Feeling Colours: Crossmodal Correspondences Between Tangible 3D Objects, Colours and Emotions

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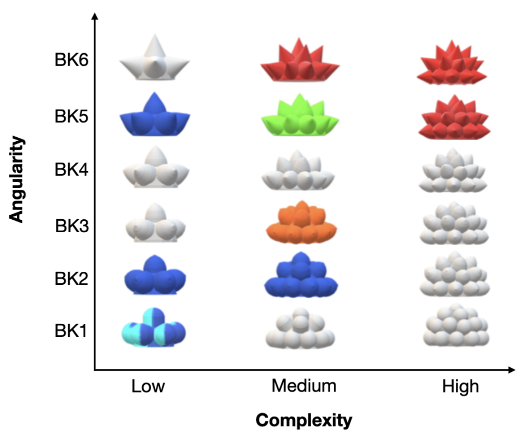


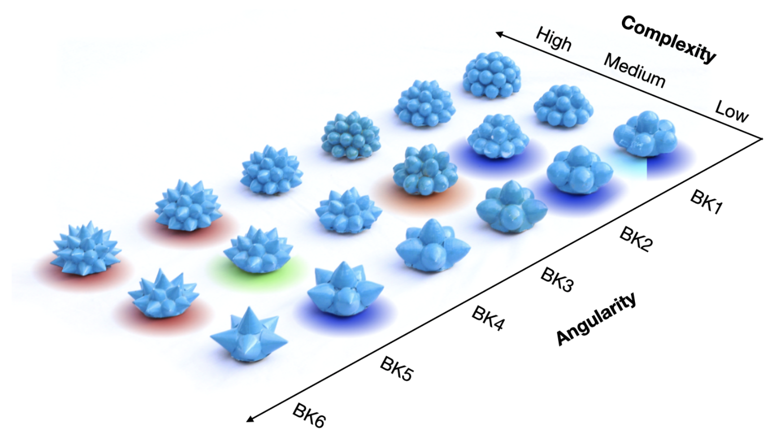


Figure 1: The 3D models (left) and 3D printed tangible objects (right) with varying levels of complexity and angularity used in the reported study. Objects' shapes are based on the Bouba/Kiki symbolism. Colours show crossmodal association tendencies.

ABSTRACT

With increasing interest in multisensory experiences in HCI there is a need to consider the potential impact of crossmodal correspondences (CCs) between sensory modalities on perception and interpretation. We investigated CCs between active haptic experiences of tangible 3D objects, visual colour and emotion using the "Bouba/Kiki" paradigm. We asked 30 participants to assign colours and emotional categories to 3D-printed objects with varying degrees of angularity and complexity. We found tendencies to associate high degrees of complexity and angularity with red colours, low brightness and high arousal levels. Less complex round shapes were associated with blue colours, high brightness and positive valence levels. These findings contrast previously reported crossmodal effects triggered by 2D shapes of similar angularity and complexity, suggesting that designers cannot simply extrapolate potential perceptual and interpretive experiences elicited by 2D shapes to seemingly similar 3D tangible objects. Instead, we propose a design space for creating tangible multisensory artefacts that can trigger specific emotional percepts and discuss implications for exploiting CCs in the design of interactive technology.

CCS CONCEPTS

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

KEYWORDS

Multisensory Interaction, Crossmodal Correspondences, Colour, Touch, Emotions, 3D Printing, Bouba, Kiki

ACM Reference Format:

Anan Lin, Meike Scheller, Feng Feng, Michael J Proulx, and Oussama Metatla. 2021. Feeling Colours: Crossmodal Correspondences Between Tangible 3D Objects, Colours and Emotions. In *CHI Conference on Human Factors in Computing Systems (CHI '21), May 8–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3411764.3445373

CHI '21, May 8–13, 2021, Yokohama, Japan

ACM ISBN 978-1-4503-8096-6/21/05...$15.00
https://doi.org/10.1145/3411764.3445373

1 INTRODUCTION

Humans combine multisensory information when interacting with the physical world. This enables us to create robust internal representations of our environment [23, 78], maintain information processing efficiency [27, 59], and compensate for impaired sensory modalities [34, 46]. It is therefore not surprising that multisensory perception takes on an increasingly important role in HCI research, particularly as digital interactive systems continue to gradually merge into physical reality [1, 12, 28]. Furthermore, continued advances in interaction techniques means that it is increasingly feasible to integrate multiple sensory modalities to achieve higher levels of realism and engagement [18, 68]. Understanding how best to combine multiple sensory modalities to create meaningful multisensory experiences thus becomes crucial. For designers, this means being able to characterise how sensory modalities relate to one another and influence each other, and to then use these characterisations in the design of interactive experiences. We propose that this characterisation should be grounded in the study of crossmodal correspondences [74].

Crossmodal correspondences (CCs) are non-arbitrary perceptual associations between different stimulus features. For example, auditory pitch is often associated with visual brightness, both mapping onto high ends of the intensity spectrum that is independent of the sensory modality assessing it [63, 74]. Studies have shown that CCs occur across a wide range of sensory modalities, e.g. visual patterns can influence linguistic judgements [39], odour pleasantness can modulate spatial attention [70], and colours can alter flavours [66]. CCs can also appear at a more abstract level, linking sensory features to emotional states and semantics [47, 55, 74].

The study of CC has received considerable attention in cognitive research on multisensory perception [74]. However, despite the general tendencies in HCI to break away from the confines of the graphical user interface and towards the integration of a broader set of sensory modalities (e.g. [18, 55, 68, 71, 82]), relatively fewer work in HCI has explicitly engaged with research on CCs to draw on its principles and examine how they could be exploited in the design of interactive multisensory experiences, particularly when using senses other than vision and audition [15, 19, 55]. To contribute to this line of research, this work builds on the rich history of tangible interaction in HCI to examine crossmodal correspondences between active haptic experiences of 3D printed tangible objects, visual colour, and emotions through the lens of the "Bouba/Kiki" CCs paradigm [67]. To do this, we present an empirical study in which we asked 30 participants to assign colours and emotional categories to 3D printed variants of the "Bouba/Kiki" models, with varying degrees of angularity (round/spiky) and complexity (low/medium/high number of protruding points).

We make the following specific contributions to the study of crossmodal correspondences in HCI. First, we extend prior work on CCs in terms of stimuli (from 2D shapes to 3D shapes) by investigating more complex stimuli that move beyond single point protrusion (e.g. [44]) and by by placing CCs in the more naturalistic context of active touch exploration. Second, we show show new evidence for transitional features of CCs between tangible, visual and emotional dimensions. Specifically, tangible and visual features of angularity and brightness share emotional valence. Thirdly, we make a methodological contribution demonstrating the importance of combining within- and between-subjects measures for identifying CCs. Finally, we propose a CCs design space for creating tangible multisensory artefacts that can trigger specific emotional percepts by combining tangible dimensions (angularity, complexity) visual dimensions (hue, brightness) linking to emotional categories (valence, arousal).

2 BACKGROUND

2.1 Crossmodal Interaction

Crossmodal interactions refer to the perceptual processes by which information is transferred between the senses; in other words, they describe how the senses influence each other. For example, when we experience a new object for the first time without seeing it, we would still be able to recognize it visually, based on features that can be accessed through both vision and touch, such as size, shape, or texture [20, 84]. This is due to perceptual representations being shared across senses. Similarly, information processing in one sensory modality can modulate processing in another modality [17, 72]. For instance, Shams et al. [72] showed that concurrent auditory stimuli influence perceptual numerosity judgements of a single visual stimulus. Notably, compared to other multisensory interactions, such as the fusion and separation of sensory information, crossmodal interactions can appear in the absence of simultaneous sensory input [24, 65].

2.1.1 Crossmodal Correspondences. A particular class of crossmodal interactions are crossmodal correspondences (CCs). These refer to the non-arbitrary perceptual mapping (association) of stimulus features both within and across senses. In many cases, they arise from the natural correlations of physical properties [24, 38, 62]. For example, while large objects resonate at lower frequencies upon impact, small objects resonate with higher frequencies, leading to perceptual associations between visual size and auditory pitch [61, 65]. However, some CCs appear more abstract and can be less easily explained by physical feature characteristics of the environment, which increases the challenges in their appropriate exploitation in the design of interactive multisensory experiences. For example, when asked to associate the names "baluma" and "takete" with two visually presented 2D shapes, one round and bulbous, the other angular and jagged (Fig. 2), the vast majority of people will associates the round shape with "baluma" and the angular shape with "takete" [40] (more commonly, the "Bouba/Kiki" effect [67]). Despite this seemingly arbitrary coupling of visual shapes and auditory sounds, humans tend to associate these features at rates far above chance level. In fact, sound symbolism is extremely prevalent in many different languages, cultures and across different age ranges, with children exhibiting similar association preferences as adults [50]. Importantly, CCs have been repeatedly shown to enhance multisensory perception and behaviour both in temporal and spatial domains [64, 74]. Over the last two decades, a vast amount of research in the cognitive sciences has demonstrated CCs between different visual, auditory, tactile, olfactory and even gustatory experiences [36, 55, 76, 81].

2.1.2 Colour and Touch Correspondences. Colour perception plays a vital role in visual recognition and objects discrimination in space

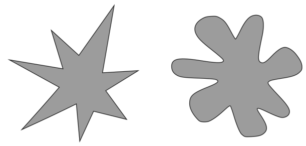


Figure 2: Which shape would you call "Bouba" and which would you call "Kiki"? The majority of people tend to agree that "Kiki" is the jagged shape on the left and "Bouba" is the bulbous shape on the right [67].

[80]. Previous studies suggest that the same crossmodal interaction mechanism also exists between visual and haptic perception, regarding object discrimination and spatial localisation [48, 75], which raises particular interest in the design of tangible technologies. Loffler et al. [43] showed visual-touch associations exist in various touch properties such as size, temperature, weight and strength regardless of cultural backgrounds. Ho et al. [33] demonstrated that colours are associated with tactile perceptions of temperatures: red corresponding to warm, and blue to cold. Slobodenyuk et al. [73] showed that high intensity vibrotactile stimuli is associated with red, violet and blue, and low intensity with yellow and green. These studies present a wealth of design opportunities for HCI research that, to a large extent, remain untapped. In the present work, we aim to explore colour-touch association in the realm of active tangible interaction.

2.2 Crossmodal Correspondences in HCI

To date, few HCI studies has sought to explicitly leverage CCs in the design of interactive technology. Hoggan et al. [34] showed that crossmodal visual, auditory and tactile feedback improved perceived quality of touchscreen buttons. Finnegan *et al.* [26] showed how using incongruent audio-visual correspondences can improve distance perception in virtual environments. Metatla *et al* [54] demonstrated how a congruent audio-visual display can result in higher engagement with game play involving estimation of vertical elevation. And Azmandian *et al.* [5] leveraged sensory information conflicts to improve alignments of physical and virtual objects. Degraen *et al.* [15] explore correspondences between 3D printed hair-like structures and the perception of texture. They found that visual-haptic augmentations enhance the users' haptic perception in virtual reality. Ion *et al.* leverages metamaterials to create transformable textures on 3D printed objects and showed that varying spike length allowed users to perceive a larger set of material impressions [35]. More recently, researchers focused specifically on replicating and transferring the visuo-linguistic Bouba/Kiki effect to olfactory and haptic experiences in the context of tangible 3D objects and emotion [55]. In the context of this paper, this suggests that such CCs paradigm could extend to further modalities and tangibility, and that an exploration of a broader feature space of these particular modalities may result in more efficient and engaging interactions.

2.3 Emotions

Emotions are elicited by multisensory stimuli that we encountered in everyday environment [14], and influenced by memories and life experiences [31]. Although, CCs have been extensively studied (see [74] for a review), their effects on our emotions have limited focus (e.g., [11]). Databases of standardized stimuli eliciting specific emotional states, are mostly collected based on unimodal stimuli (e.g. auditory [69], visual [42], or haptic [58]). And while there is a database extended to multisensory emotional stimuli [29], the stimuli were not concurrently presented. There has been recent work that examined the impact of concurrent sensory presentation on emotion. For example, Akshita et al. showed that the presence of a haptic stimulus affects the arousal of the visual stimulus without affecting valence [2]. The present work contributes to extending this line of research by assessing the emotion elicited by concurrent active explorations of haptics and colour.

2.3.1 *Touch, Colour and Emotions in HCI.*

Touch plays an important role in many forms of emotional communication [8, 32, 51]. For example, humans readily convey emotions through physical contact, such as a touch on the arm. A number of studies have looked into the emotional factors of touch. Tsetserukou et al. showed that tactile rendered emotion through wearable devices increased immersive experience of online messaging [79]. Ludwig and Simner reported correlations between haptic sensation and colour perception; e.g. that smoothness, softness and roundness correlating with brightness and saturation [44]. However, in the design of multisensory interaction, CCs between touch and emotion, and other modality features is not well investigated. This is in part due to the complexity of controlling configurations pertaining to physical touch stimuli, e.g. structure, surface texture, limited resolution of tactile display, and actuator miniaturization [3]. It is also due to a lack of understanding how touch integrates concurrently with other modalities, such as visual colour, auditory pitch or even taste and smell. There is therefore a need to increase our understanding with regards to how sensory modalities interact to deliver emotional content, and how we interpret emotional content on the basis of input from multiple sensory modalities. The work presented in this paper aims to contribute to addressing this gap.

3 STUDY

The aim of this study was to explore crossomodal correspondences between tangible 3D objects, visual colour and emotions. To do so, we asked participants to associate specific colours and emotions with 3D-printed tangible shapes that differed in levels of angularity and complexity, which we operationalised as the number of protruding points on the object surface. 30 adult participants took part in the experiment (aged 22-37 years, mean = 24.7, SD = 3.4). All participants reported having normal sight and to not experience any strong forms of synaesthesia [49]. All participants reported to be right-handed. They were recruited through opportunity sampling at the authors' institution.

3.1 Task

Participants performed two experimental tasks: colour-touch association and emotion-touch association. In both tasks participants

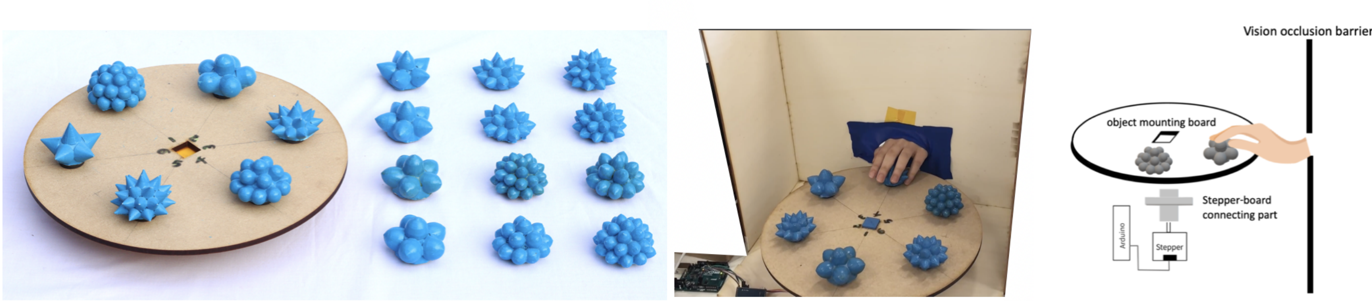


Figure 3: Schematic of the object-delivery device presentation and a photo from the real setup. The device is composed of an Arduino board, a stepper, a rotation loading board and a stepper-board connecting part.

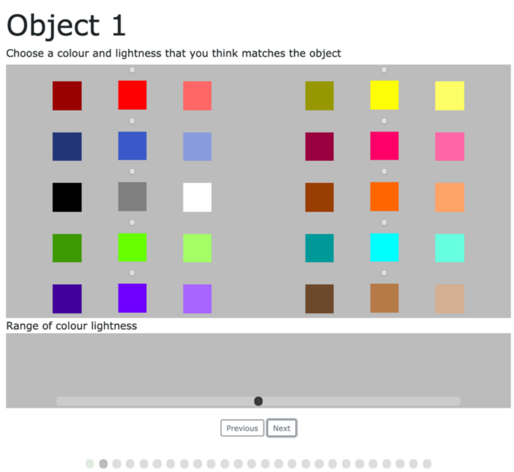


Figure 4: Colour palette presented to participants in the colour-touch task. Top: hue selection. Bottom: brightness selection using a slider.

were asked to explore 18 3D printed, tangible objects and to choose a rating of the hue and brightness of a colour that they think could correspond to the object, as well as the intensity of emotion they associated with them. The 18 objects varied in their degrees of angularity and complexity. The order of the tasks (colour-touch and emotion-touch association tasks) were counterbalanced, and the presentation of the tangible stimuli were randomised to avoid ordering effects.

Participants actively explored the objects with their non-dominant hand, and indicated association ratings on a response screen using their dominant hand. Each task lasted for about 10 minutes. In the colour-touch task, participants were asked to explore the object and to select the colour they most closely associated with it. Here, they were asked to select a colour from a palette of 10 different hues and to adjust the brightness (Fig 4). In the emotion-touch task, participants had to select the emotion they most closely associated with each object. Here we used the Pleasure-Arousal-Dominance (PAD) Emotional-State Model [52] and asked participants to focus on subjectively experienced emotions as induced by the sensory stimuli rather than as a quality of the stimuli independent of an observer. To do this, participants were asked to respond to the following instruction: *feeling the object with my hands gives me a sense of ...* and then to choose - as per recommendations for using PAD which indicate the need to choose paired terms as opposite to each other as possible [6] - a term for each dimension that captures their choice of emotion: Pleasure (terms: Pleasant-Unpleasant); Arousal (terms: Calm-Excited); and Dominance (terms: Control-Lack of Control).

3.2 Apparatus

The objects were presented to participants using a custom built rotation device (Fig. 3).The device is composed of an object presentation board on which the haptic objects can be mounted. Rotation speed and extent was controlled with help of an Arduino board delivering step-pulses to a motor. To prevent participants from seeing the objects, the presentation device was hidden in a wooden box. A touch screen was provided to allow participants to enter their response and to initiate the next stimulus presentation.

3.3 Stimuli

3D Objects: Two dimensions have been taken into consideration in the translation of "Bouba" and "Kiki" into tangible shapes: complexity (three levels of protruding frequency) and angularity (six levels of angularity, represented as BK1-BK6 in Fig. 1). The complexity of 3D shapes was varied by increasing the number of protruding points. Low complexity had 6 protrusions, medium complexity had 16 protrusions and high complexity had 26 protrusions. The angularity of models was determined by object-specific mathematical formulae that have been successfully used in a previous study [44] (though only as a single protruding point) and incrementally alter object angularity along the gradient from round to spiky. In order to allow objects to be placed stably on the presentation board, they were printed as half spheres, with a standardized size of 60x60x40mm, a weight of 300g. This resulted in 18 "Bouba-Kiki" models gradually varying along the dimensions of complexity and angularity (Fig. 1). Models were designed in open creation software Blender and sliced by Ultimaker Cura software. The Ultimaker 2+ 3D printer with 0.15mm Polylactic Acid filament and 20% of material infill used to generate models stiff enough to withstand deformation by human grip force.

Colour Preparation: In the colour-touch task, 10 colours were provided to participants: red, blue, grey, green, purple, yellow, pink, orange, aqua, and brown. These colour options are similar to the ones used in other typical studies assessing colour CCs, e.g. [21]. For each colour, a lighter and darker version was presented as a reference for brightness selection after the colour selection question. Once participants selected a hue, they were asked to adjust the colour brightness using a range slider (Fig. 4).

3.4 Procedure

The experiment was conducted in a quiet room to minimize distractions from the surroundings. Participants were seated comfortably in a chair in front of a table on which the experimental setup was placed. The wooden box containing the presentation apparatus was placed in front of the participant on the side of their non-dominant hand, allowing them to use it to explore each object, one at a time. The presentation order was counterbalanced to prevent habituation. In order to limit visual information during the exploration of the tangible objects participants had to insert their hand through a hole in the wooden box which was covered with a blue cloth (Fig. 3). Prior to the experiment participants were familiarised with the object presentation apparatus and the procedure. A button on the response screen allowed them to initiate the next stimulus presentation by triggering a rotation of the presentation platform. After familiarisation, participants started with one of the two main tasks, colour-touch association or emotion-touch association. Participants were given a break between the two tasks during which they received information about the next task. In order to mimic natural active hand exploration, participants were encouraged to use the whole hand including fingertips as well as the palm of their hand for object exploration. We interviewed participants at the end of the session. We asked general questions to elicit information about participants' rationale and strategies for associations. Interviews were semi-structured and were audio recorded for later analysis.

4 RESULTS

4.1 Colour-Touch Association

Colour-touch associations were assessed in terms of colour hue and colour brightness. Both were analysed separately and are reported in separate sections below. Object angularity was scaled on six levels from round (BK1) to spiky (BK6), while object complexity was expressed in three levels (low, medium, high) depending on the number of protruding points (Fig. 1).

4.1.1 Hue. Associations between tangible objects and colour hue were assessed using a Chi-Square test. Our approach to analysing these associations was based on similar analyses used in [21] who assessed visual shape-colour associations using Chi-Square tests. We matched our experimental design to theirs (e.g our choice of colour palette, reduction to 12 colours, several different shapes), and used the same method of analysis. We first calculated the expected frequency of colour ratings for each shape separately. Next, adjusted standardised residuals were obtained to indicate whether the actual frequency of colour associations was greater than expected. Standardized residuals greater than 2 suggested that the colour was selected more frequently than expected by chance [21] (Fig 5).

Results indicated significant associations between tangible objects and colour hue, χ^2 (180) = 950.003, $p < 0.05$. Round objects with low complexity (BK1, $z = 2.2$; BK2, $z = 2.2$) or medium complexity (BK2, $z = 2.2$) were significantly more often associated with blue than with any other colour. On the other hand, participants selected red significantly more often for spiky shapes with the highest complexity (BK5, $z = 3.6$; BK6, $z = 4.2$), or medium complexity (BK6, $z = 3.6$). Overall, blue and red were the colours most frequently associated with the different objects (see Fig. 1).

In order to test the robustness of these associations between colour and the most extreme shape expressions we assessed subject-specific internal consistency of choices. That is, while personal preference might influence the absolute colour choice, internal consistency of colour associations support the idea of a robust crossmodal colour-touch mapping that is determined by specific feature characteristics (e.g. angularity). In order to determine subject-specific internal consistency we assessed whether participants made the same colour associations between objects with similar characteristics, i.e. high complexity and angularity, low complexity and angularity. Consistency within round and spiky objects was determined through concordance of colour choices between BK1 and BK2, and between BK5 and BK6 using Pearson Chi-Square test. There was no significant difference of internal consistency between spiky or round objects ($\chi^2(1) = 2.5, p = 0.114$), suggesting that both extreme shape expressions showed equally robust associations. Analysing colour-touch associations in those individuals that showed high internal consistency confirmed significant associations between colour choice of round (BK1/2) and spiky (BK5/6) objects, $\chi^2(9) = 22.237, p < 0.05$. Round objects were significantly correlated with blue ($z = 2.3$) and sky colour choices ($z = 2.1$), whereas spiky objects were significantly associated with red colour choices ($z = 3$).

4.1.2 Brightness. To investigate CCs between tangible objects and colour brightness, we used a two-way factorial ANOVA to examine the effect of object angularity and complexity on associated brightness. Results indicated that colour brightness was highly associated with object angularity ($F(5, 521) = 4.63, p < 0.05, \eta^2 = 0.044$, Fig. 7), but not with object complexity ($F(3, 521) = 0.45, p = 0.719$). Furthermore, there was no statistically significant interaction between the effects of angularity and complexity on associated brightness, ($F(10, 521) = 0.379, p = .956$).

As complexity was not significantly associated with brightness, we compared brightness ratings between objects with different levels of angularity (BK1 and BK6), independent of complexity using Tukey post-hoc comparisons. This pairwise comparison of brightness-shape-associations revealed brightness associations to be significantly different at BK5 ($p < 0.05$) and BK6 ($p < 0.05$) compared to BK1 (Fig. 7). Overall, the round shape was associated with higher levels of brightness, while the spiky shape was associated with darker shades.

4.1.3 Colour-Touch Association Summary. Taken together, these results indicate crossmodal correspondences between tangible object features and colours. While round and simple objects were highly associated with blue colours, spiky and complex objects were more

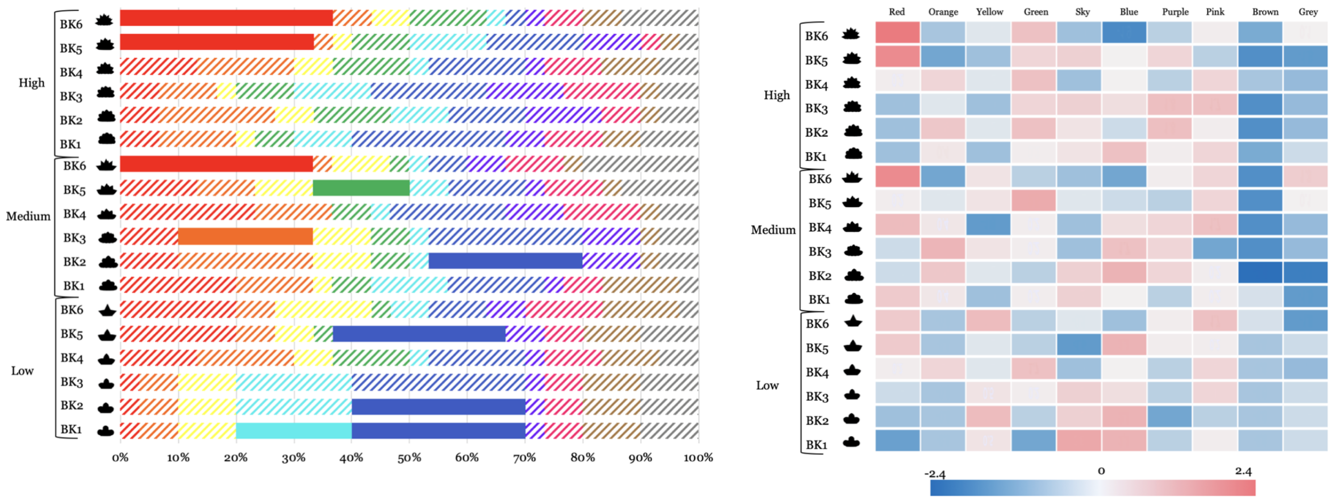


Figure 5: Chi-Square results presentation. right: The colour percentage of participants matching each object on the angularity scale. Un-shaded area indicates adjusted standardised residual of each colour is greater than 2. Note that the colour of bars is the same as the colours in the task. Left: Heat-map of adjusted standardised residual values. Labels on the left indicates complexity level of the corresponding object.

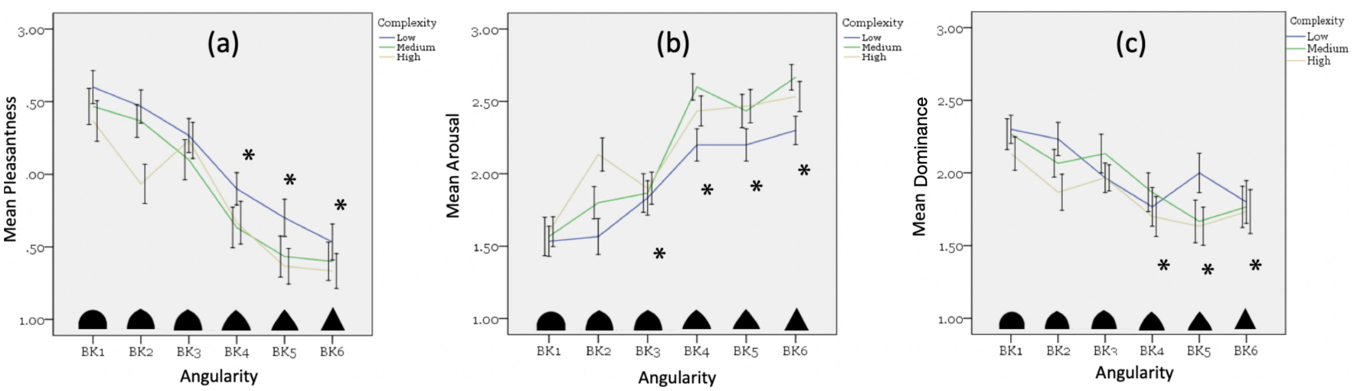


Figure 6: Scores of emotions associated with tangible stimuli in angularity scale. a) Pleasure. b) Arousal. c) Dominance. Data is presented as $mean \pm s.e.m.$, $*p < 0.05$ **vs. BK1.**

strongly associated with red colours. Furthermore, colour brightness was associated by object angularity, with round shapes being perceived as brighter and spiky shapes as darker.

4.2 Emotion-Touch Association

Emotion-Touch associations were assessed in terms of intensity for three separate emotion categories: Pleasure, Arousal, and Dominance. Emotions were rated using a 3-point scale with 1 showing a low association, 3 showing high association, and 2 showing no association (e.g. 1 = unpleasant, 3 = pleasant, 2 = neutral). Analysis was carried out separately on each of the three dimensions of emotion. We note here that the choice of a 3-point scale was based on the premise that providing a simplified view of emotion by just focusing on extremes overcomes biases related to the introspective verbalization of emotions in self-report measurements [25]. There are a number of similar works that also use a two-choice polarised value for the study crossmodal correspondence (e.g [86]). Other domains investigating colour-emotion semantic associations have also used 3- to 2-points measures (e.g [77]). Here we used a two-way ANOVA to determine the associated effect of angularity and complexity on three emotional ratings (Fig. 6). The interaction effect between two factors were firstly focused, followed by main effects indication if no significant interaction effect was found, otherwise simple main effects were reported. In addition to examination of main effects, the Tukey post-hoc test was also performed to indicate significant differences between each angularity and complexity level by multiple pairwise comparisons. Trend analysis was performed to illustrate experimental effect on emotion by a linear relationship.

4.2.1 Pleasure (pleasant-unpleasant). There was a main effect of angularity ($F(5, 522) = 35.50, p < 0.05, \eta^2 = 0.254$) and a main effect of complexity ($F(2, 522) = 6.58, p < 0.05, \eta^2 = 0.025$) on associated pleasure (Fig. 6a). However, there was no interaction effect

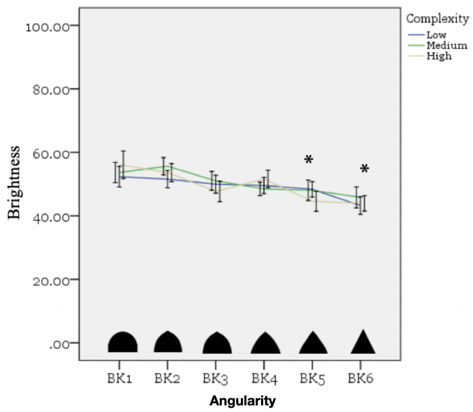


Figure 7: Angularity-Complexity-Brightness correspondences. Data represent *mean* ± *s.e.m.*, $*p < 0.05$ **vs. BK1.**

between angularity and complexity ($F(10, 522) = 0.711, p = 0.714$). Post-hoc pairwise comparisons revealed significant differences between objects of different levels of angularity, with the three most spiky objects (BK4, BK5, BK6) showing significantly lower pleasure associations compared to the roundest object (BK1, $p < 0.05$). Objects with low complexity received overall higher ratings of pleasure compared to medium and highly complex objects ($p < 0.05$). There was no significant difference between high and medium complexity levels ($p = 0.773$). Polynomial contrasts were carried out to investigate the association between object shape features and pleasure ratings. We found a negative linear relationship between pleasure and angularity ($F(1, 534) = 166.883, p < 0.05$) as well as pleasure and complexity level ($F(1, 537) = 9.577, p < 0.05$).

4.2.2 Arousal (calm-excited). There were significant main effects of both angularity ($F(5, 522) = 35.82, p < 0.05, \eta^2 = 0.255$) and complexity ($F(2, 522) = 8.46, p < 0.05, \eta^2 = 0.31$) on associated arousal but also no statistically significant interaction ($F(10, 522) = 1.21, p = 0.281$, Fig. 6b). Post-hoc pairwise comparisons indicated that participants associated arousal significantly more with spiky shapes (BK3-BK6) compared to the most round shape (BK1, $p < 0.05$). Furthermore, objects with medium and high complexity were more strongly associated with arousal, compared to those with low complexity ($p < 0.05$). Positive linear relationships were found between arousal and angularity ($F(1, 534) = 155.987, p < 0.05$) and between arousal and complexity ($F(1, 537) = 10.436, p < 0.05$).

4.2.3 Dominance (In Control-Lack of Control). There was a main effect of angularity on associated dominance ($F(5, 522) = 7.34, p < 0.05, \eta^2 = 0.066$), but no significant effect of complexity ($F(2, 522) = 2.99, p = 0.051$) and also no interaction ($F(10, 522) = 0.67, p = 0.751$, Fig. 6c). More spiky objects (BK4-BK6) received significantly lower dominance association ratings compared to the roundest object (BK1, $p < 0.05$). Moreover, the relationship between angularity and dominance cannot be represented by a linear model ($p = 0.21$). A linear relationship was only found with angularity ($F(1, 534) = 32.256, p < 0.05$) but not with complexity ($F(1, 537) = 5.368, p = 0.21$). Also, there was no non-linear relationship describing the relation between dominance rating and complexity, either ($F(1, 537) = 0.315, p = 0.575$).

4.2.4 Emotion-Touch Association Summary. Overall, these results confirm crossmodal correspondences between tangible object features and emotions. While round objects were more strongly associated with pleasant, calm, and in-control emotions, spiky shapes were more strongly associated with emotional arousal and low levels of pleasure and dominance. Furthermore, the complexity of the tangible objects influences pleasure and arousal ratings, with less complex objects being more strongly associated with pleasant and calm emotions, and more complex shapes with unpleasant and aroused emotions.

4.3 Qualitative Analysis

Audio recordings of interviews were transcribed. We used an inductive thematic analysis [7] to extract general patterns from participants feedback about their association strategies. One researcher produced initial codes of data segments and we conducted a peer validation process [4], where two researchers discussed and reviewed codes, categories and emerging themes.

4.3.1 Colour-Touch Association strategies. All participants ($n = 30$) reported an explicit strategy for colour-touch associations. Four themed strategies emerged: **1) Geometric features** where participants made explicit reference to the geometric features of the objects to describe their association strategies, e.g. *"white or pale blue colour go with flat surfaces, because it's like an absence of features and variety"*; *"Sharper edges are related with brighter red and rounder with darker red"*; **2) Everyday Objects** where participants referred to either personal or non-personal everyday objects that feels like the objects stimuli and hence is assigned a similar colour, e.g. *"that reminded me of nail clippers, mine is brown, so I chose brown"*; **3) Sense of Pleasantness** where participants chose colours that reflected their immediate emotional reaction when exploring the haptic object, e.g. *"I didn't like how that felt, so I went with black, which is not my favourite colour either"*; **4) Association Coherence** where participants explained the rationale for the current association on the basis of the previous association they made to maintain consistency and coherence, e.g. *"I chose brown for the first one, for no particularly reason, so I chose brown for everything else that felt similar"*. We also consider it interesting to note that the geometric features strategies were mostly mentioned with reference to angularity and colour ($n = 17$). Fewer participants referred to real objects when discussing angularity ($n = 7$), in which case they referred to toys, sea creatures, and plants. Only two participants referred to objects when discussing roundness, mainly bubbles and clouds.

4.3.2 Emotions-Touch Association Strategies. 22 participants discussed explicit emotions association strategies, while 8 participants were unable to articulate their strategies. We categorized those articulated into three broad themes, two of which were similar to the above strategies: **1) Geometric Features**; and 2) **Sense of Pleasantness**; and an additional theme **3) Sudden Shock** where the choice of emotion was directly linked to the extent to which consecutive stimuli belonged to extreme sides on the angularity and complexity scale, e.g. *"it went from round to super spiky, so that's exciting"*. It is also interesting that participants who articulate their strategies for emotions associations were more uniform and consistent. For example, participants tended to consistently associate angular objects with excitement and rounded objects with calmness. There were instances of dependencies between emotion and colour associations, e.g. *"lighter colours go with objects that have more of a pleasant feeling like smooth objects with less sharpness"*. Further, in contrast to the colour-touch association strategies, we did not find references to real objects for the emotion-touch associations.

5 DISCUSSION

In this paper we explored crossmodal correspondences between tangible object properties, colours, and emotions to identify their potential in the design of multisensory interactive technology. Grounded in theoretical accounts of crossmodal perception, we adapted the "Bouba/Kiki" paradigm from cognitive science and combined it with 3D tangible objects to represent the haptic feeling of shapes. There is ample empirical evidence suggesting that the "Bouba/Kiki" effect is a universal phenomenon across age and cultural background [9, 50, 85]. It exemplifies how crossmodal interactions allow our brain to categorise sensory information more efficiently and to facilitate multisensory perception. For example, these immediate associations are thought to facilitate multisensory perception by solving the sensory binding problem. As such, this phenomenon has increasingly gained popularity in the cognitive sciences, and has been investigated with the purpose of understanding people's perceptual capability and of enriching interaction experience. Building non-visual or non-auditory interfaces, such as in the field of haptics, is currently challenging and expensive, but the crossmodal correspondence approach we presented here could provide a solid foundation for advances in these domains.

To do this, the study we presented contributes novel knowledge of how tangible, visual and emotional features are perceived and interpreted alongside one another. This helps map out untapped space of crossmodal correspondences in HCI in terms of 1) an investigation of more complex stimuli features 2) focusing on active touch explorations 3) highlighting transitional features between investigated dimensions and 4) measurements needed for more rigorous identification of CCs: Studies that assessed CCs/touch looked at 2D shapes [16], word association [37], vibro-tactile feedback [16] and scent-touch stimuli [55]. We contribute evidence of CCs for more complex tangible stimuli, more specifically extending [44]'s single point protrusion stimuli to investigate more complex tangible stimuli in terms of varying levels of angularity and complexity. We also extend this prior work by placing CCs in the more naturalistic context of active touch exploration as opposed to single-point haptic contact for experimental exploration (e.g.[73]). Importantly these dimensions (i.e. complex stimuli + active touch exploration) help bring CCs closer to HCI design space. Further, We show new evidence for transitional features of CCs between tangible, visual and emotional dimensions. Specifically, tangible and visual features of angularity and brightness share emotional valence. Here, our findings highlight limitations to the linear predictability of CC translation (e.g Fig 5b), which is an important consideration for designers of multisensory HCI. Finally, we make a methodological contribution, demonstrating the importance of within- and between-subjects measures for identifying CCs. We expand on these points in the following discussion.

5.1 Colour-Touch association

Previous research on haptic crossmodal correspondences has been limited due to the complexity of creating tangible exemplars of well-documented visual or auditory correspondences. In fact, the majority of studies that assessed crossmodal correspondences involving touch have either looked at the associations of haptically relevant language [37, 87], tactile vibrations [16], 2D tactile shapes [30] or haptically-rendered virtual stimuli that could only be assessed with one point of contact at a time [73]. With this study we therefore aimed to extend previous work by examining correspondences between tangible "Bouba/Kiki" objects, colour and emotion. Very little research has investigated the tangible dimension of this effect [44]. Thus, our work contributes to increasing the systematic investigation of associations of colours and emotions with shape angularity and complexity using tangible, 3D objects and to explore subjective association strategies. Our findings showed crossmodal associations, as we find that the colour associations hold for participants with high internal consistency. Our findings also provide a methodological contribution for the study of CCs in HCI, consistent with previous studies emphasising the importance of increasing within-subjects and between-subjects measures as an approach to measuring crossmodal correspondences [21].

5.1.1 Brightness and colour category. Our results showed that there exists an angularity-brightness association, independent of the complexity of the 3D shapes. Specifically, actively touching rounded shapes was associated with higher level of brightness, while touching spiky shapes was associated with darker shades. Other than the mappings between polarised values of the colour-touch association, our results also showed a gradient in the mapping, that the brightness decreased with increasing angularity. This supports findings from a previous study using serial exploration of virtually rendered haptic shapes [73] and which reported that brightness increased for smoother compared to rougher shapes. However, comparing these results to previous studies that assessed shape-brightness correspondences in the visual domain, these findings provide an important insight: In the visual domain, higher brightness has been found to be associated with more angular shapes and darkness with more round shapes [83], opposite to our findings. Crucially, this suggests that CCs in tangible experiences underlie different principles and cannot be inferred by only studying visual CCs.

The hue value of colour appeared to have an association with tangible shape features as well. A blue colour was associated with rounded shapes with low complexity, while a red colour was associated with high angularity and high complexity. Here too, our results suggest that the tangible "Bouba/Kiki" objects elicited a different crossmodal association compared with the "Bouba/Kiki" effect observed with 2D shapes (visual perception on shapes) in previous research. Comparing these findings to colour-shape associations in the visual domain we find contrasting results [21]. While red was strongly associated with the round shape, we find associations between red and the most spiky shape. We found that, independently of the absolute angularity, participants exhibited internally-consistent associations. This suggests that there are significant mappings between two extremes of the feature pace (i.e. smooth - blue, spiky - red).

5.2 Emotion-Touch association

In relation to the touch-emotion association, our results showed significant associations between tangible shapes features and the emotional dimensions of pleasure and arousal and dominance. Specifically, the pleasantness of the objects decreased as the level of spikiness and complexity increased. The arousal level increased (to be more excited) as the tangible shape become rounder, and decreased (calm) with decreased complexity. A sense of loosing control was associated with more angular objects, and a sense of control was associated with less angular objects.

5.3 Association Strategies

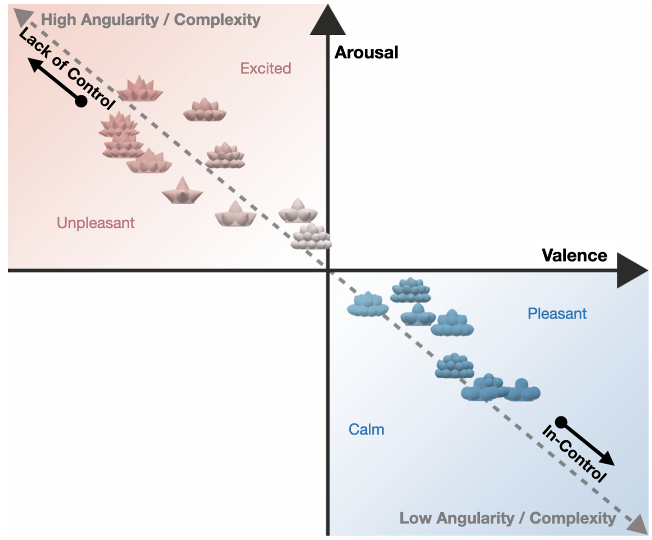
Qualitative analysis of subjective feedback revealed four association strategies in relation to the touch-colour association and three strategies to the emotions-touch association, including links to geometric features and relationship to objects and prior experiences. This suggests that emotion mediates touch-colour association to some extent, which aligns with prior research on shape-colour associations, which showed emotional mediation effect [45, 55, 60].

Combining this finding with the results from colour-touch and emotion-touch tasks, we can see an interesting regularity on crossmodal transitional association. On the one hand, increased tangible roundness associates with increased brightness, and also with increased pleasantness. On the other hand, increased tangible spikiness associates with decreased brightness, and with increased unpleasantness. Previous research suggested that crossmodal perception have transitional features between different CCs. For example, pitch correlates with elevation and elevation correlates with brightness, so the pitch and brightness also perceptually correlate [62, 65]. Our finding suggests that this transitional effect occurs not just between certain CCs, but also across perception and emotional dimensions. Though the current study cannot indicate which are the primary associations and which are the transitional one, it confirms that the tangible physical features of angularity and brightness share the same emotional valence.

5.4 A Design Space for 3D Tangible and Visual Crossmodal Correspondences

We thus show evidence for 3D tangible and visual CCs linking to emotional categories. Specifically, between angularity and brightness, and between complexity and hue. Active touch of rounder objects were associated with higher levels of brightness, and angular objects with lower level of brightness. These findings are important because they contrast findings from CCs triggered by 2D shapes [16, 83]. Blue was associated with less complex tangible objects, and red with more complex ones (with complexity operationalised as no. of protruding points) Here too, moving from 2D shapes to tangible 3D objects and from passive touch and single-point haptic contact (e.g [73]) to active touch exploration led to contrasting outcomes. In actionable terms, this means that designers cannot simply extrapolate potential perceptual and interpretive experiences elicited by 2D shapes to seemingly similar 3D tangible objects Other principles are at play and direct extrapolation may lead to undesirable outcomes. Instead, we can start to articulate a CCs design space for creating tangible multisensory artefacts that can trigger specific emotional percepts. Based on our findings, such a design space combines tangible dimensions (angularity, complexity) visual dimensions (hue, brightness) linking to emotional categories (valence, arousal and dominance) as shown in Figure 8, where low angularity/low complexity of tangible objects could be combined with high brightness/Blue to trigger Clam/Pleasant/In-control emotions, and those with high angularity/high complexity could be combined with low brightness/Red to trigger excited/Unpleasant/Lack-of-Control emotions.

Such a design space can provide concrete actionable design recommendations on how to exploit CCs. For example, in domains such as storytelling, different combinations of tangible/visual stimuli can be used to present different "Activation" scenes: from relaxing to high arousing. Multiple sensory modalities in storytelling have been investigated elsewhere (e.g. [22]) but did not account for CCs effects. In education and in therapeutic applications [41, 57] they could support understanding of emotional states for young children and children with complex needs, and for providing more engaging and inclusive sensory learning experiences (e.g [10, 53]).



Tangible	Visual	Emotion
Low Angularity Low Complexity	High Brightness/ Blue	Calm Pleasant In-Control
High Angularity High Complexity	Low Brightness/ Red	Excited/ Unpleasant/ Lack of Control

Figure 8: An initial design space of 3D tangible objects features, visual colour and emotion categories showing distribution of objects by emotion plotted as a function of arousal, valence and dominance.

5.5 Design Implications

In general, the current research provided insights into how to combine tangible physical features, i.e. colour and 3D objects, and the emotional categories that they could elicit. This systematic exploration helps to expand how we understand the affordances of this potential interactive features. Our participants employed three association metaphors centred around the tangible character of shapes, which brought meanings to their perceptual experiences. This leads us to speculate potential challenges that would influence designing interactive technologies that exploit crossmodal correspondences in this space. Firstly, the tension between systematic and intuitive association strategies, which points to different uses of these mappings depending on the levels of tasks or experiences that they are used for. For instance, tasks that require eliciting a particular percept in the user could be readily supported by the particular association that we uncovered. Whereas applications supporting more experiential and aesthetic interactions might explore opposite mappings to exploit incongruities in associations [26, 55]. Secondly, shape-to-emotion mapping could be a more readily usable mapping in design. Colour then becomes more of an add-on with mapping forced onto the ideas that emerged from exploring mappings between tangible objects and emotions. Thirdly, that the heterogeneity of association rationales expressed by participants both increase the potential design spaces that could be explored but also point to a need for flexibility and customisation. This calls for a further need to focus on creating tools that would allow users to specify their own crossmodal associations.

Overall, we consider these insights to contribute novel knowledge of how tangible sensory stimulation is perceived alongside colour and categories of emotion, which extends the rich space of crossmodal correspondences in HCI. We believe this contribution can connect to at east 3 immediate areas of computing technologies a) design of richer interactive multisensory experiences (e.g. augmenting tangible bits with more meaningful colour display to explore photo applications, or tagging content in storytelling applications, b) design of accessible technologies, particularly to support interaction between people with and without disabilities, e.g. sensory substitution devices for visually impaired and deaf people, c) design of novel interactive devices (e.g. a shape-changing mouse controller morphing into Bouba- or Kiki-like shape with colour projection to relay reassuring or disconcerting notifications as per workshop design outcomes). In education, shape/colour pairings could be embedded in tangible objects to support understanding of emotional states for young children and children with complex needs, providing more engaging sensory learning experiences.

5.6 Limitations and Future Work

In terms of limitation, it is important to note the following: Firstly, we had 30 participants only all sampled from the same institution, which is a relatively small number of participants. However, we note that it is in a higher range compared to similar studies in HCI (e.g. [15, 26, 54]). Secondly, our investigation focused on interpretations of "greater than chance" effects, which is important to clarify. The criterion that associations are determined by 'exceeding chance level' is typically used in many studies assessing crossmodal correspondences (e.g. [13, 56]), and is closely linked to the definition of Crossmodal Correspondences, describing them as associations between features that occur at rates far above chance level. Furthermore, given that we did not restrict participants to choose to associate one tangible object with one out of two or three colours, but out of 12 colours, our chance level of finding an association between a specific object and a specific colour is reduced to around 8%. As previous research has not assessed correspondences between colour and tangible objects that vary in both complexity and angularity we aimed to establish the presence of associations and whether they differ along this continuum, before comparing these associations against prevalence levels in other modalities (i.e. visual inspection of shape-colour associations). Finally, we assessed associations between emotion and touch and between colour and touch separately, however, we did not examine the potential for combined effects. Although some colours were assigned to particular features of our tangible stimuli, the extent of these associations should be examined more systematically by performing congruency tasks to assess the strength of potential associations from combined effects, e.g. degree of red to sharpness and degree of blue to roundness. The presented results suggest that the equidistant objective measures of tangible stimuli failed to create a gradual intensity of perception. Hence, future work should examine subjective tactile perceptions and its associations with visual colour.

6 CONCLUSION

We presented the first exploration of the tangible "Bouba/kiki" crossmodal correspondence with visual colour and emotions. Our findings provide evidence for the association between the tangible experience of angularity/roundedness and the visual colour-brightness and colour-hue, as well as emotional dimensions of pleasure, arousal and dominance. These results extend prior research on crossmodal correspondences by increasing our knowledge about how sensory modalities influence one another. The findings were summarised in a design space covering several interactive themes, thus providing broad insights for informing the design of potentially richer and more engaging multisensory experiences.

ACKNOWLEDGMENTS

We would to thank the participants who took part in the reported study. Oussama Metatla's research is partly supported by EPSRC Fellowship Grant EP/N00616X/2. Michael J. Proulx's research is partly funded by CAMERA 2.0, the UKRI Centre for the Analysis of Motion, Entertainment Research and Applications (EP/T014865/1).

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