It Sounds Squishy: Understanding Cross-Modal Correspondences of Deformable Shapes and Sounds

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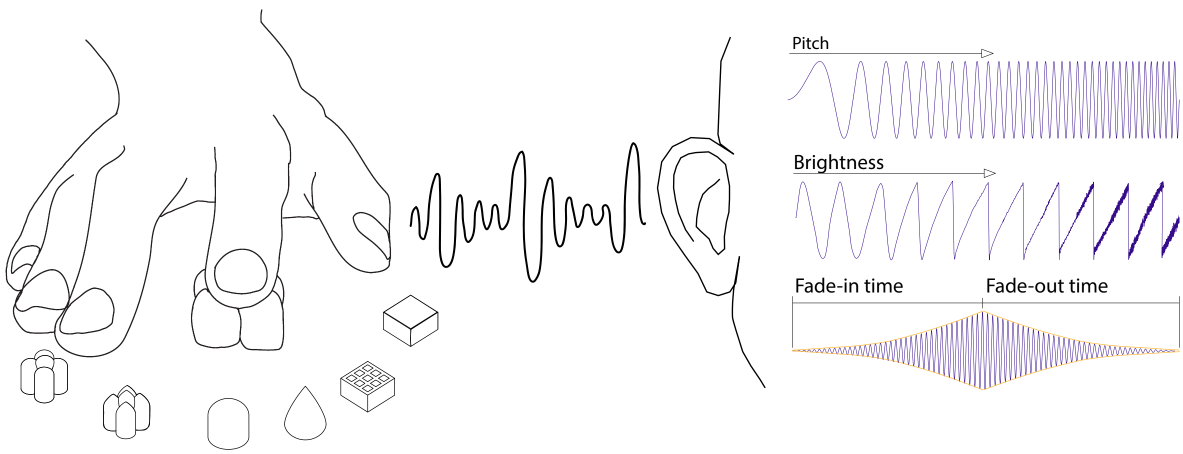

Figure 1: We explore the cross-modal correspondences with deformable shapes and sounds. Left: Stimuli took the form of poly (multi-curved), mono (single-curved), and flat (no curve) shapes (left to right). Mono and poly shapes varied in angularity (bouba, kiki), while flat shapes varied in porosity (solid, porous). We used three stiffness levels: soft, medium, and hard. Right: Participants associated shapes with the fundamental sound parameters of pitch, brightness, fade-in, and fade-out.

Abstract

Computing interfaces are becoming increasingly sophisticated, with systems that engage multiple sensory channels simultaneously. Deformable and shape-changing interfaces offer rich tactile experiences, but there is limited understanding of how they can be combined with other modes of sensory feedback. We systematically explored the audio, visual and tactile cross-modal correspondences of deformable shapes with a particular focus on auditory feedback. 50 participants were asked to associate deformable tactile stimuli, varying in stiffness and shape, with the sound qualities pitch, brightness, fade-in time and fade-out time, under visuo-tactile and tactile-only conditions. Our findings provide the first insights on how (1) shape, both its form and visibility, play a significant role in associations for pitch and brightness; (2) stiffness plays a dominant role in associations over a sound's fade-in and fade-out times. These findings are distilled into the first design guidelines for integrating auditory feedback into physical interfaces.

CCS Concepts

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

Keywords

Multisensory Interaction, Deformable, Shape, Sound, Crossmodal Correspondences, Force, Touch, Visuo-tactile, Tactile-only

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1 Introduction

Humans build internal representations of their surroundings by synthesising information that is carried by multiple perceptual channels [65]. This process of fusing multi-sensory stimuli into a coherent percept is often referred to as cross-modal integration [24, 67]. Combinations of visual, auditory, tactile, olfactory and somotosensory interaction can open up new interaction opportunities and contexts. Multimodal interaction aims to enrich human experiences of technology by engaging multiple sensory channels simultaneously [38]. Furthermore, when information is distributed across multiple sensory modalities, task performance is enhanced and cognitive workload is reduced [15, 38]. Multimodal interaction is especially helpful in scenarios where a user's visual attention is otherwise occupied. For example driving [43], flying [122], robotic teleoperation [111], manufacturing [96] and VR [14].

The use of auditory and tactile feedback is a crucial design factor that supports user interactions and enables designers to leverage intuitive mappings for interface signifiers [89]. The introduction of deformable and shape-changing interfaces represents a significant advance in tactile interaction design, offering physically dynamic and adaptable interfaces that can respond to user input [2, 7, 34, 84, 102]. Deformable input devices are increasingly being explored in domains such as wellbeing [30], simulation [84, 127] and creative technology [47, 116, 124]. This presents a new challenge: the effective integration of sensory feedback [2, 7]. For example, complex tools, such as a graphic design software, could combine different shapes and deformable properties with sounds to better communicate system states and reinforce user actions. Prior research focuses predominantly on prototypes rather than foundational principles, where fundamentals have been studied, the exploration of auditory feedback is still notably absent [31, 115, 118]. Consequently, there is a need to understand the integration of tactile, auditory, and visual elements for deformable and shape-changing interfaces, which supports designers in creating intuitive multi-sensory experiences.

Understanding the relationships between these senses is often studied through cross-modal correspondences (CCs) [113]. Our research draws on CCs as a robust method for understanding non-arbitrary connections between senses. Recently, the HCI community has started to map out fundamental design principles for tangible interfaces using CCs as the underlying foundation for the associations of shapes [69], shape-changing [31] and deformable surfaces [115, 118] across colours, emotions and visual signifiers. However, these works have not yet addressed the integration of sound with deformable input and how the tactility of the different stiffness and forms affects how associations are made. To address this gap, we formulated the following research questions:

RQ1 How do people associate temporal and timbral sound attributes with pressing different deformable shapes?

RQ2 How does the visibility of deformable shapes affect these sound-shape associations?

By answering these questions, our study provides the first set of fundamental sound design principles for designers, developers and users of deformable interfaces. The findings were collected from a within-subjects user study with 50 participants. We investigated how people associate different deformable shapes, varying in form and stiffness, with the fundamental attributes of sound: pitch, brightness, fade-in time and fade-out time (see Figure 1). To understand the impact of visibility, we explored visuo-tactile and tactile-only conditions. We also recorded and examined the participants' interaction force.

We observed that the shapes had significant effects on participants' sound associations as well as force that they applied. We found that: (1) the angularity of shapes had affected the pitch selection, which was different for the visuo-tactile and tactile-only conditions; (2) the stiffness of shapes influenced the brightness and fade-in times of the associated sounds, with harder shapes generally leading to brighter sounds and shorter fade-in times; (3) the shape affected pitch, brightness, and fade-in times differently; (4) the findings indicate that increased stiffness, and rounder shapes resulted in users exerting greater force. These findings highlight the interplay between user interactions, shape properties and auditory feedback, providing guidelines for designing more intuitive and engaging interfaces. This has significant implications for the design of deformable and shape-changing interfaces, eyes-free interaction, and multi-sensory experiences in Human-Computer Interaction (HCI). This work makes the following contributions:

(1) Empirical evidence demonstrating the associations between tactile interactions with deformable shapes and auditory feedback.
(2) Insights into the role of visual modality in sound associations and where it is relevant.
(3) Guidelines for designing physical user interfaces that combine visible, tactile, and auditory modalities.

2 Background

Computer interfaces typically rely on visual feedback, with the use of high-resolution screens to convey information to users. However, as devices become increasingly sophisticated and immersive, interaction is now spread across multiple perceptual channels [38]. This section gives an overview of auditory feedback, its key role in HCI, its under-use in the field of shaping-changing deformable interfaces and how CC research can be used to inform the design of auditory feedback in this growing research area.

2.1 Deformable and Shape-Changing Interfaces

Deformable and shape-changing interface research examines how tangible interfaces can be physically and dynamically changed through shape [2, 34] or rigidity [7, 83]. One approach to deformable interfaces is to create devices with dynamic stiffness, which is commonly achieved through pneumatics [33, 48, 87, 93, 129, 134], and mechanical actuation [83, 84, 95]. Materials such as ferrofluids [52, 53, 126] and hydrogels [58, 80, 117] can also be used to trigger magnetic fields for dynamic surface stiffness, while Microfluidics provide the opportunity to down-scale the form factor of shape-change [110, 133]. These devices can then imitate real-world properties, such as flexibility, elasticity, and viscosity, to enable a richer embodied interaction. These advancements show a rapid development toward deformable interfaces with shape and stiffness-changing properties taking the form of everyday devices.

Alongside research into implementation techniques for deformable and shape-changing interfaces, there is a growing area of research into understanding related user experiences. Early works outlined the framework for shape resolution in the form of *Morphees* [106] and follow-up work *Morphees++* [61]. These efforts provided the foundation for thinking about the types of abstract shapes and transitions possible for interaction design. Furthermore, *Emergeables* [104] and *KnobSlider* [60] build on these discussions to incorporate widget-level input and eyes-free interactions. Alongside this work, we also see more application-driven taxonomies and classifications. Sturdee and Alexander [120] classified different forms of shape-changing interfaces; several authors have explored their affordances, signifiers and constraints [34, 123]. Similarly, recent work is developing an understanding of shape perceptions [28], usability, and task performance [40, 109]. Alongside this work in HCI, there is a large body of work that explores the haptic perception of deformable material [5, 17, 22, 114]. Combined, these studies highlight the interaction potential of deformable and shape-changing displays.

2.2 Cross-modal Correspondences in HCI

CCs are the non-arbitrary perceptual mapping of stimulus features, both within and across different sensory modalities. One of the most widely-known CC phenomena is known as the "bouba-kiki" effect [101], see Figure 2, where people consistently associate the round shape with the sound "baluma" and angular shapes with "takete" [63]. This fusion of senses, often referred to as cross-modal integration, explains the tendency of people to match distinct features or dimensions of experience across different sensory modalities [113]. Moreover, CCs are often consistent across languages, cultures [21] and age groups, which underscores their potential to yield reliable and inclusive designs [73, 76].

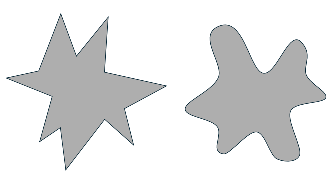


Figure 2: Image used as a test for the bouba-kiki effect. People across many cultural and linguistic communities label the left shape "kiki" and the right shape "bouba" [101].

This ability for CCs to inform design explains their prominent use in recent years in HCI literature [32, 75, 76, 118]. In particular, CCs are growing in use for studying physical interfaces, where there is an expanding need for design guidelines for novel haptic and tactile experiences. Recent work in this area has shown visual signifiers and emotions can be associations with tangible objects [69], shape-changes [31], and deformable shapes [118]. However, this prior work has, so far, focused on visual factors, colours, and emotions [115, 118]. This paper provides an important addition to a growing framework for physical interface design and multi-sensory experiences by examining associations between tactile interactions and auditory feedback.

2.3 Auditory Feedback

Auditory feedback refers to the sounds that devices transmit to users, often in response to their actions [39]. Typically, sound is used to convey information, and several categories of non-speech auditory feedback have been defined, including: auditory icons, sounds used to represent specific events, objects, and actions [41]; earcons, brief, nonverbal, distinctive audio messages to represent specific events or convey other feedback to users [6, 12]; and sonification, where data elements are mapped to sound parameters [49, 64]. Sound is critical for accessibility [59, 88], and in situations where visual feedback is undesirable, e.g., slow technology [46], and when the visual channel is occupied [43, 96, 111, 122] or already congested [72].

Musical instruments are interactive devices that translate human motion into sound [79] to enable intimate musical control and virtuosity [130]. Musical instruments often incorporate aspects of deformability, for example, strings can be plucked and stretched to modulate the qualities of the sound that is produced [97]. This requirement for expressive and nuanced interactions has informed the design of digital musical instruments [23], where there is no direct coupling between a players actions and the consequent sound [55], and physical interfaces can be easily interchanged and redesigned [51]. This has led to the development of many deformable musical instruments [8, 68, 90, 98, 124, 125], and evaluations of fabrics and shape-changing materials within this context [132, 135].

However, none of this work has studied the CCs between tactile interactions and auditory feedback. Interfaces with congruent CCs have been shown to reduce reaction times [94], and enhance memory[75] and motor learning tasks [119]. This highlights a need for more fundamental research into the perceptual associations of auditory feedback and deformable interfaces.

3 Methodology

This study aims to understand the CCs between tactile interactions and deformable shapes of varying stiffness and form, with attributes of auditory feedback. We also measured the user-applied force. These associations were measured in both visuo-tactile and tactile-only conditions. The study followed a within-subjects design.

3.1 Study Stimuli

We developed a set of physical stimuli created with different *Stiffness* levels and shape *Forms*. We primarily focused on touch and finger-based input, to align with previous HCI CC research establishing design principles for deformable input [69, 115, 118], to enable easy comparison and to extend the existing literature. Our approach takes into consideration deformable and shape-change interaction with button presses [1, 48, 110], applying pressure to non-rigid screens [52, 127] and dynamic stiffness devices [83, 87].

3.1.1 Object Shape and Forms. The individual shapes and forms (See Figure 3) are based on past literature on CCs [69, 115, 118] and shape-changing interfaces [61, 106] research.

Mono-Bouba/Kiki: This stimulus was designed based on the use of a single protruding point, following the approach used in the crossmodal study by Ludwig and Simner [70]. To ensure alignment with perceptual characteristics associated with the bouba-kiki effect,

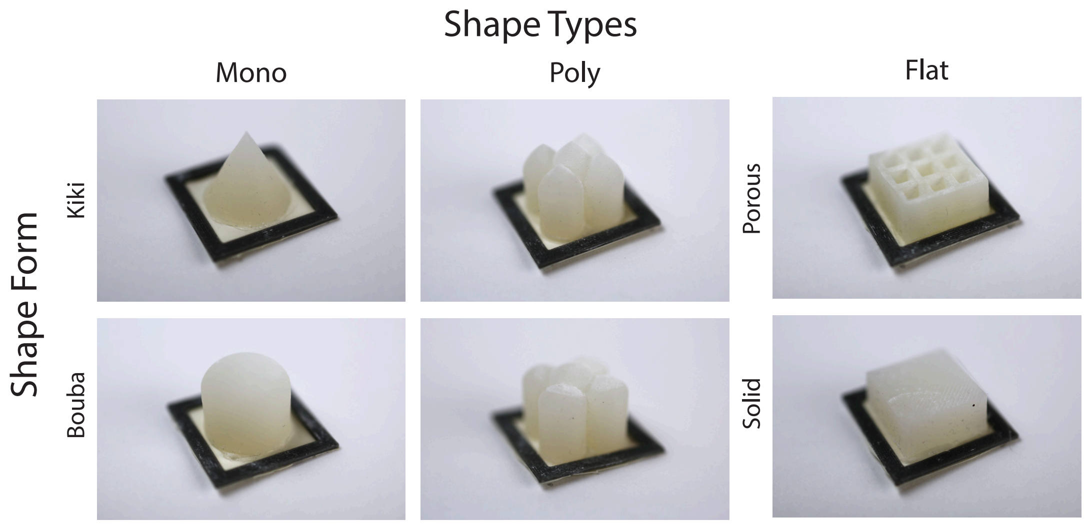


Figure 3: The three shape types used in the study (Left to right: Mono, Poly, and Flat). For Mono and Poly, Top: shows the Kiki forms of the shape, Bottom: shows the Bouba forms of the shapes). For Flat, (Top: shows the Porous forms of the shape, Bottom: shows the Solid forms of the shape). Each shape was cast three times at the three *Stiffness* levels. The image shows the Medium stiffness versions of the shapes.

we implemented the mathematical formulas provided in that study. These formulas have been employed in subsequent crossmodal correspondence research [69, 115, 118], offering a consistent basis for calibrating stimuli in accordance with established perceptual patterns.

Poly-Bouba/Kiki The complex bouba-kiki shapes were adapted from tangible stimuli used in prior crossmodal correspondence studies [69, 115, 118], which in turn built upon the single-point curvature approach introduced by Ludwig and Simner [70]. These studies extended Ludwig's original mathematical formulation to generate more intricate 3D shapes while maintaining the perceptual characteristics associated with the bouba-kiki effect. The continued use of Ludwig et al's curvature-based formula [70] across these works provides strong empirical grounding for the selection and design of our stimuli. To ensure the shapes functioned effectively as tactile buttons, we rotated the peripheral spikes so that all features could be clearly perceived under the fingertip during interaction.

Flat Solid/Porous This shape is based on the Morphees shape feature porosity [106]. Porosity refers to discontinuities or perforations within a shape, and quantifies the proportion of the perforated sections relative to the total shape area. We used shapes similar to the visual measures in Steer et al. [115], using porous and solid (non-porous) flat shapes to study the effect of surface porosity on sound association.

3.1.2 Object Stiffness. To investigate the effect of surface stiffness, we moulded soft, medium, and hard versions of each stimuli. This was informed by prior CC studies [115, 118] and user perceptions of deformation and shape [27, 28]. The chosen stiffnesses are based on the reference point of the index finger pad, and the three levels of stiffness are as follows:

Soft: Softer than the index finger pad (Shore hardness rating: 00-10).

Medium: Similar to the index finger pad (Shore hardness rating: 00-50).

Hard: Harder than the index finger pad (Shore hardness rating A-30 ≈ 00-80) .

3.1.3 Stimuli Development. The stimuli were digitally designed using Fusion 360 in combination with modelling tools and Python scripts to generate their exact curvature, angularity and porosity. The shapes were used to 3D-print moulds for casting the stimuli, using three Ecoflex silicone types for the different stiffness levels [28, 115, 118]. For consistency, all shapes were modelled to the dimentions 20mm × 20mm × 20mm. To reduce any surface texture effects, the stimuli were dusted in calcium carbonate (chalk) [28, 42, 118].

3.2 Auditory Controls

Sound is fundamentally understood and studied in terms of the four perceptual qualities: pitch, loudness, duration and timbre [56]. Pitch relates to perceived frequency, and is the quality that enables sounds to be ordered on a scale from low to high [99]. Loudness is the perceived sound pressure level (SPL), and is the property that enables sound to be ordered on a scale from quiet to loud [112]. Duration is simply the time between a sound's beginning and end [4]. Timbre is an important but more challenging attribute [74], and is described as the qualities enabling two sounds with the same pitch, loudness and duration to be differentiated [56]. A definitive set of timbre attributes is elusive [26, 44]; however, the spectral and temporal aspects of sound are considered key components [26, 50, 112]. Several researchers have found "brightness" and "attack time" to be the most salient and perceptually consistent dimensions of timbre [54, 107, 131]. Where brightness describes the presence (or absence) of high-frequency content: sounds with a high spectral centroid containing noise, harmonics and/or overtones are consistently perceived as brighter [50]. Attack time relates to the duration of a sound's fade-in from silence, and is a common label ascribed to the initial region of a sound's loudness envelope [108].

3.2.1 Parameters. For our study, we chose to expose four auditory parameters representing and controlling the significant perceptual qualities of sound/timbre described above: pitch, brightness, fade-in time and fade-out time. The first three map directly onto the fundamental perceptual attributes identified and defined above, and fade-out time controls the time taken for the sound to fade from full loudness to silence. Combined, the fade-in and fade-out times control the sound duration. We chose not to include a separate volume (or loudness) control, as this is normally set globally for computing systems, and to prevent any interactions with the fade-in and fade-out time measures, which modulate loudness with respect to time. The effects of these parameters are illustrated in Figure 4. We also chose for participants to manipulate a synthesised note, rather than designing auditory icons or earcons, to keep the design space open for a wide variety of implementations using the study's findings as a foundation.

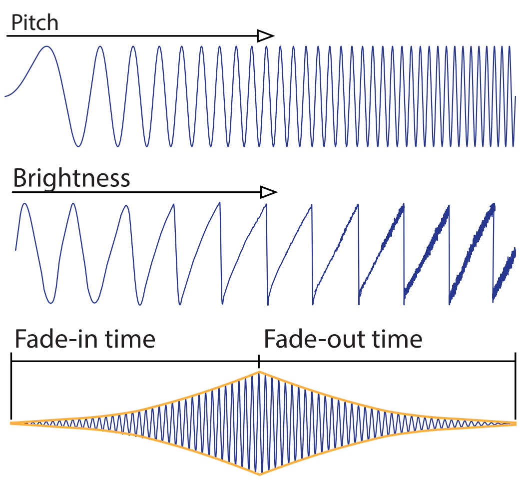


Figure 4: The effects of the four auditory parameters: top: pitch, middle: brightness, bottom: fade-in and fade-out time. Pitch increases result in a reduction in the cycle period of the waveform. Brightness increases high-frequency content, shown as sharper, noisier waveform artefacts. Fade-in controls the time taken for the sound to increase from silence to maximum loudness. Fade-out controls the time taken for the sound to decrease to silence again. Combined, the fade-in and fade-out times control the loudness envelope and duration of the sound.

3.2.2 Implementation. A simple audio synthesiser application was created, enabling participants to audition the sounds and manipulate the four auditory parameters. The application also logged all participant data. For the sound synthesis, we referred to the vocal origins of the bouba-kiki effect [100] and selected an approach based upon the source-filter model [29, 66], which is widely used in voice [62, 82] and sound synthesis (referred to as *subtractive synthesis* [19, 78]). Our model included an oscillator connected in series with a low-pass filter. Different waveforms were trialled for the application, and a sawtooth oscillator was chosen as it naively models the vibrations of the vocal folds [62], and presents a richer and fuller harmonic spectra than other simple wave types [3]. We were not aiming to simulate unvoiced speech, so non-pitched sounds were not used [82]. To prevent aliasing distortions, a PolyBLEP approach was implemented [128]. The low-pass filter was a second order recursive biquad filter built into the JUCE framework, derived from Bristow-Johnson's "EQ Cookbook" [13]. We chose not to use a band-pass filter, which is typical in voice synthesis, as this produces resonant interactions with the oscillator pitch, which could result in non-linearities in perceived sound brightness.

The implementation details for each auditory parameter is provided below, and a block diagram is shown in Figure 5:

Pitch: This parameter provided a continuous control of pitch, limited to the range of an 88-note concert piano. Spanning MIDI notes C0 to A8, or notes 21 to 108 (using the A4 = 440 Hz convention). This was then mapped to control the frequency of the oscillator using the equation $f = 440 \times 2^{(n-69)/12}$ where n is the note, and f is the frequency [86].

Brightness: To control brightness, participants could change the cutoff frequency of the low-pass filter in the range 20 Hz to 16 kHz, to approximately match the sensitivity of the human auditory system to lower frequencies. Participants controlled a real number in the range 0 - 1, which was then mapped to the cutoff frequency using the equation $c_f = 15980x^2 + 20$, where x is the input value (0 - 1) and c_f is the cutoff frequency [19].

Fade-in time: (attack) The fade-in time controlled the time taken for the sound to fade from silence to maximum loudness, and could be varied in the range 0 - 2 seconds. A cubic exponential ramp was generated in the range 0 to 1 to control the gain of the filtered oscillator, approximating the non-linear perception of volume change over time [103].

Fade-out: (decay/release) This parameter was identical to the fade-in parameter, except that it controlled the time taken for the sound to fade from maximum loudness to silence.

For clarity and simplicity, we use a normalised range of 0 - 1 for each auditory parameter throughout the remainder of the paper, unless specified otherwise. These values can be mapped easily onto frequency and time units as described above.

3.3 Measurement of User Force

To examine the CCs between touch and sound in an HCI context, we defined a set of auditory parameters that participants could manipulate to design sounds that were representative of the tactile stimuli. In addition, we were also interested in examining any effects that the stimuli had on the level of interaction force that was applied.

During the tasks, we recorded the force applied by each participant to the stimuli, as this is a key element of tactile sensory interaction with surface properties, as demonstrated in studies exploring input tasks [40, 109], the effects of shape [28], and CCs with colour and emotions [118]. Applying force to the tactile stimuli immediately activated the corresponding sounds, much like the

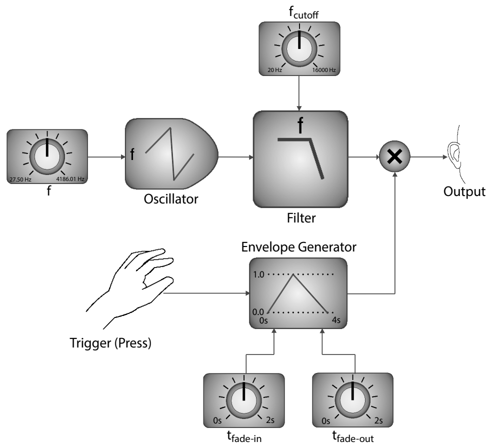


Figure 5: Block diagram of the subtractive audio synthesiser used in the study. A sawtooth oscillator is first filtered by a low-pass filter, before being multiplied by the output of an envelope generator, which is triggered by user interaction with the tactile stimuli. Combined, these components provide controls for pitch, brightness, fade-in and fade-out times.

expected behaviour of a button, ensuring the auditory feedback was directly linked to participant interactions.

3.4 Study Setup and Apparatus

Our study took place within a recording studio and was controlled to minimise unintended sensory effects (e.g. background noise, colours and shapes). Participants sat on a chair at a table opposite the researcher facilitating the session. On the table was a force-sensing platform, on to which stimuli were placed, and an iPad for participants to control the auditory feedback. In the tactile-only condition, a box covered the stimuli (see Figure 6). Participants were told to rest their wrists on the table while touching the shapes, ensuring consistency in both tactile perception and force application. The chalk used to remove the texture effects from the silicone was available for participants throughout the study.

3.4.1 Sound Interface. To the left of the stimuli, we placed an iPad Air (4th Gen). This recorded the participants' shape and stiffness associations for the different auditory parameters. The system was coded using C++ and the audio framework JUCE[1]. This was integrated with the sensor (see Figure 6), and the iPad interface connected via TouchOSC[2]. Participants could adjust the sound produced via 4 sliders, one for each auditory parameter (from Section 3.2.2). The stimulus could be pressed, generating the sound, as many times as required, with chosen parameter values continuously updating the sound output, until they reached their desired associated sounds. Because there was no conceptual absolute 0, it was not intended for participants to quantify the sound perception as a number, so they did not see any numeric values on the slider. The slider produced values between 0 and 1 for statistical analysis, although values were mapped, as described in section 3.2.2, for the synthesis process. Sliders were displayed on the screen over the top of a neutral grey (BCBCBC) background.

Participants were not provided with reference sounds, but had a brief familiarisation period where they could explore the effect of the sound parameters and gain confidence with the task.

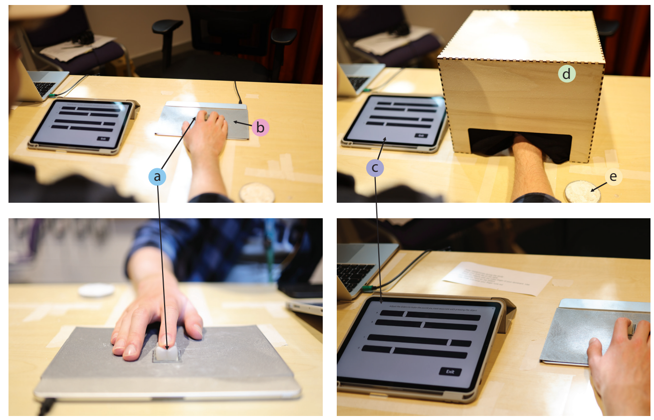


Figure 6: The study set up in both conditions. Top Left: Study setup from the participant's perspective during the visuo-tactile condition. The (a) stimulus is positioned on the (b) sensor under their index finger. Top Right: Study setup from the participant's perspective during the tactile-only condition. In both, the (c) iPad is used to answer questions (on the left). Here the (d) box cover is used to hide the stimuli (on the right). To maintain textural consistency, (e) chalk is placed nearby for regular application.

3.4.2 Force Sensing Platform. We used a Sensel Morph platform[3] as the force sensor during the study. This was used due to suitability to the task and high precision. Similar force sensors could be used to yield the same effect with appropriate calibration [28]. On the platform, we mounted a jig to hold the shapes, to ensure consistent and secure placement of the stimuli for force sensing. The platform collected force values for each task. Despite high force levels appearing more demanding on soft surfaces, performance accuracy had been seen to be high across pressure levels and stiffnesses [40]. A threshold force of 100g, one that distinguished between conscious application of force and adjustments by the facilitator was used to ensure that participants had consciously applied force to the shape before the sound could be generated.

3.4.3 Sound Equipment. The participant wore headphones throughout the study. We used Audio-Technica ATH-M30x[4] headphones and connected them to the audio output through an Audient iD4[5] interface. The use of this interface enabled the researcher to use a second pair of headphones to monitor the output. A ceiling of 70dB (A-weighted) was measured using a Sound Pressure Level (SPL) meter [81], as this is the recommended level of comfortability for

[1] JUCE: https://juce.com/
[2] TouchOSC: https://hexler.net/touchosc
[3] Sensel Morph: https://morph.sensel.com/
[4] ATH-M30x: https://www.audio-technica.com/en-gb/ath-m30x/
[5] Audient iD4: https://audient.com/products/audio-interfaces/id4/overview/

listening over a long duration [92]. This was maintained throughout the studies to ensure consistency in loudness for all participants.

3.5 Procedure and Tasks

After obtaining consent, participants were asked to complete a demographic questionnaire (gender, age, dominant hand) and rate their musical experience on a scale of 1–5, where 1 is not at all and 5 is very experienced. The experimental procedure comprised two main tasks: tactile-only and visuo-tactile. In both tasks, participants were asked to press 18 tactile stimuli with the index finger on their dominant hand with a downward force (similar to a button press) and to match this to a sound (creating a total of 36 trials per participant). During these presses, the system recorded the force applied by the participant's finger. In the visuo-tactile tasks, participants saw the stimulus while pressing it, while in the tactile-only tasks, the stimuli were hidden from view. Throughout the tasks, participants were reminded that there were no right or wrong answers. The task sequences were counterbalanced, and the order of presented stimuli was randomised to avoid ordering effects. The study concluded with a semi-structured interview, where participants were asked about their underlying rationales and strategies for sound associations. Each session took approximately 45 minutes (with around 40 minutes for the tasks and 5 minutes for the interview).

3.6 Participants

We recruited 50 participants, 24 identifying as female and 26 as male (aged 19–69 years, Mean: 40.52, SD: 12.97). During the study, participants used their dominant hand to interact with the stimuli. Of the participants, 7 were left-handed. All participants had typical or corrected-to-typical visual and auditory acuity. All participants were compensated with a £5 gift voucher. In terms of musical experience 4 participants rated themselves 5, 11 rated themselves 4, 12 rated themselves 3, 8 rated themselves 2, and 15 rated themselves 1. Our organisation's ethics review committee gave a favourable ethical opinion for this research project.

4 Results

We analysed (1) which properties of the deformable shapes affected sound associations, (2) how people interacted with the shapes, (3) what effect seeing the shape had on these associations, and (4) the qualitative responses, to understand participants' approach and rationale.

4.1 Data Analysis

Quantitative data was collected from the sound interface and force sensor. We collected 1800 responses from our 50 participants. From each response, we collected force data during the trial. A frame of force data was read every 6ms whilst the sound was activated. This force data was then post-processed by averaging the force over time for each shape interaction.

For the quantitative data, for each of the *Shapes* (Mono, Poly, Flat), we ran repeated measures analysis of variance (ANOVAs) investigating the effects of *Stiffness* (Soft, Medium, and Hard), *Visibility* (Visuo-Tactile and Tactile-Only), and *Form* (Bouba/Kiki or Porous/Solid). The ANOVAs tested for effects on sound properties pitch, brightness, fade-in, and fade-out. We used the same approach for the force data and studied the effect on applied force during the interaction with each *Shape*.

Our analysis employs Holm-corrected post hoc pairwise comparisons for significant main effects and interactions. We checked the assumption of sphericity using Mauchly's test where applicable. If sphericity was violated, we reported the results with Huynh-Feldt corrections. We mark *p-values* with p^* for significant results where $p < .05$, p^{**} for significance of $p < .01$, and p^{***} for significance of $p < .001$. We also report η^2 effect size to show the magnitude of the observed differences for main effects and Cohen's d for post hoc tests. An overview of mean values and 95% Confidence Interval (CI) upper and lower results can be seen in Appendix A [20].

Qualitative data was collected from the post-study interviews and audio-recorded with participants' consent. Recordings were transcribed, and 499 quotes were extracted. These were categorised through a deductive approach along three research themes: reflections in relation to (i) sound associations and (ii) the force applied to the stimuli. The quotes were analysed using reflexive thematic analysis [10, 11] to iteratively develop themes that encapsulated participants' key reflections. Subsequently, all quotes were categorised based on these themes. We have incorporated these quotes into relevant sections of the results.

4.2 Visual, Tactile and Auditory Associations

We used a repeated measures ANOVA (see Tables 1, 2, 3, & 4) followed by a post hoc pairwise comparison to investigate the effect of the shape's *Stiffness*, *Form*, and *Visibility* on the associated sound parameters.

4.2.1 Pitch. The Mono and Poly shapes showed significant pitch selection differences (See Table 1). For the Mono shapes, Table 1 shows significant differences in lines 1–6. A post hoc analysis for *Visibility* revealed a difference in visuo-tactile and tactile-only ($t(49) = 3.83, p < .001^{***}, d = .338$), where visuo-tactile was associated with higher pitches. The post hoc for *Form* revealed a difference in Bouba and Kiki ($t(49) = -9.011, p < .001^{***}, d = -1.060$), here Kiki shapes were selected with higher pitches. From the interviews, 76% of participants (n = 38) connected angularity with a higher pitch: *"...the more pointy ones I thought were higher-pitched and the flatter ones I thought were lower-pitched"* (P28). Roundness, observed in mono-bouba shapes, was described as impacting pitch for 12 participants. However, this was often used interchangeably with flatness: *"... a spikier shape would have a higher pitch, or like a round or flat shape would have a lower pitch"* (P34). Then, for *Stiffness*, we see a difference in the Soft and Hard ($t(49) = -3.659, p = .001^{**}, d = -.304$), where hard was associated with higher pitches. When describing pitch associations, participants were less consistent for stiffness, with 24% of participants (n = 12) associating softness with a lower pitch, and 16% (n = 8) finding softness to be higher: *"they were soft and rounded, which makes me think of a gentler sound, so they were a higher pitch"* (P21). In the *Visibility* × *Form* interactions we see a difference between all cases ($p < .001^{**}$), excluding the Visuo-tactile-Bouba and tactile-only-Bouba ($t(49) = 0.977, p = 0.331, d = 0.114$) where there was no difference. For *Visibility* × *Stiffness*, We saw a significant difference were the tactile-only-Medium was lower than tactile-only-Hard ($t(49) = -2.938, p = 0.033*, d = -0.344$). Other

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

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Mono (Bouba/Kiki)	*Visibility*	1.00	49.00	14.72	$< .001^{***}$	.026
2		*Form*	1.00	49.00	81.19	$< .001^{***}$	.252
3		*Stiffness*	1.78	87.78	6.60	$.003^{**}$	.014
4		*Visibility* × *Form*	1.00	49.00	8.42	$.006^{**}$	.011
5		*Visibility* × *Stiffness*	2.00	98.00	4.50	$.012^{*}$	.009
6		*Form* × *Stiffness*	2.00	98.00	10.12	$< .001^{***}$	.021
7	Poly (Bouba/Kiki)	*Visibility*	1.00	49.00	10.46	$.002^{**}$	.030
8		*Visibility* × *Form*	1.00	49.00	18.00	$< .001^{***}$	.053
9		*Visibility* × *Stiffness*	2.00	98.00	4.88	$.009^{**}$	.011

significances are highlighted in the *Stiffness* and *Visibility* post hoc results. For *Form* × *Stiffness*, the post hoc analysis showed significant differences in all cases ($p < .001^{***}, d > -1.486$), excluding comparisons of Bouba-Soft and Bouba-Medium, Bouba-Soft and Bouba-Hard, Kiki-Soft and Kiki-Medium, and Bouba-Medium and Bouba-Hard (all: $p > .182$). Over half of the participants (n = 27) stated that stiffness impacted their pitch associations, in conjunction with form: *"[as] the [. . .] toughness got stronger, the spikiness came less into it"* (P7).

For the Poly shapes, Table 1 shows significant differences in lines 7–9. A post hoc analysis for *Visibility* showed a difference in visuo-tactile and tactile-only ($t(49) = -3.233, p = .002^{**}, d = -.313$), where tactile-only was selected with higher pitches. In *Visibility* × *Form*, we see a difference in form had an effect in visuo-tactile-Bouba and visuo-tactile-Kiki ($t(49) = -4.537, p < .001^{***}, d = -.569$), here the kiki form was associated with higher pitches when compared to bouba in the visuo-tactile condition.

4.2.2 *Brightness.*

The Mono, Poly and Flat shapes showed significant brightness selection differences (See Table 2). Many participants were unfamiliar with brightness control and relied on instinct, with 16% of participants describing a spontaneous approach: *"I don't think I really did have a rationale with that."* (P4). Nine participants found that their pitch strategy informed their brightness choices: *"they corresponded quite a lot"* (P12).

For the Mono shapes, Table 2 shows significant differences in lines 1–3. For *Form*, kiki was associated with higher brightness, with the post hoc revealing a difference between Bouba and Kiki forms ($t(49) = -6.638, p < .001^{**}, d = -.789$). Half of the participants (n = 25) incorporated form in their brightness strategy, with 20 participants associating sharper shapes with higher brightness: *". . . pointy, expressive ones were high... flat ones were lower"* (P19). Then, for *Stiffness*, the post hoc analysis revealed a difference in Soft–Hard ($t(49) = -6.638, p < .001^{**}, d = -.789$), and Medium–Hard ($t(49) = -6.638, p < .001^{**}, d = -.789$), in both comparisons hard was associated with higher brightness. This reflected in the qualitative analysis, where 32% of participants (n = 16) considered harder shapes to be brighter: *"the harder it was, the brighter it was"* (P35), and conversely 36% of participants (n = 18) described softer shapes as less bright: *"softer shapes. . . it felt like it needed to be a softer thing. So brightness was lower"* (P25). For the *Form* × *Stiffness*, we saw significance in all combinations (all: $p < .33^{*}, d > 1.319$), excluding cases of Bouba-Soft and Bouba-Medium, Bouba-Hard; Kiki-Soft and Bouba-Medium, Bouba-Hard; Bouba-Medium and Bouba-Hard (all: $p > .1$). P41 expressed associations between stiffness and clarity: *"When it is harder, [. . .] it was more clear"*, which often reinforced their stiffness and brightness couplings.

For the Poly shapes, Table 2 shows significant differences in lines 4–6. Post hoc analysis for *Form* showed a difference between Bouba and Kiki forms ($t(49) = -6.197, p < .001^{***}, d = -.546$), where kiki was associated with higher brightness. Then, for *Stiffness*, soft was associated with lower brightness, in both Soft–Medium ($t(49) = -2.836, p = .011^{*}, d = -.258$) and Soft–Hard ($t(49) = -4.697, p < .001^{***}, d = -.427$). Stiffness was often considered more important than form: *". . . pointed shapes tended to feel brighter, but not when they're really squishy"* (P18).

For the Flat shapes, Table 2 shows significant differences in line 7. For *Stiffness*, the post hoc analysis showed significant differences in Soft–Hard ($t(49) = -2.836, p = 0.017^{*}, d = -.303$), where hard was associated with higher brightness.

4.2.3 *Fade-in.*

The Mono, Poly and Flat shapes showed significant fade-in selection differences (See Table 3). For the Mono shapes, Table 3 shows significant differences in lines 1–4. For *Form*, Bouba was associated with longer fade-in times compared to Kiki forms ($t(49) = 4.890, p < .001^{***}, d = .399$). When discussing fade-in associations, eight participants associated sharpness with a shorter fade-in: *". . . it was pointed, so it was like a short start"* (P39). For *Stiffness*, the post hoc analysis revealed a difference in Soft–Medium ($t(49) = 2.831, p = .006^{*}, d = .275$), where Soft was associated with longer fade-in times. Then again in Medium–Hard ($t(49) = 6.685, p < .001^{***}, d = .649$), and Soft–Hard ($t(49) = 3.854, p < .001^{***}, d = .374$), where hard was associated with shorter fade-in durations. Interviews showed stiffness was the most common factor for fade-in associations (n=38). 64% of participants associated a softer shape to a longer fade-in duration: *"The more squishy it was. . . felt like it was a longer sound, because your finger would feel like it was on the squishy shape for longer"* (P44). The desire for the sound to match the responsiveness of the shape impacted participants' fade-in associations, but their perception of responsiveness differed. Two participants expressed their inclination to push the fade-in time shorter for every shape, regardless of stiffness or form, P30: *"I just tended to set the attack very sharply because. . . I want response. I want to know I've hit the button"*.

Table 2: Significant effects from the ANOVA of *Visibility*, *Form*, and *Stiffness* on sound brightness associations. * indicates significant results where $p < .05$, ** significant results where $p < .01$, and *** significant results where $p < .001$.

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Mono (Bouba/Kiki)	*Form*	1.00	49.00	44.06	$.001^{**}$	.162
2		*Stiffness*	1.81	88.73	11.65	$< .001^{***}$	.047
3		*Form* × *Stiffness*	2.00	99.07	10.23	$.001^{**}$	.023
4	Poly (Bouba/Kiki)	*Form*	1.00	49.00	38.30	$< .001^{***}$	.083
5		*Stiffness*	1.52	74.23	11.19	$< .001^{***}$	.034
6		Form × Stiffness	2.00	99.79	3.15	$.047^{*}$	.008
7	Flat (Solid/Porous)	Stiffness	1.88	92.20	4.14	$.021^{*}$	.023

Table 3: Significant effects from the ANOVA of *Visibility*, *Form*, and *Stiffness* on sound's fade-in associations. * indicates significant results where $p < .05$, ** significant results where $p < .01$, and *** significant results where $p < .001$.

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Mono (Bouba/Kiki)	*Form*	1.00	49.00	23.91	$< .001^{***}$	.051
2		*Stiffness*	1.61	78.99	22.52	$< .001^{***}$	.091
3		*Visibility* × *Form*	1.00	49.00	5.31	$.026^{*}$	.009
4		*Form* × *Stiffness*	2.00	98.00	6.50	$.002^{**}$	.016
5	Poly (Bouba/Kiki)	*Stiffness*	1.85	77.98	23.18	$< .001^{***}$	.121
6		*Visibility* × *Form*	1.00	49.00	5.38	$.025^{*}$	.005
7	Flat (Solid/Porous)	*Form*	1.00	49.00	12.30	$< .001^{***}$	.028
8		*Stiffness*	1.67	81.62	29.64	$< .001^{***}$	.136

For the Poly shapes, Table 3 shows significant differences in lines 5 & 6. For *Stiffness*, Hard was associated with shorter fade durations and Soft was associated with longer fade-in times. The post hoc analysis revealed a difference in Soft–Medium ($t(49) = 3.327, p = .002^{**}, d = .327$), Medium–Hard ($t(49) = 3.569, p = .001^{**}, d = .360$), and Soft–Hard ($t(49) = 6.806, p < .001^{***}, d = .687$). For the Flat shapes, Table 3 shows significant differences in lines 7 & 8. Porosity was associated with longer fade-in times, with *Form* showing a difference between Solid and Porous ($t(49) = 3.507, p < .001^{***}, d = .278$). Then, for *Stiffness*, the post hoc analysis revealed a difference in Soft–Medium ($t(49) = 2.963, p = .004^{*}, d = .286$), Medium–Hard ($t(49) = 7.636, p < .001^{***}, d = .737$), and Soft–Hard ($t(49) = 4.672, p < .001^{***}, d = .451$), where harder shapes were associated with shorter fade-times.

4.2.4 Fade-out. For the Mono shapes, Table 4 shows significant differences in lines 1 & 2. For *Form*, Bouba was associated with longer fade-out times, with the difference between Bouba and Kiki ($t(49) = 3.791, p < .001^{***}, d = .352$). We observed that 24% of participants did consider the form of the stimuli in their fade-out perception, with five associating sharpness with a shorter fade-out times: *"The triangular ones… don't last as long when you touch it because it is pointy"* (P22). For *Stiffness*, the post hoc analysis revealed a difference in Soft–Medium ($t(49) = 2.932, p = .004^{*}, d = .297$), Medium–Hard ($t(49) = 4.509, p < .001^{***}, d = .457$), and Soft–Hard ($t(49) = 7.441, p < .001^{***}, d = .754$), where harder shapes were associated with shorter durations. 68% of participants (n = 34) attributed their fade-out strategy to stiffness of the shape. 48% of participants associated softer shapes with longer fade-out times: *"The softer ones, the decay feels more appropriate than for the harder ones"* (P30). Eleven participants explicitly stated that harder shapes should have a shorter fade-out.

For the Poly shapes, Table 4 shows significant differences in lines 3 & 4. For *Visibility*, visuo-tactile was associated with shorter durations compared to tactile-only ($t(49) = -3.061, p = .004^{**}, d = -.254$). Then, for *Stiffness*, there was a difference in Soft–Medium ($t(49) = 3.311, p = .001^{**}, d = .320$), Medium–Hard ($t(49) = 3.577, p = .001^{**}, d = .666$), and Soft–Hard ($t(49) = 6.888, p < .001^{***}, d = .346$), where harder shapes were associated with shorter durations. Fourteen participants described their strategy for the fade-out as mimicking the reformation of the shape after they had disturbed it: *"With the softer ones, you can feel the material come back… that would affect the decay of the note"* (P26).

For the Flat shapes, Table 4 shows significant differences in lines 5–8. Analysis for *Form* showed a difference between Porous and Solid, where the Solid was associated with shorter fade durations ($t(49) = 3.600, p < .001^{***}, d = .282$). The post hoc analysis for *Stiffness* revealed a difference in Soft–Medium ($t(49) = 2.755, p = .007^{*}, d = .281$), Medium–Hard ($t(49) = 5.695, p < .001^{***}, d = .581$), and Soft–Hard ($t(49) = 8.450, p < .001^{***}, d = .862$), where harder shapes were associated with shorter durations. For *Visibility* × *Form*, the visuo-tactile-Porous had longer fade-out times than visuo-tactile-Solid ($t(49) = 4.313, p < .001^{***}, d = .452$), tactile-only-Porous had longer fade-out times than visuo-tactile-Solid ($t(49) = 3.612, p = .002^{**}, d = .394$), and visuo-tactile-Solid had shorter fade-out times than tactile-only-Solid ($t(49) = -2.739, p = .029^{*}, d = -.282$). The intersection of *Form* × *Stiffness* showed significant difference in comparisons of Porous-Soft to Solid-Medium ($t(49) = 4.993, p < .001^{***}, d = .678$), Porous-Hard ($t(49) =$

Table 4: Significant effects from the ANOVA of *Visibility, Form,* and *Stiffness* on sound's fade-out associations. * indicates significant results where $p < .05$, ** significant results where $p < .01$, and *** significant results where $p < .001$.

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Mono (Bouba/Kiki)	*Form*	1.00	49.00	14.37	$.007^{**}$	.017
2		*Stiffness*	1.77	86.91	28.10	$< .001^{***}$	.227
3	Poly (Bouba/Kiki)	*Visibility*	1.00	49.00	9.37	$.004^{**}$	.022
4		*Stiffness*	1.00	49.00	23.73	$< .001^{***}$	.102
5	Flat (Solid/Porous)	*Form*	1.00	49.00	12.96	$< .001^{***}$	.024
6		*Stiffness*	1.56	79.32	37.15	$< .001^{***}$	.155
7		*Visibility* × *Form*	1.00	49.00	0.39	$.018^{*}$	.009
8		*Form* × *Stiffness*	2.00	98.00	7.10	$.001^{**}$	.016

$7.364, p < .001^{***}, d = .933$) and Solid-Hard ($t(49) = 7.261, p < .001^{***}, d = .986$), where Porous and Soft was associated with longer fade-out durations. Similarly, Solid and Hard were together associated with shorter fad-out durations, revealed in comparisons of Solid-Soft to Solid-Medium ($t(49) = 3.811, p = .001^{**}, d = .483$), Porous-Hard ($t(49) = 5.437, p < .001^{***}, d = .738$), and Solid-Hard ($t(49) = 6.24, p < .001^{***}, d = .791$). This showed significance again in comparisons of Porous-Medium to Solid-Medium ($t(49) = 5.119, p < .001^{***}, d = .599$), Porous-Hard ($t(49) = 3.612, p < .001^{***}, d = .854$), and Solid-Hard ($t(49) = 6.678, p < .001^{***}, d = .907$).

4.3 Force Input

We used a repeated measures ANOVA followed by a post hoc pairwise comparison to investigate the effect of *Visibility*, *Form*, and *Stiffness* on the force users applied during tasks (see Table 5). Table 10 shows an overview of the force applied to each shape under each condition.

For the Mono shapes, Table 5 shows significant differences in lines 1–3. A post hoc analysis on the *Form* showed a significant difference between Bouba and Kiki ($t(49) = 4.968, p < .001^{***}, d = .368$), where The Bouba form had greater force applied. This aligned with participants' comfort considerations when applying force: *"maybe I didn't press the spiky ones as hard, because they can be a bit painful"* (P34). The *Stiffness* post hoc analysis showed a significant difference in Soft compared to Medium stiffness ($t(49) = -2.725, p = .015^{*}, d = -.175$) and the Hard stiffness ($t(49) = -4.714, p < .001^{***}, d = -.302$), where the soft had less force applied. P14 described a hesitation towards applying equal pressure on the mono-kiki-hard shape: *"I didn't want to slam my finger into a point"*. Despite no overall effect from visibility, there was an interaction with stiffness. In this case of significant difference where seen in visuo-tactile-Soft is lower than visuo-tactile-Medium ($t(49) = -3.065, p = .033^{*}, d = -.244$), visuo-tactile-Soft lower than visuo-tactile-Hard ($t(49) = -5.37, p < .001^{*}, d = -.427$), and tactile-only-Soft lower than visuo-tactile-Hard ($t(49) = -3.252, p = .02^{*}, d = .339$).

For the Poly shapes, Table 5 shows significant differences in lines 4–8. A post hoc on the *Visibility* showed a difference between visuo-tactile and tactile-only ($t(49) = 3.098, p = .003^{**}, d = .229$), where the visuo-tactile form had greater force applied. 32% of participants (n = 16) found their applied force varied between visibility conditions, and 3 participants felt their pressure increased in the visuo-tactile condition, as they were more confident in the interaction: *"I was more confident when I could see the spikes"* (P14). A post hoc analysis on *Form* showed a difference between Bouba and Kiki ($t(49) = -2.426, p = .019^{*}, d = -.124$), where the kiki form had greater force applied. The *Stiffness* post hoc analysis showed a significant difference in Hard compared to Soft ($t(49) = -6.029, p < .001^{***}, d = -.476$) and Medium ($t(49) = 3.098, p < .001^{***}, d = -.609$), where the hard shapes had greater force applied. For example, P50 compared different shapes and their required pressure: *"... the B3 [mono-bouba-hard] shape... they were quite easy to press down... A1 [poly-bouba-soft] to A6 [poly-kiki-hard] felt stronger in structure"*.

For the Flat shapes, Table 5 shows significant differences in lines 9–12. For *Visibility*, there was a difference in pressure applied between visuo-tactile and tactile-only ($t(49) = 2.859, p = .006^{**}, d = .248$). The *Stiffness* post hoc analysis showed a difference in Soft compared to Medium stiffness ($t(49) = -4.937, p < .001^{***}, d = -.315$), and the Hard stiffness ($t(49) = -5.593, p < .001^{***}, d = -.357$), where the harder shapes had greater force applied. Despite there being no overall effect from form, there was an interaction with stiffness. Noteworthy cases where Porous-Soft and Solid-Soft ($t(49) = -2.941, p = .027^{*}, d = -.264$), Porous-Medium and Solid-Medium ($t(49) = -3.027, p = .023^{*}, d = -.272$), Porous-Medium and Porous-Hard ($t(49) = -3.499, p = .005^{**}, d = -.309$), and Porous-Hard and Solid-Hard ($t(49) = 2.911, p = 0.027^{*}, d = .262$). This could be due to porosity increasing a sense of softness. Where form was viewed to impact the force applied, 12 participants referenced the stiffness of the stimuli:*"For the more softer ones... there's instinctively more force put towards it"* (P22).

5 Discussion

The results of our study revealed (i) the significant influence that stiffness has on the associated sound fade-in and fade-out times, (ii) specific visibility and form effects for angled shapes, and (iii) the differences in applied and perceived force when pressing deformable shapes. We discuss these trends and their potential impact on the future design of physical user interfaces.

5.1 Visual, Tactile and Auditory Associations

To illustrate the associations of the tactile stimuli with auditory feedback measures, visualisations of the average sound associated

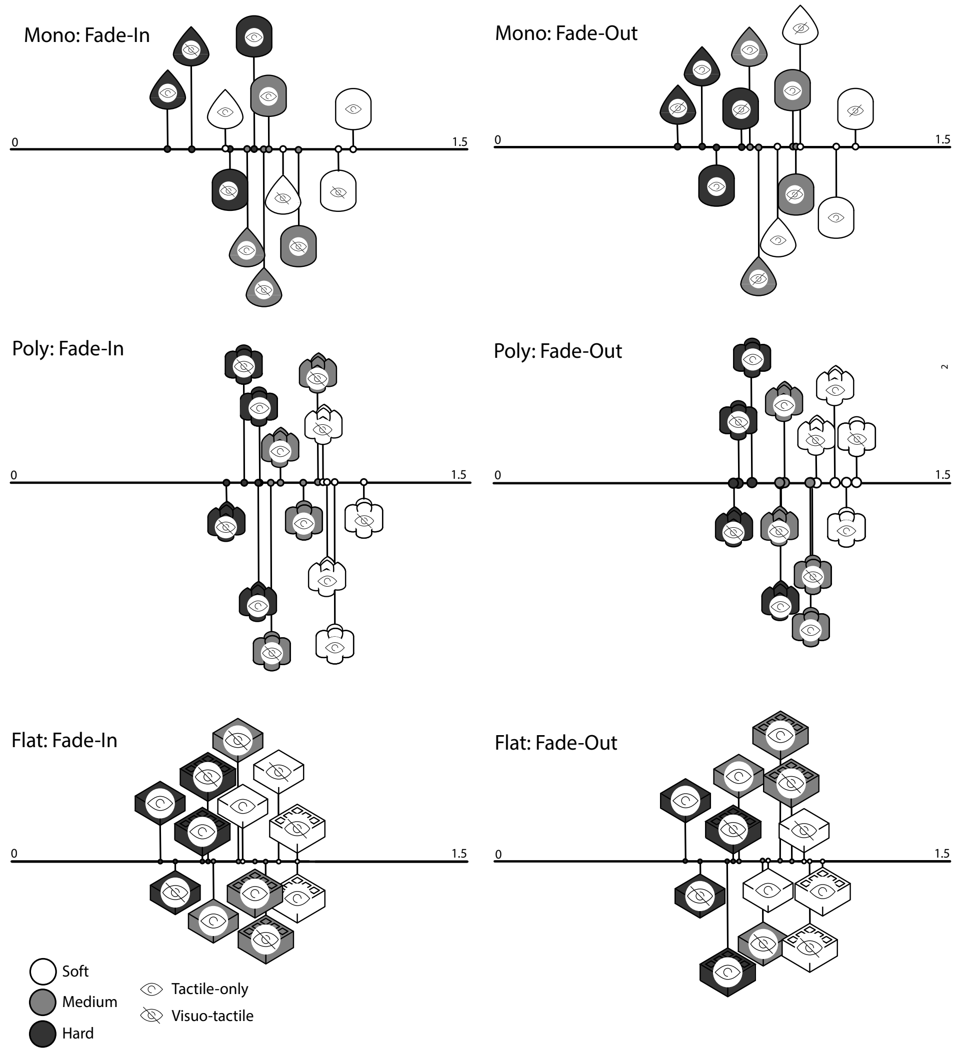


Figure 7: Overview distribution of fade-in (left) and fade-out times for each shape for each visibility condition. Each fade duration is plotted on axes for 0 to 1.5 seconds. Normalised statistical results were converted to times in seconds using the mappings described in section 3.2.1.

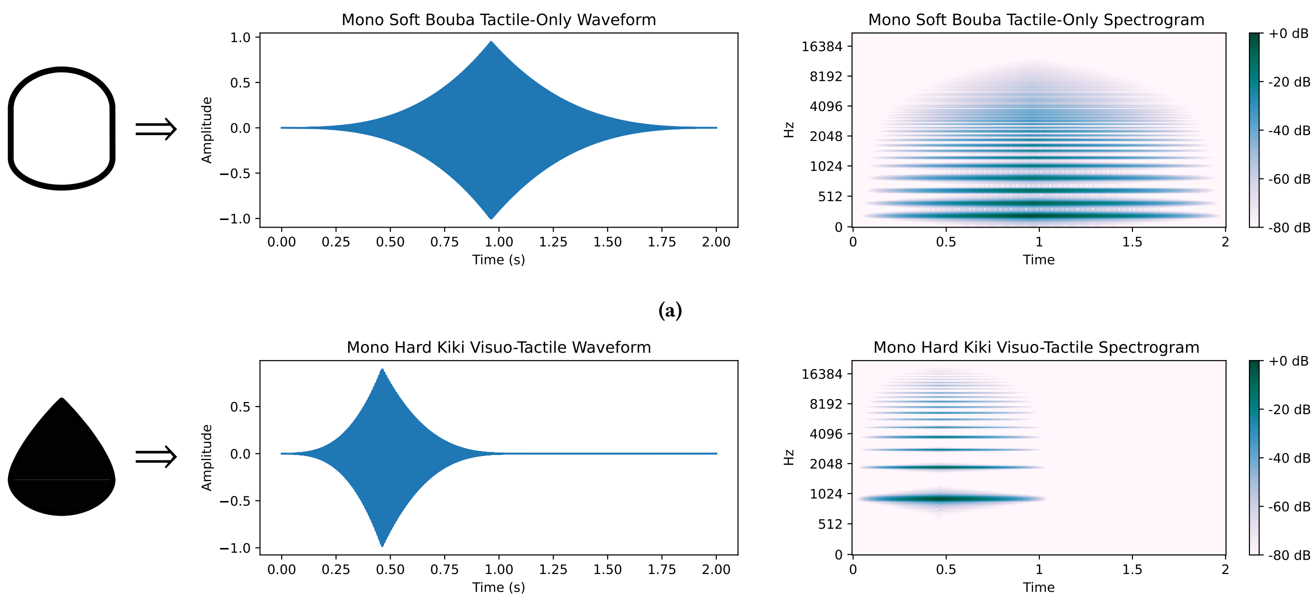
with the mono-bouba and mono-kiki shapes are plotted in Figure 8, for additional plots of the average poly and flat shapes see Appendix A.

5.1.1 Shape, Stiffness and Visibility Associations with Pitch. The shape of the mono tactile stimuli had a large effect on pitch selection (n^2 = .252), where the bouba shape was associated with lower, and the kiki shape with higher pitched sounds. This association was also reflected in the qualitative results, with 76% of participants correlating sharpness with a higher pitch. This aligns with previous scientific studies that have rooted bouba-kiki effect in the physical properties of objects [57], where round items are mathematically bound to produce lower-frequency sounds [35]. We also saw that stiffness affects pitch selection for the mono bouba-kiki shapes, with softer shapes associated with lower-pitched sounds. This corroborates previous audio-tactile research where higher pitches were associated "harder" tactile metaphors [25]. The flat shapes did not show significant pitch associations, highlighting the neutrality of the most ubiquitous button design and the importance of shape complexity in pitch associations.

Visibility also played a role in these tactile-auditory associations. On average, visible shapes were associated with higher pitches ($Mean$ = .54) than the tactile-only condition ($Mean$ = .48). However, this trend was not consistent for all shapes and stiffness levels. Furthermore, the participants' strategies highlighted a desire for consistency across visibility conditions (50%) and often without a clear rationale. Participants noted that their strategies were not impacted by the visual modality (36%), suggesting no definitive trend across shape and stiffness. This visibility effect diverges from previous findings related to deformable shapes concerning emotional and colour associations, where visibility was found to play a

Table 5: Significant effects from the ANOVA of *Visibility*, *Form*, and *Stiffness* on force applied. * indicates significant results where $p < .05$, ** significant results where $p < .01$, and * significant results where $p < .001$.**

Line #	Shape	Effect	df	Residuals	F	p	n^2
1	Mono (Bouba/Kiki)	*Form*	1.00	49.00	24.68	<.001***	.077
2		*Stiffness*	1.68	82.06	11.20	<.001***	.035
3		*Visibility* × *Stiffness*	2.00	98.00	3.54	.033*	.006
4	Poly (Bouba/Kiki)	*Visibility*	1.00	49.00	9.60	.003**	.028
5		*Form*	1.00	49.70	5.89	0.019	.008
6		*Stiffness*	1.60	81.70	32.94	<.001***	.146
7		*Visibility* × *Stiffness*	1.84	89.99	3.27	.047*	.008
8		*Form* × *Stiffness*	1.44	70.51	13.59	<.001***	.032
9	Flat (Solid/Porous)	*Visibility*	1.00	49.0	8.18	.006**	.035
10		*Stiffness*	1.94	95.16	18.69	<.001***	.058
11		*Visibility* × *Stiffness*	2.00	98.00	3.76	.027*	.008
12		*Form* × *Stiffness*	1.52	74.43	12.62	<.001***	.036



(a)

(b)

Figure 8: Shape, waveform and spectrogram plots for (a) the average mono soft bouba tactile-only sound and (b) the average mono hard kiki visuo-tactile sound.

minimal role [115]. This discrepancy highlights the unique influence of visual elements on pitch associations, even when tactile properties such as stiffness and shape are prominent.

5.1.2 Shape and Stiffness Associations with Sound Brightness. The mono tactile stimuli had a large effect on brightness ($n^2 = .162$), with kiki shapes associated with brighter sounds. The poly shapes resulted in similar associations, although with medium effect ($n^2 = .083$). Despite this clear association, interviews highlighted uncertain (22%) and instinctual approaches (16%). Brightness presented a less obvious auditory response than the other parameters, which may have made it harder for participants to articulate their strategy. As with the pitch associations above, this correspondence could relate to the "physical properties" explanation of the bouba-kiki effect [35]: as round (bouba) items are bound to produce lower-frequency spectra and brightness has a robust connection with a sound's spectral centroid [45]. Conversely, kiki features were associated with higher sound brightness. Again, this pattern did not extend to flat shapes in solid and porous forms, suggesting that flat shapes are more neutral in their associations. Across all three shape types studied, the stiffness of the stimuli had a small effect on brightness, with harder shapes associated with brighter sounds, while softer shapes corresponded with less bright sounds. This relationship could again relate to how the material world shapes sound; for example, in acoustics, softer furnishings have a filtering effect that reduces the brightness of reverberation [36]. Similarly, softer materials used in percussion mallets produce sounds with lower spectral centroids (e.g. lower brightness) [37].

5.1.3 Stiffness and Shape Associations with Fade-in and Fade-out Times.

Across all shape types, the stiffness of the tactile stimuli had a significant medium effect on the fade-in times. Harder shapes were associated with shorter fade-in times, and conversely, softer shapes with longer fade-in times. That is, harder shapes are associated with sounds that reach maximum loudness more quickly than softer shapes. The kiki and solid forms had shorter fade-in times, while the bouba and porous forms had longer fade-in times. Again the physical properties of sound could again explain this relationship, where rounded shapes are associated with sounds that have high temporal continuity, e.g. slower changes with respect to time [35].

For fade-out times, softer, porous and mono-bouba shapes were associated with longer fade-out times, while harder, solid and mono-kiki shapes had shorter fade-out times. This indicates that softer shapes are associated with sounds that decay more gradually, creating a prolonged and fading auditory effect. For poly shapes, fade-out times were not affected by form but were influenced by visibility. Unseen poly shapes were associated with longer fade-out times, suggesting that the absence of visual cues leads to prolonged sound decay. Visible poly shapes had shorter fade-out times. This is in line with the qualitative data, which showed that participants' selection of fade-in and fade-out times was predominately influenced by stiffness (68%). Here, we also saw participants adjust their fade duration in response to the force they applied and the physical deformation of the shapes (28%), indicating a possible link between tactile feedback and time.

5.2 Auditory Feedback and Force Input

The results indicate that stiffness significantly influenced the force applied by participants across all shapes during the tasks. This finding suggests a direct correlation between the hardness of the shapes and the amount of force exerted by participants. Specifically, as the stiffness of the shapes increased, participants applied greater force. For shapes with varying angularity, notably those categorised as mono and poly, shapes in the bouba form elicited higher levels of force. The interviews revealed that tactile comfort was a factor with 16% of participants explaining their tendency to apply lower forces on the kiki shapes. This has been seen in other work on deformable shapes [115]. More broadly, these findings further advance our understanding of deformable force input [40, 109].

6 Design Implications

Our findings have significant implications for multi-sensory experiences and eyes-free interaction in HCI. Users can more easily understand and interact with an interface when the auditory and visual/tactile elements are harmonised [9, 91, 113]. By leveraging the associations between sound and tactile stimuli, designers can create more intuitive and engaging user interfaces. Our results provide a foundation upon which more ecologically valid studies can be built, ensuring that subsequent research is grounded in solid, fundamental findings. In this section, we distil our findings into actionable design recommendations to enable this work to be used by interface researchers, designers, and practitioners.

6.1 Implications for Sound Pitch and Brightness Mapping

Design recommendations 1–2 support the mapping of sound pitch and brightness to deformable and shape-changing interfaces.

Design Recommendation 1: Rounder shapes should be used in conjunction with lower pitched and low-brightness sounds, while spikier shapes should be used with higher pitched and higher brightness sounds.

Design Recommendation 2: Low-brightness sounds should be used in conjunction with softer shapes, while harder shapes should be used with sounds with higher brightness.

These recommendations show that designers should aim to pair rounder shapes with lower-pitched, low-brightness sounds and spikier shapes with higher-pitched, high-brightness sounds. Going forward, these fundamental sound mapping could be used for notifications or alerts. For example, spikier shapes with high-pitched sounds can indicate danger or obstacles, while rounder shapes with low-pitched sounds can signify safe zones or rewards. Other applications could be aimed at relaxation or meditation [30].

6.2 Implications for Sound Time Envelope Mapping

Design recommendation 3 focuses on the mapping of the sound envelope, which combines the fade-in and fade-out time of sounds to deformable and shape-changing interfaces.

Design Recommendation 3: Longer fade-in and fade-out times should be used in sounds for softer surfaces and rounder or porous shapes, while harder surfaces and spikier, or solid, shapes should be used with sounds that have shorter fade-in and out times.

Everyday interactions such as document scrolling and image zooming are common examples of deformable input methods [16, 85, 121]. In these types of interactions, dynamic stiffness can be used for haptic feedback to communicate the scroll or zoom position [71]. This could be accompanied by fade-in and fade-out sounds that match the stiffness of multi-modal feedback, acting similarly to "clicks" on dials and sliders [60, 77, 129].

6.3 Implications for Input and Visual-tactile Interactions

Alongside recommendations 1–3, design recommendations 4 and 5 have wider implications for the input of force on and visibility of physical interfaces with sound feedback.

Design Recommendation 4: Sound properties of brightness, fade-in and fade-out can be used interchangeably in eyes-free and eyes-on contexts where stiffness and/or shapes are used in conjunction.

Design recommendation 4 describes how associations for properties of brightness, fade-in, and fade-out can be used regardless of interface visibility. Instead, the stiffness and/or shapes have a more significant effect on the associations. This is partially relevant to work that outlines the benefits of tangibility and shape-change in eyes-free interactions [18, 104, 105]. Our findings imply that these particular sound properties can be used interchangeably in eyes-free and eyes-on contexts, which could allow users to use more modalities with concurrent audio feedback. The use of sound and tactile feedback could aid in understanding the system state (using recommendations 1–3) and maintain multi-modal harmony throughout the interaction.

Design Recommendation 5: When combining sounds with deformable interfaces, the input of lower force should be applied to harder, pointier shapes, while higher forces are applied to softer, rounder shapes.

Design recommendation 5 gives researchers and designers insight into the force interaction applied to deformable and shape-changing interfaces when used with sound. This should be taken into consideration for deformable input tasks [40, 109].

6.4 Summary

Our design recommendations highlight how to use sound, shape and stiffness to design intuitive interface mappings. These recommendations contribute to the growing body of work [31, 69, 115, 118] that provides actionable insights that researchers and designers can directly apply to interface design. Our contributions will help ensure that sound feedback aligns intuitively with the dynamic changes in shape and deformation. We anticipate these principles being applied not only to traditional UI components like buttons but also to innovative applications involving deformable surfaces.

7 Limitations and Future Work

This paper contributes to the understanding of how to design and develop sounds that integrate with deformable and shape-changing interfaces. Our foundational results are based on tightly-controlled psychological testing, however, many factors, such as external environment sounds and task semantics, might influence the associations found in this study. To further validate and refine these findings, future work should focus on applying and testing these principles within ecologically valid studies and real-world scenarios, some of which are implied in our design implications (Section 6). Exploring the findings in these real-world scenarios ensures that sound design principles are not only theoretically robust but also practical and effective in everyday applications. While this study presents foundational considerations for incorporating CCs between touch, sound and vision, into the design of deformable interfaces, future research could expand on these findings. For example, this study explored tactile associations with monaural sounds. As shape-changing interfaces are dynamic, a promising future direction would be the investigation of sound spatialisation and how the perceived location and movement of a sound source could affect the perception of interactions with deformable shapes. Additionally, this study intentionally constrained the range of sounds that were examined to enable the fundamental properties of sound to be explored. Future work could examine whether the findings apply to more complex synthesised sounds and naturally occurring sounds. Examining further sound and timbral attributes beyond those explored here (see Ziemer [136] for an extensive list) would also make a helpful addition to this work. Perceived loudness and its impact on shape and softness associations would also be beneficial to explore in future studies. One possible approach would be to reverse the method employed here, using recorded sounds as the stimuli, where the auditory properties are known, and asking participants to associate each sound with different deformable, tactile shapes. Additionally, further studies could include the design of auditory icons and earcons integrated with deformable input devices, to compare these findings with those of a more commonly used interaction context. This could also be examined for use in assistive technology, where the integration of shape and sound could further diversify the feedback available to users. This opens up possibilities for practical applications in a music performance context, providing guidelines for a sound-led design process, by designing interfaces for specific auditory feedback, e.g., when designing the interface for a particular digital musical interface for an existing sound process.

8 Conclusion

This paper provides the first set of foundational sound design principles for deformable and shape-changing interfaces. We examined 50 participants' cross-modal associations between tactile interactions with deformable shapes and sound. We found that: (1) the angularity of shapes significantly affected pitch selection, with visibility playing a crucial role, with visuo-tactile and tactile-only conditions resulting in different pitch associations; (2) the hardness or softness of shapes influenced their associated brightness and fade-in times, with harder shapes generally having brighter sounds and softer shapes having longer fade-in times; (3) the form of the shapes affected pitch, brightness, and fade-in times differently; (4) increased stiffness resulted in greater force exerted on all shapes, specifically with shapes in the bouba form requiring higher force levels. Design guidelines accompany these findings to provide designers and researchers with the framework for developing sounds for the next generation of physical user interfaces.

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A Detailed Results & Audio Plots

We report the detailed results of the user responses and force values in Tables 6–10. Note that all sound parameters are normalised into the range 0 to 1 in these results. For a description of how these values were mapped onto the synthesis parameters, see section 3.2.1. We also provide graphs for each condition (See Figures 9– 13). Finally, Figure 15 shows additional sound plots of the average poly and flat shapes.

Table 6: Mean values and Confidence Intervals (CI ±95%) for Pitch associations made during the tasks in each condition (values normalised 0 to 1).

			Visuo–Tactile Condition			Tactile–Only Condition		
				95% CI Mean			95% CI Mean	
Shape	Form	Stiffness	Mean	Upper	Lower	Mean	Upper	Lower
Mono	Bouba	Soft	0.428	0.481	0.375	0.403	0.449	0.357
		Medium	0.443	0.492	0.394	0.398	0.446	0.349
		Hard	0.383	0.438	0.329	0.443	0.495	0.391
	Kiki	Soft	0.631	0.685	0.576	0.622	0.674	0.571
		Medium	0.663	0.708	0.618	0.675	0.723	0.628
		Hard	0.703	0.754	0.652	0.710	0.760	0.660
Poly	Bouba	Soft	0.455	0.511	0.400	0.425	0.473	0.376
		Medium	0.472	0.513	0.431	0.463	0.505	0.422
		Hard	0.454	0.505	0.403	0.445	0.491	0.400
	Kiki	Soft	0.481	0.524	0.438	0.499	0.549	0.449
		Medium	0.540	0.579	0.501	0.538	0.580	0.496
		Hard	0.576	0.627	0.524	0.587	0.636	0.538
Flat	Porous	Soft	0.411	0.458	0.363	0.417	0.460	0.374
		Medium	0.398	0.438	0.358	0.413	0.454	0.371
		Hard	0.401	0.441	0.361	0.395	0.442	0.348
	Solid	Soft	0.385	0.431	0.340	0.403	0.445	0.361
		Medium	0.393	0.440	0.346	0.390	0.442	0.339
		Hard	0.368	0.420	0.317	0.370	0.427	0.313

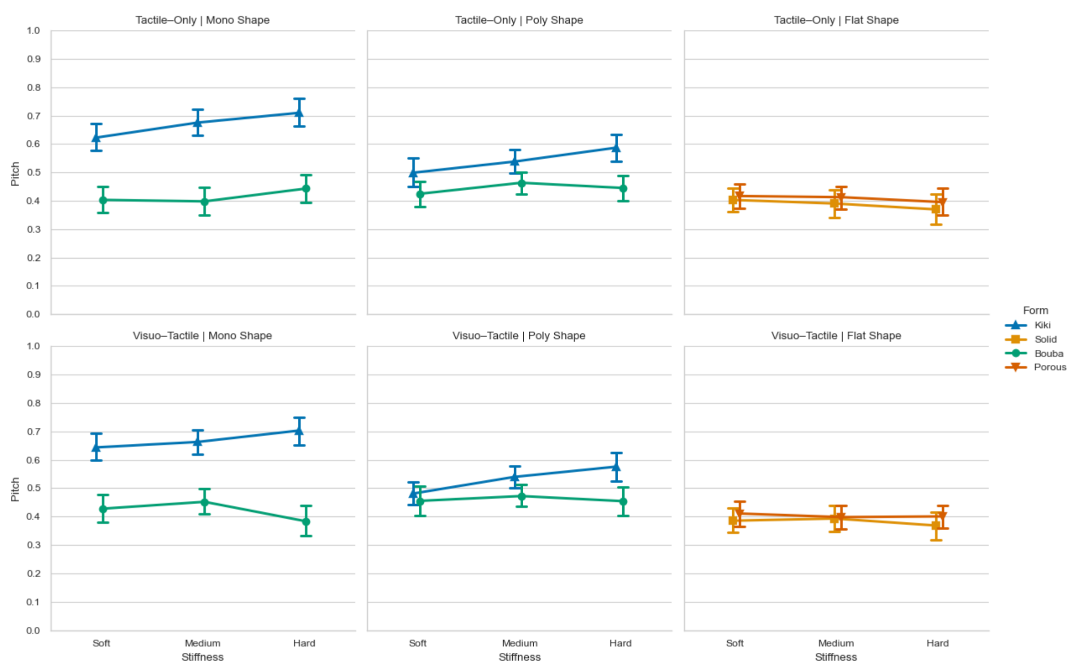


Figure 9: Mean pitch associations (y-axis) across stiffness levels (x-axis: Soft, Medium, Hard), separated by visibility (rows: Tactile–Only, Visuo–Tactile) and shape type (columns: Mono, Poly, Flat). Each line indicates a form category (Kiki, Bouba, Solid, Porous). Error bars represent ±95% confidence intervals.

Table 7: Mean values and Confidence Intervals (CI ±95%) for Brightness associations made during the tasks in each condition (values normalised 0 to 1).

			Visuo–Tactile Condition			Tactile–Only Condition		
				95% CI Mean			95% CI Mean	
Shape	Form	Stiffness	Mean	Upper	Lower	Mean	Upper	Lower
Mono	Bouba	Soft	0.373	0.428	0.318	0.383	0.443	0.324
		Medium	0.377	0.428	0.325	0.398	0.454	0.342
		Hard	0.413	0.479	0.346	0.407	0.462	0.352
	Kiki	Soft	0.462	0.523	0.402	0.476	0.536	0.417
		Medium	0.558	0.620	0.496	0.536	0.593	0.479
		Hard	0.648	0.715	0.580	0.660	0.722	0.598
Poly	Bouba	Soft	0.389	0.441	0.337	0.336	0.384	0.288
		Medium	0.426	0.474	0.378	0.412	0.464	0.360
		Hard	0.448	0.507	0.389	0.467	0.522	0.411
	Kiki	Soft	0.450	0.503	0.398	0.430	0.488	0.371
		Medium	0.517	0.566	0.467	0.464	0.515	0.413
		Hard	0.583	0.644	0.523	0.607	0.662	0.552
Flat	Porous	Soft	0.390	0.443	0.336	0.370	0.429	0.311
		Medium	0.397	0.445	0.349	0.382	0.433	0.331
		Hard	0.507	0.563	0.451	0.397	0.451	0.343
	Solid	Soft	0.388	0.441	0.335	0.374	0.425	0.323
		Medium	0.420	0.484	0.357	0.408	0.462	0.355
		Hard	0.439	0.510	0.369	0.421	0.485	0.357

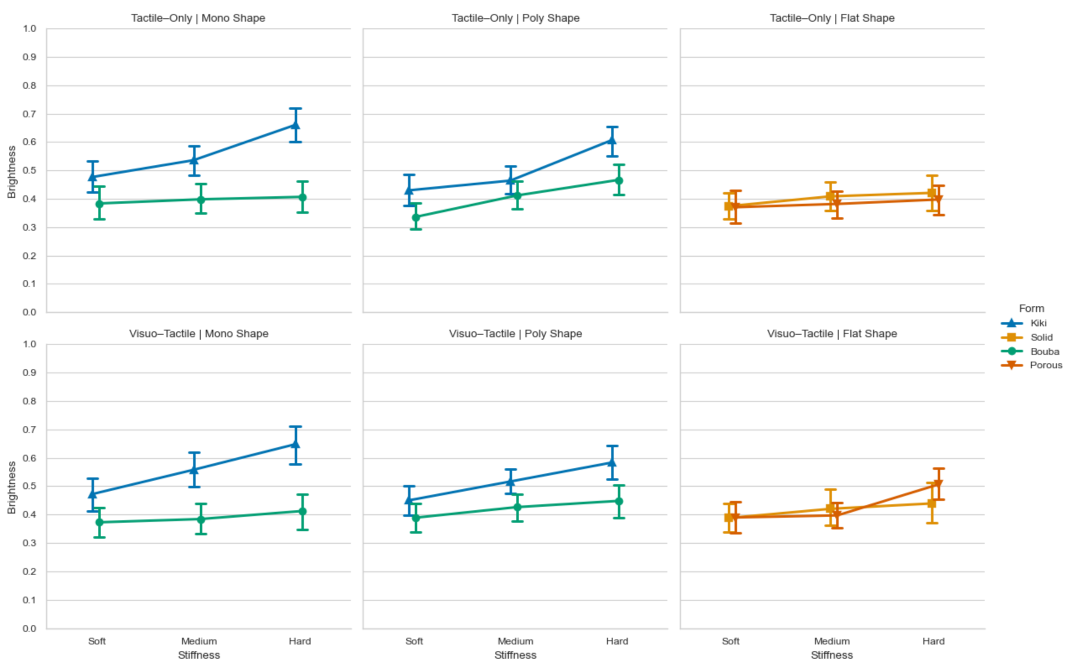


Figure 10: Mean brightness associations (y-axis) across stiffness levels (x-axis: Soft, Medium, Hard), separated by visibility (rows: Tactile–Only, Visuo–Tactile) and shape type (columns: Mono, Poly, Flat). Each line indicates a form category (Kiki, Bouba, Solid, Porous). Error bars represent ±95% confidence intervals.

Table 8: Mean values and Confidence Intervals (CI ±95%) for Fade-in associations made during the tasks in each condition (values normalised 0 to 1).

			Visuo–Tactile Condition			Tactile–Only Condition		
				95% CI Mean			95% CI Mean	
Shape	Form	Stiffness	Mean	Upper	Lower	Mean	Upper	Lower
Mono	Bouba	Soft	0.503	0.554	0.453	0.482	0.550	0.414
		Medium	0.380	0.431	0.329	0.378	0.439	0.318
		Hard	0.352	0.415	0.289	0.326	0.386	0.266
	Kiki	Soft	0.308	0.367	0.250	0.411	0.470	0.351
		Medium	0.345	0.407	0.283	0.373	0.429	0.317
		Hard	0.231	0.288	0.173	0.258	0.315	0.202
Poly	Bouba	Soft	0.465	0.521	0.408	0.514	0.566	0.462
		Medium	0.424	0.478	0.370	0.376	0.429	0.323
		Hard	0.354	0.412	0.296	0.325	0.380	0.269
	Kiki	Soft	0.447	0.500	0.393	0.460	0.520	0.401
		Medium	0.388	0.439	0.337	0.439	0.500	0.378
		Hard	0.308	0.366	0.250	0.355	0.417	0.292
Flat	Porous	Soft	0.478	0.534	0.421	0.477	0.535	0.418
		Medium	0.405	0.460	0.351	0.426	0.481	0.371
		Hard	0.319	0.375	0.264	0.326	0.383	0.270
	Solid	Soft	0.385	0.445	0.325	0.447	0.512	0.383
		Medium	0.339	0.391	0.287	0.382	0.447	0.316
		Hard	0.253	0.310	0.196	0.283	0.344	0.223

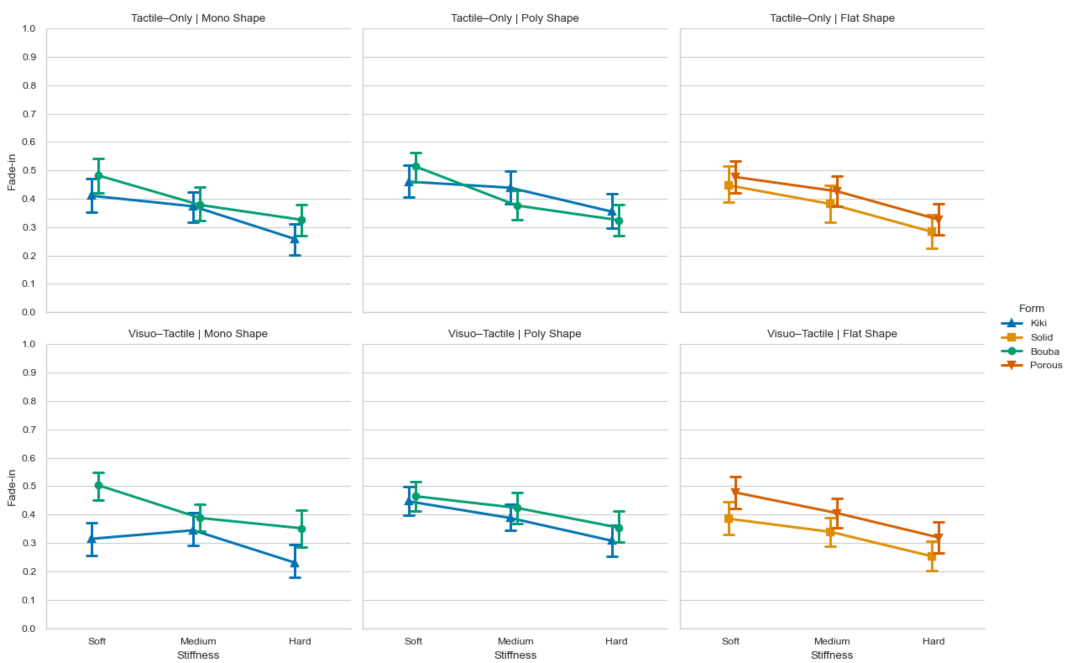


Figure 11: Mean fade-in associations (y-axis) across stiffness levels (x-axis: Soft, Medium, Hard), separated by visibility (rows: Tactile–Only, Visuo–Tactile) and shape type (columns: Mono, Poly, Flat). Each line indicates a form category (Kiki, Bouba, Solid, Porous). Error bars represent ±95% confidence intervals.

Table 9: Mean values and Confidence Intervals (CI ±95%) for Fade-out associations made during the tasks in each condition (values normalised 0 to 1).

			Visuo–Tactile Condition			Tactile–Only Condition		
				95% CI Mean			95% CI Mean	
Shape	Form	Stiffness	Mean	Upper	Lower	Mean	Upper	Lower
Mono	Bouba	Soft	0.500	0.553	0.446	0.531	0.593	0.470
		Medium	0.437	0.488	0.385	0.438	0.495	0.380
		Hard	0.343	0.398	0.288	0.373	0.436	0.310
	Kiki	Soft	0.414	0.469	0.359	0.441	0.493	0.388
		Medium	0.383	0.440	0.326	0.393	0.446	0.341
		Hard	0.305	0.365	0.246	0.267	0.323	0.212
Poly	Bouba	Soft	0.514	0.569	0.460	0.526	0.577	0.475
		Medium	0.458	0.506	0.409	0.460	0.512	0.408
		Hard	0.378	0.429	0.328	0.358	0.416	0.301
	Kiki	Soft	0.479	0.533	0.424	0.501	0.555	0.448
		Medium	0.432	0.484	0.380	0.422	0.471	0.373
		Hard	0.358	0.416	0.301	0.409	0.466	0.352
Flat	Porous	Soft	0.509	0.569	0.448	0.495	0.554	0.437
		Medium	0.482	0.533	0.432	0.492	0.544	0.440
		Hard	0.341	0.392	0.290	0.312	0.362	0.263
	Solid	Soft	0.435	0.489	0.382	0.495	0.545	0.445
		Medium	0.347	0.391	0.302	0.403	0.461	0.345
		Hard	0.295	0.349	0.241	0.338	0.395	0.282

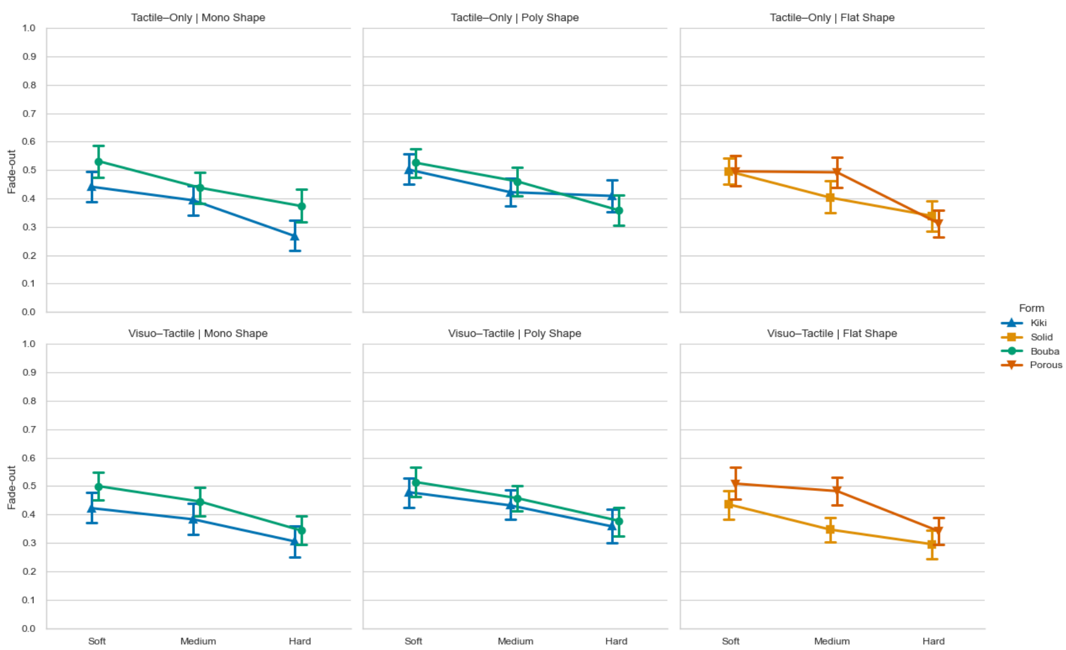


Figure 12: Mean fade-out associations (y-axis) across stiffness levels (x-axis: Soft, Medium, Hard), separated by visibility (rows: Tactile–Only, Visuo–Tactile) and shape type (columns: Mono, Poly, Flat). Each line indicates a form category (Kiki, Bouba, Solid, Porous). Error bars represent ±95% confidence intervals.

Table 10: Mean values and Confidence Intervals (CI ±95%) for force (in Newtons) applied by the participants associations made during the tasks in each condition (values normalised 0 to 1).

			Mono Shapes			Poly Shapes			Flat Shapes		
				95% CI Mean			95% CI Mean			95% CI Mean	
Visiblity	Form	Stiffness	Mean	Upper	Lower	Mean	Upper	Lower	Mean	Upper	Lower
Visuo–Tactile	Bouba/Porous	Soft	1.934	2.303	1.565	2.298	2.731	1.864	2.115	2.408	1.822
		Medium	2.407	2.886	1.928	2.015	2.355	1.675	2.748	3.132	2.365
		Hard	2.880	3.412	2.347	2.607	3.120	2.094	3.478	4.185	2.771
	Kiki/Solid	Soft	1.587	1.899	1.274	2.076	2.489	1.663	2.568	3.095	2.041
		Medium	1.829	2.177	1.482	1.835	2.152	1.518	3.165	3.741	2.590
		Hard	1.895	2.330	1.461	3.576	4.356	2.797	2.880	3.405	2.355
Tactile–Only	Bouba/Porous	Soft	2.070	2.507	1.633	1.854	2.186	1.522	1.922	2.206	1.639
		Medium	2.338	2.818	1.859	1.749	2.050	1.448	2.336	2.665	2.007
		Hard	2.343	2.819	1.867	2.238	2.684	1.792	2.644	3.101	2.187
	Kiki/Solid	Soft	1.710	2.056	1.364	1.954	2.369	1.539	2.358	2.789	1.927
		Medium	1.751	2.091	1.411	1.750	2.077	1.424	2.833	3.433	2.233
		Hard	1.956	2.343	1.570	2.725	3.203	2.247	2.363	2.787	1.938

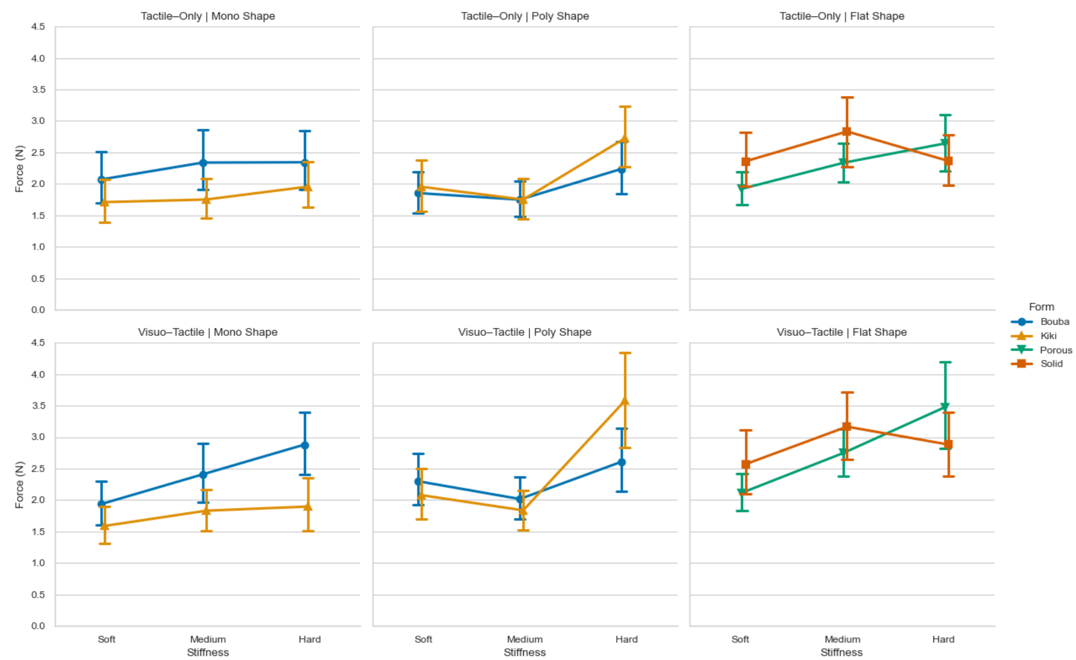
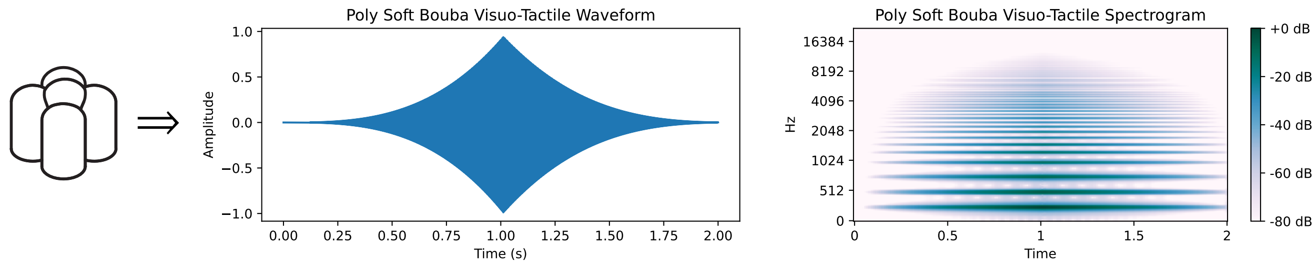
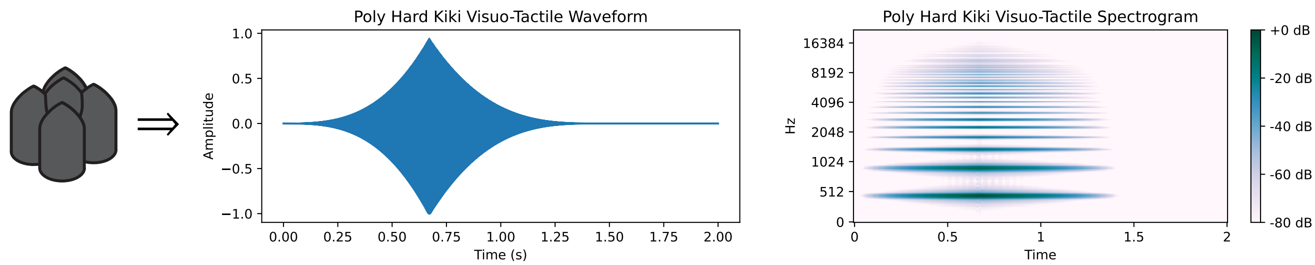


Figure 13: Mean force levels in newtons (y-axis) across stiffness levels (x-axis: Soft, Medium, Hard), separated by visibility (rows: Tactile–Only, Visuo–Tactile) and shape type (columns: Mono, Poly, Flat). Each line indicates a form category (Kiki, Bouba, Solid, Porous). Error bars represent ±95% confidence intervals.

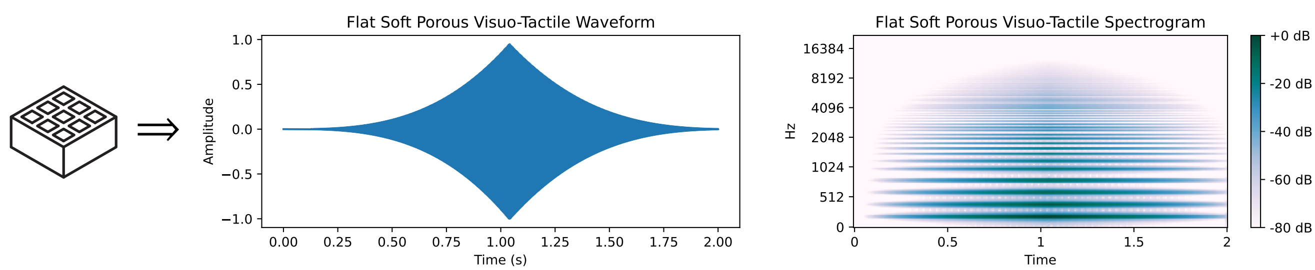


(a)

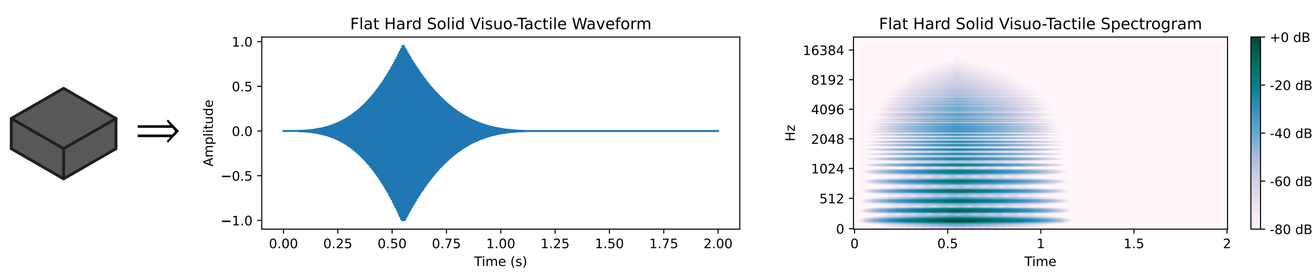


(b)

Figure 14: Shape, waveform and spectrogram plots for (a) the average poly soft bouba visuo-tactile sound and (b) the average poly hard kiki visuo-tactile sound.



(a)



(b)

Figure 15: Shape, waveform and spectrogram plots for (a) the average flat soft porous visuo-tactile sound and (b) the average flat hard solid visuo-tactile sound.