input and output [10, 13, 60]. Yet, there is still limited exploration into the human perception of shape-changing interfaces and use-case scenarios [2]. In particular, there exists no framework to determine the design of intuitive signifiers for variable stiffness on deformable interfaces.

One promising field that could offer such a framework is that of Crossmodal Correspondences (CCs). CCs have been defined as the non-arbitrary associations humans make between features of stimuli, both within and across senses [28]. Perhaps the most widely known example is the Bouba/Kiki phenomenon, where people are more likely to name shapes with sharp jagged edges "Kiki" and more rounded and bulbous shapes "Bouba" [26]. Recent studies have deployed CCs to study the relationship between tangible objects and their association with properties such as emotions and colours [10, 28]. In this paper, we build on this work by studying the crossmodal correspondence between deformable stimuli of different stiffness levels, colours, and sets of graphical and physical shapes. From this study, we present findings and implications for the use of shape and colour in the design of interfaces for deformable surfaces.

We conducted a study that asked 30 participants to assign five different stiffness surfaces to colours, 2D shapes and 3D shapes. The visual stimuli used in the study were based on the "Bouba/Kiki" paradigm and colours commonly used in CC studies due to their well-tested significance [28, 47]. However, novel to our approach, we also test the shape resolutions framework outlined in Morphees [50]. This gives our findings wider implications for the field of deformable and shape-changing interfaces and extends approaches to exploring CCs in HCI. More specifically, this paper makes the following contributions:

(1) The use of shapes derived from the shape-changing interfaces literature [50] for the first visual force-deformable CC study in the context of HCI.
(2) The evidence for transitional features of CCs between stiffness levels for a subset of the 2D/3D shapes used in the study. Along with a collection of user-defined colour associations.
(3) Results that show an initial mapping of shape resolutions and colours to associated stiffness levels.
(4) Implications and design recommendations for the development of variable stiffness user interface elements.

2 RELATED WORK

We summarise closely related literature in input and deformable displays, perceptions of shape-changing interfaces, and the use of crossmodal correspondences in HCI.

2.1 Force Input and Deformable Displays

The first work capable of visual display with force vector detection was seen in 1984 from Minsky et al. [36]. Since then, the field of HCI has extensively explored force gestures on touch-screen displays [19, 27, 59]. Heo et al. explored the usability of force-sensitive tapping, pivoting, pressing, sliding and dragging and found higher degrees of force levels can be problematic for users. Work in this space has also studied the use of shear force, including multi-touch points [17, 20]. To understand the discoverability of the force gestures in a text selection context, Goguey et al. [15] studied visual signifiers and visual output for force interactions on touch screens.

There has also been an extensive characterisation of the use of force on current interfaces. This includes understanding the forces applied during touchscreen gesture input [59] and with physical buttons [1]. Alexander et al.'s [1] characterisation of everyday buttons shows how physically modified controls can make critical actions harder to invoke, highlighting the role resistance plays in users' interaction with buttons.

Force-based interactions are moving beyond traditional touch screens and becoming more tangible by employing the use of shape-changing [38] and deformable surfaces [22, 62]. Deformable interfaces can change shape or deform under external force or pressure. This allows users to interact with the interface using physical gestures and movements, such as pushing, squeezing or bending [4]. Work in this area explores various methods to provide dynamic resistance in deformable interfaces [22, 62]. Follmer et al. demonstrated a mechanism for jamming materials to hold different shapes on demand, for example, changing from a flat surface to a chair that can hold the weight of its user [12]. Other approaches include tubes and air pulses that allow force interaction to be detected via a measured air wave [18]. For pushing into displays, there are examples of interfaces that use magnets and ferrofluids to allow the user to push through the screen with haptic resistance [21, 62]. Much like the use of magnets, other smart materials support resistance change via methods of heat or light for viscosity changes [37, 57]. Similar interactions can be implemented through materials such as fabric and elastic [16, 52, 63], while resistance can be simulated via electro-static forces across the display surface [3].

We are also beginning to see deformable force-based input combined with shape-change output. This combination has the ability to provide dynamic affordances and signifiers, offering the opportunity to design intuitive signifiers for deformable input. Particularly where the interfaces are beginning to offer richer deformable input, such as the shape-changing prototype InFORCE [38] and it bi-directional force capability. These papers show the potential of new methods and materials for both deformable input, stiffness change and shape change. We extend this work by developing a new understanding of the human perception of these changes in stiffness to provide insight into signifiers for the stiffness of interface components in deformable displays.

Recent work has enhanced our understanding of force-based interactions on soft surfaces via usability studies [14, 53]. These papers have examined surface stiffness' effect on force-based interaction for visual targeting tasks. We see from this how high force levels appear more demanding for soft surfaces [14]. Furthermore, there is a large body of work that explores the haptic perception of deformable material [6, 9, 56, 61]. This literature provides the foundations for understanding the psychological and cognitive aspects of the perception and interaction with deformable materials. The results of this paper expand this work by studying perception through crossmodal correspondences (CC), in particular, the correspondence between deformable surfaces and shapes and colours.

2.2 Perceptions of Shape-Changing Interfaces

There is a growing body of literature that aims to classify the use and form factors of shape-changing interfaces. Morphees presents a framework for the resolution of actuated mobiles [50]; this framework was further evaluated and expanded by the authors in workshops that created taxonomies of everyday re-configurable objects. Similarly, Sturdee et al. classified shape-changing forms based on application, resulting in eight categories of prototype, including enhanced 2D, bendable, paper and cloth, elastic, and inflatable, actuated, liquid, malleable and hybrid [58].

Researchers are also looking to understand how users perceive shape-changing interfaces. Pedersen et al. used Morphees to understand people's feelings and perceptions of handheld mobile device shape-change through a large-scale video study [44]. Similarly, the feelings and perceptions of users were studied in 'Imagined Physics'. This work reviewed examples of shape-changing interfaces and analysed human responses to the changes [34, 40].

Furthermore, there is work that explores affordance, system state, and feedback in shape-changing buttons. This work begins to show the maturity of the field and research considerations beyond technical feasibility, contributing to an understanding of the mental models for interacting with shape-changing interfaces [60].

To date, much of the work in the area of deformable and shape-changing interfaces has focused on display fabrication, novel interaction possibilities [13, 39], or classifications of the types of shape-changing [24, 58]. Some key work in the field had focused on user perceptions [44, 60] aimed to inform building mental models of interaction. This paper builds on this work by providing guidelines for how to utilise shapes and colours can be used to design intuitive signifies for deformable input on deformable and shape-changing interfaces.

2.3 Crossmodal Correspondences in HCI

Crossmodal correspondences (CC) refer to the non-arbitrary perceptual mapping (association) of stimulus features both within and across senses. For example, studies have looked at audio and visual associations with object size, resulting in large objects being associated with lower frequencies, and small objects being associated with higher frequencies, leading to perceptual associations between visual size and auditory pitch [42, 43].

The most well-known CC phenomenon is the "Bouba/Kiki" effect [47]. This study dates back to the 70s, where participants originally associated the names "baluma" and "takete" with two visually presented 2D shapes, one round and bulbous, the other angular and jagged. The results showed the majority of people will associate the round shape with "baluma" and the angular shape with "takete" [26], and the same with later studies substituting those with "bouba" and "kiki", respectively.

Much of HCI is inherently multisensory [23], common computer interfaces include some combination of vision (a monitor) paired with touch (touchscreen, keyboard or mouse). There is robust evidence, ranging from neuroscience and psychology to HCI, that multisensory congruence allows for more efficient processing compared to unimodal [29]. Exploring CCs has many benefits for the exploration of novel fundamental HCI research where associations between modalities, either during presentation or input, are being made. These include understanding which cues result in what reactions from humans, knowing how to use these cues, and which of them to avoid. A remarkable characteristic of CCs is that they are prevalent in many different languages and cultures [7], and even across different age groups, which means they can provide reliable and inclusive design solutions [31]. Therefore, it can be concluded that studying CCs in the persuasive and global area of technology is both relevant and applicable.

For these reasons, there is a growing use of CCs in HCI studies, and designs [11, 28, 35]. This includes studies exploring novel tangibles [28] and studies for shape change [10]. These studies have focused on the feel of the shapes themselves in relation to other characteristics, such as colour, to characterise the potential design space that could be exploited for future designs.

In contrast, our work is the first to focus on shapes as a visual basis for the final products of tangible shape-change designs. Recently, HCI research with CCs has focused on the context of tangible interactions, such as how the feeling of shapes corresponded to colours and emotions [10]. We take a different approach: this paper further extends the array of tangible shapes by incorporating the framework of Roudaut et al. [24, 50]. This framework gives us practical shapes and a resolution spectrum based on and utilising existing shape-changing interface research [25, 44, 46], showing how the findings from the CC studies can be used in future.

3 DESIGN OF STUDY MATERIALS

Our Crossmodal Correspondence study requires a range of physical and virtual materials, including 2D and 3D shapes, colours, and stiffness stimuli. This section describes these materials and the rationale behind their selection. Our work seeks to understand how people relate stiffness to different shapes and colours. We focus on finger-based input, rooting the development of the study materials around interface elements for single-finger touch interaction, such as pressing buttons on a traditional touch screen, pressing onto parts of the screen itself or interacting with any other physical elements of a deformable interface.

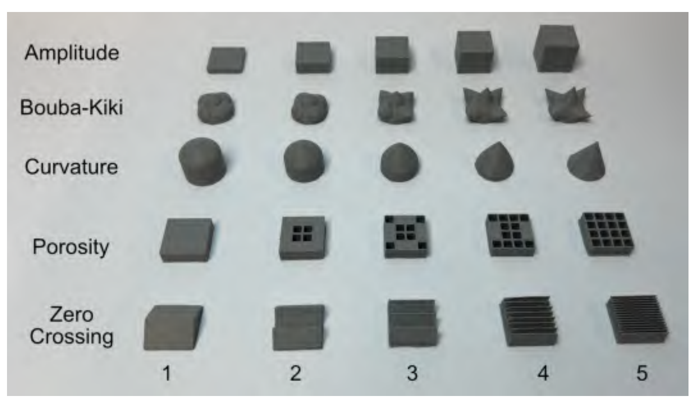

Figure 2: 3D-printed 3D shapes for the study. Rows show Amplitude, Bouba-Kiki, Curvature, Porosity, and Zero Crossing. The column numbers label the shape-change levels.

3.1 Shapes

The variable properties for shapes are drawn from past literature on crossmodal correspondences [28, 30] and shape-changing interfaces research [44, 50]. We used Bouba-like and Kiki-like shapes as baseline shapes due to their extensive background in crossmodal correspondence studies in the psychology literature [7, 26].

The design and shape of the objects and graphics used are based on the Morphees framework [50] as they provide a suitable starting point for generating shape resolutions that have applications in deformable interfaces. This is a widely-used approach to collecting user perceptions of deformable interfaces [5, 24, 44, 45] and has become a commonly used framework in the field of shape-changing interfaces [25, 41, 51]. As we are focused on visual-tactile associations, we chose a subset of shape properties that had strong visual elements and did not need to actuate to signify their properties to the participant. Based on these criteria, we selected the following shape properties, definitions are taken from [50]:

- *Amplitude* is the range of displacement of a point on the surface. This is commonly used in actuated pin-array style shape-changing displays [13, 38, 49].
- *Curvature* intuitively describes the curviness of the surface. Curvature is computed by measuring the angle between three consecutive control points, inherently defining how round the shape is, as opposed to sharp.
- *Porosity* is the nature of discontinuousness or perforation in a shape. Porosity is the ratio of the area of the perforated parts to the total area of the shape.
- *Zero crossing* describes the ability of a shape to have groves or ridged patterns. It is calculated as the enumeration of sign changes between each pair of consecutive angles across the surface.

The angularity of models for Bouba and Kiki was determined by the mathematical formulae that been successfully used in a previous study [30]. This gave us the five points of transitions between Bouba and Kiki shapes. We then used the descriptions of the shapes from Roudaut et al. [50] to create five levels of resolution for the four chosen Morphees shapes.

The 3D shapes were created via a combination of Fusion 360, for modelling, and Python scripts to generate and calculate the exact curvature and angularity of the shapes. For consistency, all shapes were modelled to be within the size footprint of the stiffness stimuli. These 3D shapes were then printed on an Ultimaker S5 and in a grey[1] to avoid colour influence throughout the study (see Figure 2).

Wherever possible, the 2D shapes (Figure 3) are designed with the intention of resembling a direct top-view of the 3D shapes, inherently looking to translate them from 3D to 2D. This allows us to more closely compare the outcomes of the study. However, for amplitude shapes, we used a drop-shadow with increasing length to represent greater heights—otherwise, the top view is identical for all five shapes.

All shapes were displayed on a tablet screen with a size of 20×20mm. This sizing best matched the sizes of the physical stiffness stimuli. Each of the shape sets was displayed in the top centre of the study interface.

[1]Grey PLA Filament: shorturl.at/abU28

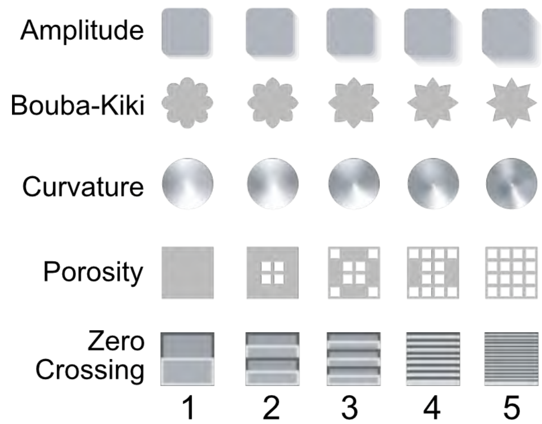

Figure 3: Graphics for the 2D shapes for the study.

3.2 Colours

Alongside shape, colour is a key factor in the design of user interfaces and the decision process for UI designers. We therefore study colours to help understand their associations with surface stiffness levels to help inform these design factors in deformable displays. This helps align our work with other CC studies associating colour with tangible-based interactions [28, 54] and to help extend their understanding for the HCI community. For our colour selection task, we used 10 different colours based on approaches used in previous CC studies in HCI [28] that study CCs and tangible interactions. These colours were shown to the participants on a digital display. 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. See Figure 4.

The squares of colours were 20×20mm to match the sizes of the stiffness stimuli. Six columns were presented (Figure 4): columns (2) and (5) were the primary selection columns, while adjacent columns ((1,3) and (4,6) respectively) displayed the primary selection colour at the highest and lowest possible brightness value. These acted as a reference for the participant before they proceeded to adjust the brightness value through a slider. The selected colour is displayed on the left side of the slider and then pressed to confirm the selection.

3.3 Stiffness Stimuli

We used five stimuli (S1, S2, S3, S4, and S5), each at a different level of stiffness (Figure 5). These stimuli were modelled as cubes from two-part rubber silicon mixtures and separated by shore hardness ratings (Table 1) provided by the manufacturers[2]. Silicon is readily available and is used in a variety of deformable input research for sensing techniques and user interaction [14, 55, 65]. The material properties of silicone meant it was able to withstand repetitive force application during testing and return to its original form. Each of the stimuli was modelled as 20mm × 20mm × 20mm cubes and, where necessary, the shapes and colour swatches shown in the tasks were

[2]Smooth-on: https://www.smooth-on.com/

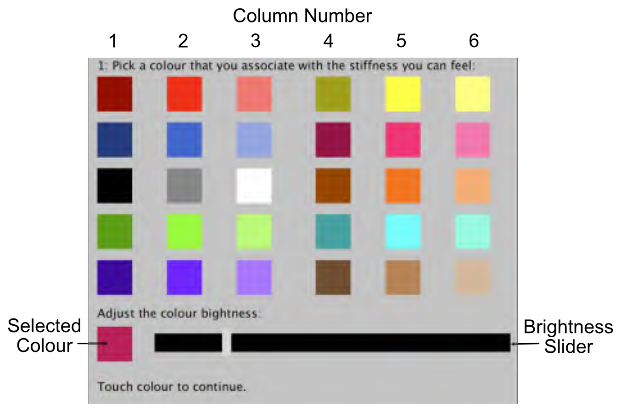

Figure 4: Colour selection interface used in the study. The colour columns (2, 5) were the primary selection columns, while adjacent columns, (1,3) and (4,6) respectively, displayed the primary selection colour at its brightest (right) and darkest (left). The selected colour appears to the left of the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

the same surface area as the top of the stimuli (20mm × 20mm). We also coated the surfaces with latex[3] to ensure a consistent texture with touch.

4 STUDY DESIGN

The overarching goal of this study is to explore how people correlate deformable tactile stimuli of different stiffness levels to colours and sets of graphical and physical shapes. To achieve this, we asked participants to associate specific shapes and colours with a certain stiffness of the stimuli.

4.1 Participants

We recruited 30 participants through the authors' institution, 15 women and 15 men (aged 19–59 years, average age of 27). During the study, participants (three of whom were left-handed) used their dominant hand to touch the stiffness stimuli. The study followed a within-subjects design and each session took approximately 75 minutes. All participants were compensated with a £10 gift voucher.

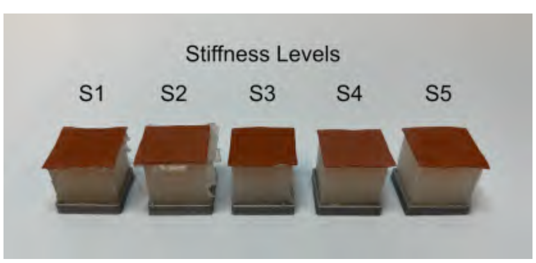

Figure 5: The five force stimuli in order of Soft (S1) to hard (S5).

[3]4D Rubber: https://www.fourdrubber.com/

4.2 Study Set-up

Our study setup (Figure 6) consisted of: (1) a box in which the participants placed their hand to feel the stimuli, and (2) a tablet and keyboard which they used to input answers depending on the respective task. These components are described below.

4.2.1 Stimuli Box. The stimuli box was placed in front of the users, with a single opening where participants could insert their hand. The general placement and design allowed participants to rest their wrists flat on the table, as instructed by the researcher (see Figure 6). This ensured that the stimuli were pressed without a change of hand or wrist position that could affect how the stimuli felt; this also made the study more comfortable for the participant. The stimuli were hidden from sight in the box to avoid visual influence.

4.2.2 Tablet. To the left of the stimuli, we placed a tablet; this was swapped for left-handed participants. The tablet was used to record stiffness associations throughout the study. Participants had five options presented on-screen, either 2D shapes or numbers corresponding to the physically displayed 3D shapes that were placed on top of the stimuli box.

4.3 Tasks

The experimental procedure was composed of two main tasks. In the first task, participants matched the stiffness stimuli to a series of colours and shapes. In the second task, each participant's selected colours and shapes were seen again and matched to a stiffness stimulus. Throughout the tasks, participants were reminded that there were no right or wrong answers.

4.3.1 Task 1: Matching stiffness to colour, 2D shapes, and 3D shapes. Participants were tasked with pressing stiffness stimuli (see Figure 6) and matching them to colours, 3D shapes, and 2D shapes. Between each participant, the sequence of picking colours, 2D shapes, and 3D shapes followed a Latin square design to avoid ordering effects.

For each set of selections, the stiffness stimuli were presented one by one, in a randomised order. Participants were allowed to explore each stimuli with their dominant hand's index finger for however long needed to be able to select the associated 2D shape, 3D shape, or colour on the study computer using their non-dominant hand. When choosing a colour, users were also presented with a slider to adjust its brightness before making a final selection.

4.3.2 Task 2: Matching colour, 2D shapes, and 3D shapes to stiffness. Participants were given all five stiffness stimuli and asked to pick the one that they most closely associated with each of their Task 1 selections (colours, 2D shapes, 3D shapes); previous selections were presented one at a time.

Stiffness stimuli were presented in order of 1 to 5 (soft to hard) in the box, in a similar manner to task 1. Each of the stiffnesses had a number that corresponded with a labelled button on the tablet. To make a selection the user picked the number they associated with the stiffness. The tablet also individually displayed their colour and 2D shape selections from task 1, the 3D shapes were placed in front of the participant by the researcher.

Before each selection, the participants were required to press each of the five stiffness stimuli in alternating order between 1–5

Stiffness	Shore A Hardness	*Modulus (PSI)*	Tensile Strength
S1	000-34	N/A	N/A
S2	00-10	8	120
S3	00-20	8	160
S4	00-30	10	200
S5	00-50	12	350

Table 1: Technical specifications for silicon used to create study stimuli. These specifications are taken from the manufacturer's (Smooth-on) datasheet. Full information was not available for S1 due to it being below the shore hardness 00 and not tested by the manufacturer.

and 5–1. This order was reversed for all other participants and indicated on the tablet screen.

Figure 6: Study setup from the participant's perspective.

4.4 Procedure

After the consent procedure, participants were asked to complete a demographic questionnaire. The study then iterated through all tasks. The study ended with a semi-structured interview where we asked participants about their rationale and strategies for their associations. The interviews were recorded in audio for later transcription and analysis.

5 RESULTS

From the user study, we collected stiffness matches from each of the participants. For each participant in task 1, we collected five colours, 25 3D shapes, and 25 2D shapes, each matched to a stiffness. Then for Task 2, each participant provided five stiffness matches to their five colours, 25 stiffness matches to 3D shapes, and 25 stiffness matches to 2D shapes from task 1. Overall, for the analyses, this gave us 300 data points that associated colour with stiffness and 3000 data points associating stiffness with shapes.

We first show the significant associations from the stiffness matching in task 1 (all tests for significance were made at the $\alpha = 0.05$). Then as the colours and shapes picked in task 1 is shown again in task 2. We used this data to perform a cluster to group shapes and colours based on the frequency their stiffness was matched again in task 2.

5.1 Task 1: Colour Associations

We used repeated measures ANOVA to compare the hue and brightness levels of the colours selected for each of the stiffnesses presented in task 1. We saw a significant effect on brightness levels ($F_{3.381,98.044} = 27.948,\ p < .001,\ \eta^2 = .491$). Mauchly's test indicated that the assumption of sphericity had been violated, ($\chi_2(9) = 22.979,\ p = .006$) therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\epsilon = .845$).

Post-hoc comparisons of the stiffness and brightness values showed a significant difference between stiffness levels S1 and S2 ($p < .001$), S4 ($p < .001$) and S5 ($p < .001$). S5 with levels S2 ($p < .001$), S3 ($p < .001$), and S4 ($p = .004$). Finally, also levels S3 and S4 ($p < .001$)

We also observed a significant difference in the selections of the hue level ($F_{4,116} = 27.948,\ p = .04,\ \eta^2 = .083$) chosen for the different stiffnesses. Post hoc comparisons of stiffness did not reveal significance.

These results begin to show us crossmodal correspondences between stiffness and colour properties, particularly brightness associations for participants. In particular, softer stiffnesses were associated with brighter colours and harder stiffnesses with darker colours.

5.2 Task 1: Shape Associations

We used a repeated measures ANOVA followed by a post-hoc pairwise comparison to investigate the effect of stiffness on shape selection for each of the stiffnesses presented in task 1. We saw a significant effect on shape selections in the shapes of 3D Bouba-Kiki, 2D Bouba-Kiki, 3D porosity, 2D amplitude, and 2D curves (see Figure 7).

We saw a significant effect on shape selection in the 3D Bouba-Kiki ($F_{2.52,73.077} = 3.692,\ p < .005,\ \eta^2 = .438$). Mauchly's test indicated that the assumption of sphericity had been violated, ($\chi_2(9) = 23.970,\ p = .005$) therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\epsilon = .760$). Post-hoc comparisons of stiffness levels of 3D Bouba-Kiki shape selections indicated that there was a significant difference between stiffness levels S1 with S2 ($p = .003$), S3 ($p < .001$) S4 ($p < .001$), and S5 ($p < .001$). Level S5 was significantly different from S2 ($p < .001$) and S3 ($p < .001$) and S4 ($p = .002$).

We saw a significant effect of shape selections in 2D Bouba-Kiki ($F_{2.750,78.443} = 22.389,\ p < .005, \eta^2 = .436$). Mauchly's test indicated that the assumption of sphericity had been violated, ($\chi_2(9) = 37.867,\ p < .001$) therefore degrees of freedom were

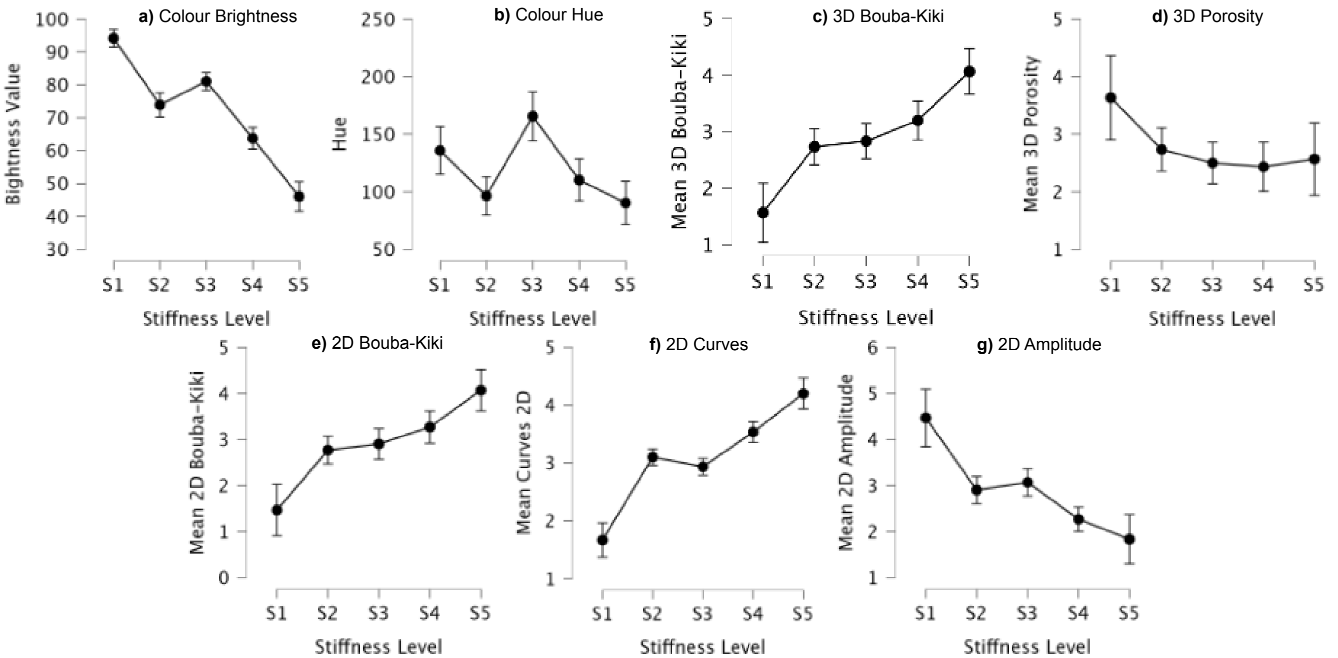

Figure 7: Shape and colour selections for each of the five stiffness levels that showed significance, in order a) brightness values, b) hue values, c) 3D Bouba-Kiki, d) 3D porosity, e) 2D Bouba-Kiki, f) 2D curves, g) 2D Amplitude. The data is presented as mean with error bars illustrating the standard error in each data set

corrected using Huynh-Feldt estimates of sphericity ($\epsilon = .676$). Post hoc comparisons of the stiffness levels for 2D Bouba-Kiki showed significantly different stiffness levels S1 from S2 ($p < .001$), S3 ($p < .001$), S4 ($p < .001$), and S5 ($p < .001$). Level S5 was significantly different from S2 ($p < .001$) S3 ($p = .004$) and S4 ($p = .007$).

The shapes for 3D porosity also yield significance ($F_{11.52,73.077} = 22.690$, $p < .05, \eta^2 = .113$), Mauchly's test indicated that the assumption of sphericity had been violated, ($\chi_2(9) = 32.086$, $p < .001$) therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\epsilon = .630$). Post hoc comparisons of stiffness levels of 3D Porosity showed significantly different stiffness levels S1 with S3 ($p < .023$) S4 ($p < .013$), and S5 ($p < .040$).

We saw a significant difference for 2D amplitude ($F_{1.786,51.796} = 22.690$, $p < .005, \eta^2 = .439$). Mauchly's test indicated that the assumption of sphericity had been violated, ($\chi_2(9) = 74.807$, $p < .001$) therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\epsilon = .447$) The comparisons for the 2D amplitude showed significantly different stiffness levels S1 with S2 ($p < .001$), S3 ($p < .001$), S4 ($p < 0.001$) and S5 ($p < .001$). Then, stiffness S2 with S4 ($p = .037$) and S5 ($p = .009$) and stiffness S3 with S4 ($p = .001$) and S5 ($p = .003$).

Finally, we saw a significant difference for 2D curves ($F_{2.256,65.425} = 18.867$, $p < .001, \eta^2 = .394$). Mauchly's test indicated that the assumption of sphericity had been violated, ($\chi_2(9) = 43.004$, $p < .001$) therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\epsilon = .564$) The comparisons for the 2D curves showed significantly different stiffness levels S1 with S2 ($p < .001$), S3 ($p = .001$), S4 ($p < 0.001$) and S5 ($p < .001$). Then stiffness S2 with S5 ($p = .005$) and stiffness S3 with S5 ($p = .002$).

To summarise, the ANOVA identified five distinct sets of shapes which showed significant differences: 2D Amplitude, 2D Curve, 2D Bouba-kiki, 3D Bouba Kiki and 3D Porosity. Each set of shapes presented significance in associating its own varying levels with stiffness. 2D Amplitude showed an even spread between shape level significance, with its level five presenting a clear association with the softest stiffness values. 2D Curve presented a significant difference between associations with S1 and most others, as well as between middle stiffness levels and S5; also showed S1 and S5 as correspondents to the lowest stiffness and, respectively, the highest ones. 2D and 3D Bouba-Kiki yielded significant differences between associations with S5 and most other stiffness levels; averages also correlated the extremities S1 and S5 to the lowest and highest stiffness. 3D Porosity showed a significant difference between correlations with S1 and most other stiffness levels.

These results show us initial crossmodal correspondences between stiffness and the characteristics of the shapes used in the study. Figure 7 depicts these feature selections as a function of stiffness level. Overall there are some clear linear trends that relate the level of stiffness to the levels of the other variables.

5.3 Task 2: Colour Associations

Using the data collected from tasks 1 & 2, we grouped all participants' colour selections via a cluster analysis using R[4]. We processed the data so that each colour selected and adjusted by the user gets a

[4]R Project: https://www.r-project.org/

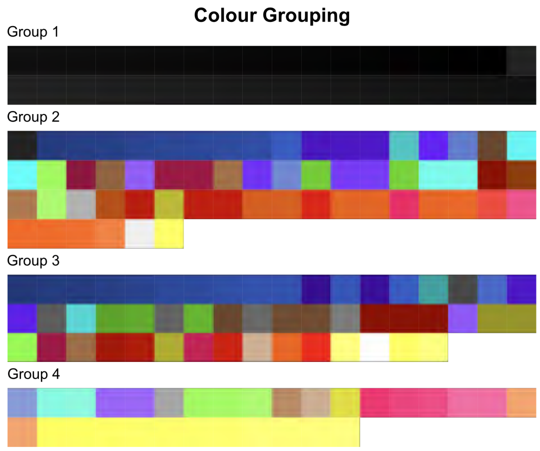

Figure 8: Colours selected by the participants in task 1, in the groups formed by the cluster analysis based on the matches with stiffness levels across both task 1 & 2.

property for stiffness that was selected in task 1 (matching stiffness to shapes) and task 2 (matching shapes to stiffness).

We conducted a hierarchical cluster analysis on the colour properties in responses from both tasks. We calculated similarities of the colours using Euclidean distancing and used the Ward method [64] to cluster the colours. Based on the output from the dissimilarity matrix, we formed the colours into four groups. The average values of the colours within each grouping are shown in Table 2, and the colours in each of the groupings can be found in Figure 8.

Group	H	S	B	T1 Stiffness	T2 Stiffness
G1	0	0	11	4.91	4.91
G2	131	69	77	2.50	3.10
G3	123	64	65	4.41	3.61
G4	136	53	94	1.00	1.37

Table 2: Average colour and stiffness values for the four groups of colours. The colour properties are made up of hue (H), saturation (S), and brightness (B). The stiffness values refer to the stiffness stimuli levels. T1 referrers to Task 1 and T2 refers to Task 2

The general cluster grouping shows a difference between groups 1 and 4, representing the extremities of each condition, lowest and highest for stiffness (See Table 2).

The dark colours in Group 1 shown in Figure 8 were associated with high levels of stiffness seen in the table. The colours presented in Group 1 are very dark, averaging out to be the group with the lowest brightness. This starkly contrasts with the lighter, primarily yellow colours in Group 4 that were associated with the lowest stiffness. Group 4 shows that users, on average, associated the lightest colours with the lowest levels of stiffness much more frequently than the colours in the other groups.

Groups 2 and 3 of the colours ended clustered with intermediate levels of stiffness. These groups do not follow any pattern as notably as groups 1 and 4 for stiffness associations, nor do they offer any significant insights (See Table 2).

5.4 Task 2: Shapes Associations

We also performed a cluster analysis on the shape selections with the data from tasks 1 & 2. We processed the data by shape, so each of the shapes we used in the study is assigned a frequency of selection in task 1 (selecting a shape to the stiffness) and task 2 (selecting a stiffness level for the shape).

We conducted a hierarchical Ward cluster analysis, where we calculated the distances between each shape using the Euclidean method and plotted the output in a dissimilarity matrix. From these distance calculations, we used a Ward hierarchy cluster and plotted the dendrogram. We clustered data into four groups and looked for the shapes in the groups with higher-than-average matches to the different stiffness levels.

The average values of the shape properties are shown in Table 3. We also provide a visual representation of the groups in Figure 9. First, group 4 contains a total of five shapes. This group yielded more correspondence to the softest level of stiffness (Table 3), with a higher average selection of S1 in both tasks 1 & 2. The shapes assigned to group 1 were found to be stiffer out of the four groups, shown by a higher average selection of S5 in both tasks. All shapes in group 1 are on the opposite extremes of each set in comparison to the shapes featured in Group 4.

Groups 2 and 3 covered the middle stiffness levels throughout all sets of shapes. The table further shows shapes mostly distributed across the stiffness S2-S4.

5.5 Qualitative Analysis

At the end of the study, we conducted an interview with each participant. All participants consented to audio recordings of their interview; these recordings were transcribed, anonymised, and analysed using a classical inductive coding approach. More specifically, we used and followed the qualitative steps of Inductive Category Development [32, 33]. This process started with determining the inductive categories, broadly, based on our research question, followed by adapting them according to the data. To confirm the observations, the initial codes were revised and presented to all contributing researchers. We report these results as categories of colour association strategies and shape association strategies.

5.5.1 Colour Association Strategies. Participants reported a multitude of explicit strategies when associating colours with stiffness, within these, only three were prevalent and noteworthy: **a) Emotions**, where participants correlated colours through the emotion each stiffness elicited, e.g. *"Squishy? Happy, Bright! Stiff? The opposite", "Squishy is fun, bright colours are fun. Then cold dark colours are kind of the opposite."*; **b) Objects**, where participants made decisions based on associations with objects they have previously interacted with in their everyday life, e.g. *"I picked a dark grey as if it was stone, you wouldn't be able to compress it much", "this is how it's often portrayed in products, think workout bands, the more powerful ones are black and easier ones are like yellow or green", "In my mind I was thinking purple like a yoga mat"*; **c) Intensity**, where participants associated stiffness levels through the intensity or physical density correlated with them e.g. *"A darker colour has more intensity to it,*

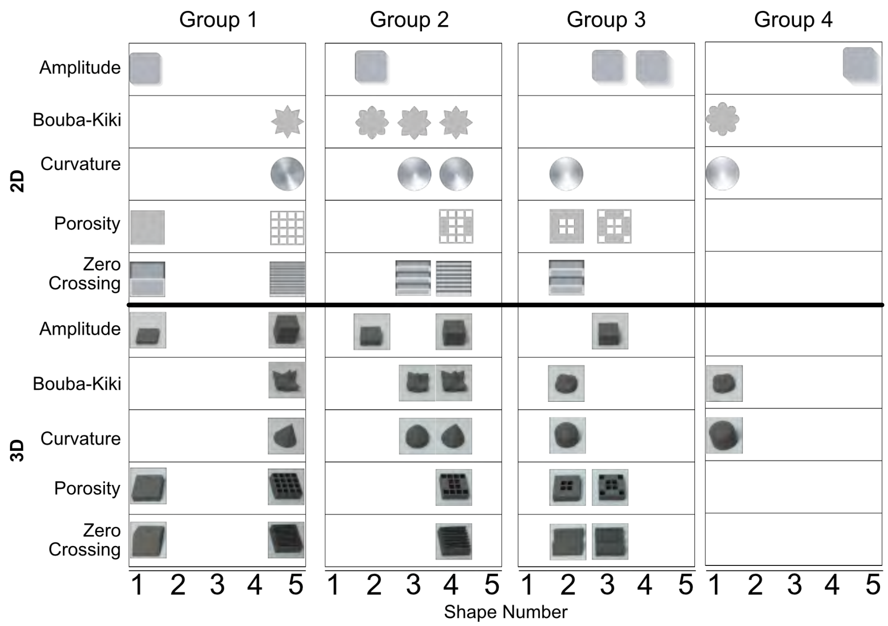

Figure 9: Shapes in the four cluster groups. The top half showing the 2D shapes and the bottom half the 3D shapes.

	Task 1					**Task 2**				
Group	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
1	8.53	1.13	1.60	4.07	12.80	6.60	2.33	1.80	4.07	13.33
2	1.71	8.06	8.12	8.71	3.35	1.06	5.00	7.29	12.00	4.59
3	2.33	10.17	9.00	6.75	2.42	2.42	10.92	11.33	4.83	1.17
4	22.25	2.50	3.00	1.25	3.75	15.25	8.75	3.25	2.75	2.75

Table 3: The average frequency of shape selection within each group, for all stiffness levels for tasks 1 & 2. The highest average for each group is highlighted.

so like a deep blue which I associate with a lot of pressure, whereas floaty pink or orange the opposite", "The stiffer, the more saturated and darker the colour", "For the really squishy ones I though light pale yellow felt more airy".

All participants were clear when explaining their strategies behind picking colour brightness. Regardless of the selected colour, decreased brightness was associated with increased levels of stiffness, while increased brightness with higher levels of softness; some participants directly stated that the colour did not matter as much as its level of brightness, when associating it with stimuli—e.g. *"I was more interested in the brightness than the actual colour"*. The same categories and strategies as above were also noticed on the topic of brightness.

5.5.2 Shape Association Strategies. When making tactile-shape associations, participants reported various strategies; some being reiterations of strategies for colour correlations: **Objects** e.g. *"Basically, this looks like it was made out of foam, looks like a mattress", "This looks like a computer component and I wouldn't want to press on it to not break it"*; **Intensity** e.g. "Looked hard to compress because there was more of it" and **Emotions** e.g. *"This looked more aggressive and dangerous so it was stiffer.* A set of additional categories were found within shape associations: **Geometric Features** refers to the impact of certain geometric aspects of a shape on participants' associations, such as angularity—*"This looked sharper so it was more stiff", "This was more round so I associated it with being softer"*—and height *"This looked more pushable because it had more depth, so you could squish it more and so seemed softer"*. For strategies rooted in geometric aspects of particular shapes, there was a tendency observed within participants to make associations via how breakable the presented shape looked; the structural integrity of the shape was observed as a defining factor when associating it with stimuli, e.g. *"This looks easy to break, fragile so I thought it was softer", "It just looked like it would be more breakable, flimsier so it was softer."*

6 DISCUSSION

In this study, we explored crossmodal correspondences between deformable tactile stimuli of varying stiffness, and visual stimuli, respectively, colours, 3D and 2D shapes. Our study has presented a novel approach to studying CC in the context of HCI. Our work is, to the best of our knowledge, the first to focus on shapes as a visual basis for final products of tangible shape-change designs in relation to deformable input. We extend prior work that studies haptic and tangible CCs and HCI by using variable stiffness silicon stimuli that participants were able to actively explore and deform.

The shape designs were based on the visual stimuli from the "Bouba/Kiki" paradigm [28] and shape resolutions outlined in Morphees [50]; each of these varied on a spectrum of complexity. The use of the crossmodal correspondence approach we presented in the paper provides a framework that advances how researchers develop future deformable and shape-changing interfaces. Therefore, the approaches and findings in this paper further both the use of CCs in HCI and contribute to the understanding of shape-changing interface theory where shapes can signal stiffness interaction [2].

Finally, for the wider community, the work continues to show the applications of crossmodal correspondences in HCI research [10, 28, 35]. Our results allow the HCI community to better understand the connection between user deformable input to colour associations and 2D/3D shape associations. This allows us to begin to form the design implications for the development of future interfaces.

6.1 Colour Associations

Our analysis reveals that the correlations between S1 and higher brightness levels were of greater significance over most other stiffness levels. The average brightness decreases as the stiffness level increases, reaching its lowest average at S5. The results from the clustering defined four groupings of the colours participants picked in the study.

Our analysis approach provides overlapping conclusions as the grouped attributes align with the ANOVA observations and vice versa. Therefore, elements that are part of group 1 transfer over to the averages observed in correlation with S5 and the lowest levels of brightness. In contrast, the attributes assigned to group 4 are the highest brightness values which are presented through the ANOVA as correlations of high significance with S1.

These outcomes are also supported by the categories outlined in the qualitative analysis. Although we have noticed multiple strategies behind participants' associations (emotions, objects, and intensity), there is a consistent variable throughout, which is participants' focus on the brightness of a colour. The general tendency among participants was to form a direct association of increased brightness with increased softness and decreased brightness with increased stiffness, with hue holding considerably less meaning to the user: *"I was more interested in the brightness than the actual colour."*.

Both of our quantitative and qualitative outcomes present *brightness as the main scale on which participants placed stiffness* Our results also show the lack of importance hue and saturation hold within the visual-tactile crossmodal correspondence with stiffness.

Overall, this work builds on research studying crossmodal associations of tangible interactions and colour, including vibrations [8], touching objects [28], and haptic controllers [54] demonstrating an understanding of the association of deformable surface stiffness with colours.

6.2 Shape Associations

Developing on existing CC literature [28], we contribute towards the understanding of how people associate deformable stiffness with an array of shapes based not only on traditional CC shapes ("bouba/kiki") [26] but also on a framework of shapes rooted in the field of shape-change resolution [50]. Due to the novel nature of the correlations with these shape types, we also developed and explored shapes in both 2D and 3D dimensional forms.

Through the study, we judged the visual-tactile CC of 10 different sets of shapes, five sets of 2D, and five sets of 3D shapes. In a similar manner to colours, four groupings featuring both our 2D and 3D shapes were formed. Our findings show tendencies to associate stiffer surfaces with higher angularity (2D & 3D) and softer surfaces with rounder shapes (2D & 3D) and deeper drop shadows (2D). This emerged from seeing the highest (5) and lowest (1) levels of the shapes significantly correspond with distinct stiffness levels in task 1. This was then further backed up by the analysis combining the results from task 2, where groups 1 and 4 contained the counterparts, presenting the two extreme ends of the stiffness scale.

Although Group 2 features the majority of shape matches assigned to S2 and S4, it has the lowest overall frequency of shape selection. It can be argued that this group contains the shapes that are generally least associated with stiffness, in particular, the softest S1 and hardest S5.

Combining the results and observations from the ANOVA and cluster analysis grouping, there is an overlap of shape association approaches. Groups 1 and 4 present a clear set of transferable attributes and associations using both analyses approaches. Shapes associated with Group 4 present the same low stiffness through the clustering algorithm as they do through the averages and ANOVA approach. This repeats for Group 1, on the opposite end of the spectrum, where the assigned shapes are associated with the highest levels of stiffness and force.

The qualitative analysis further supports these outcomes, especially through the observed categories behind associations: Objects, Geometric features, Intensity and Emotions. All of these were used by participants in different combinations and measures to reason the already presented stiffness associations.

All of our qualitative and quantitative results have built towards *extreme stiffness values as the most defined and easiest to form associations with, especially in the cases of 2D Amplitude, 2D Curvature, 2D Bouba-Kiki, 3D Bouba-Kiki and 3D Porosity.*

6.3 Design Implications

The findings of this paper begin the mapping of a framework for linking shapes and colours to the stiffness of deformable surfaces. The shape groupings shown in this paper can support researchers and designers when creating interface elements that influence user expectations of the stiffness and the amount of they can push into the surface and, in doing so, merge haptic and visual senses. We see these as a means to create multi-sensory interaction possibilities in deformable input surfaces using shapes and colours.

The clustered groups of colours provide a palette of colours that designers can begin to leverage for the UI design, much like the use of colour for signifying error messages, the intent of buttons, or the state of sliders. The colours in the groups of 1 and 4, are associated with hard and soft, respectively. This colour labelling could be employed for signifying areas of the screen that are softer or indicate, for example, a button would be hard to press. This colour feedback could also be used in continuous interactions where dynamic stiffness change takes place. Here, colour change can easily be used as an extrasensory output alongside tangible stiffness sensations, creating multi-sensory experiences.

Design Recommendation 1: lighter, high-brightness colours should be used to indicate soft surfaces, and darker low-brightness colours should indicate stiff surfaces. Gradients of brightness, from high to low, should be used to show increasing levels of stiffness.

By using the shape resolutions already widely recognised by HCI researchers [24, 50], we offer an initial step towards building mental models for shapes in physical interfaces and deformable input. The results of the study indicate that the shape properties that appeared in groups 1 and 4 can very strongly indicate types of shape features that can be used for showing stiffness ranges. The rounded features, such as the shape's curvature and bouba-like features indicated associations with softness. Whereas the less curved and kiki-like features offer designers more definitive contrast for shapes indicating if the surface is stiffer. In addition, larger 2D drop-shadows were associated with softer surfaces and the small drop-shadows with stiffer surfaces, making them the shape features most ideal for designers to use across the UI development to indicate polar differences between a hard or a soft surface.

Design Recommendation 2: rounded shapes should be used to indicate soft surfaces, while less-curved shapes should be used to indicate stiffer surfaces.

Design Recommendation 3: longer 2D drop-shadows should be used to indicate softer surfaces, while shorter drop-shadows should be used to indicate stiffer surfaces.

These shape and colour recommendations can be used to enhance the usability and learnability of deformable surfaces, especially for new users. They can be applied across traditional-style UI elements (e.g. buttons) and into novel applications of deformable surfaces, such as video games and entertainment.

7 LIMITATIONS & FUTURE WORK

This study is a starting point for examining CCs in the context of deformable user interfaces. In this work, we chose a subset of shapes that we judged to be relevant to deformable user interface design. Clearly, there is scope to study a wider range of shapes, and deformability now that we have the first results. For example, the Bouba/Kiki phenomenon has seen extensive study over the years. Still, our results show that there is a lot of work which still needs to be done to understand all crossmodal phenomenon that characterises these stimuli.

Currently, limitations within this type of study are rooted in the general novelty of the field of deformable interfaces (both from a hardware and software perspective). As this field develops, there will inevitably be an increasing number of variables and conditions to be tested via deformable-centric CC studies. Such advances might include studying surface textures and their correspondences with force-based interactions and stiffnesses.

We independently studied correspondence with graphics (2D shapes) and physical objects (3D shapes). Future work could also seek to explore force-based deformable interactions and CCs in AR and VR environments and evaluate the associations of stiffness to 3D shapes in virtual environments.

8 CONCLUSION

In this paper, we explore how people correspond surface stiffness to colours, graphical shapes, and physical shapes. Our work is the first to focus on shapes as a visual basis for the final products of tangible shape-change designs. The results of our study demonstrate evidence for transitional features of CCs between stiffness levels for a subset of the 2D/3D shapes used in the study. The findings are presented in a grouping of shape resolution and colour user associations with a spectrum of stiffness levels, demonstrating an initial mapping of colour and shape to stiffness levels. From these findings we developed three design recommendations: (1) lighter colours should be used to indicate soft surfaces, and darker colours should indicate stiff surfaces; (2) rounded shapes should be used to indicate soft surfaces, while less-curved shapes should be used to indicate stiffer surfaces, and; (3) longer 2D drop-shadows should be used to indicate softer surfaces, while shorter drop-shadows should be used to indicate stiffer surfaces. These recommendations will support the user interface design of the next-generation of deformable displays.

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