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Tamar Levy, Hadas Erel & Oren Zuckerman

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Crafting shape-changing experiences: emotional evaluation of morphing metamaterials

Tamar Levy, Hadas Erel, and Oren Zuckerman

Media Innovation Lab, School of Communications, Reichman University, Herzliya, Israel

ABSTRACT

We introduce a novel approach to evaluate how the design properties of morphing metamaterial influence shape-changing experiences. We leverage parametric design to create cutting patterns that change the *Density* and *Geometry* material properties. Using laser-cutting, we apply the patterns to a non-stretchable woven textile, resulting in a stretchable metamaterial that we actuate using an electromagnetic coil. This systematic design approach leads to programmatic control over the material movement, making it suitable for controlled evaluation of perceived experience. In a 2×2 mixed-method study, we assess how the metamaterial's *Density* and *Geometry* properties impact the observed experience. Our findings indicate that such changes significantly and independently affect participants' perceived emotions, mood, associations, and preferences. Our research contributes to the body of work of systematic studies in the shape-changing community. By using our morphing metamaterial design and implementation technique, coupled with our controlled evaluation of specific design properties, we have revealed new insights about the influencing factors of shape-changing experiences. We have incorporated these insights into our morphing metamaterial design guidelines, which outline the impact of *Density* and *Geometry* properties on an observer's perceived emotions. We hope our work will open up new possibilities for expressive, evocative metamaterial-focused shape-changing experiences.

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Shape-changing; morphing materials; design guidelines; emotional experience

1. Introduction

The HCI community has explored shape-changing experiences since 1965, when Ivan E. Sutherland first introduced the Ultimate Display *"a room within which the computer can control the existence of matter"* (Sutherland, 1965). In recent years, material science research has shown progress in developing novel materials that can morph their shape (Cheng et al., 2020; Z. Wang et al., 2020; Zadpoor et al., 2023; Zhai et al., 2021; Zhang & Krushynska, 2022). HCI researchers can leverage such morphing materials to create new experiences, classified by Qamar et al. (2018) into four categories: stretchable structures, deployable structures, variable stiffness materials, and shape-memory materials. The first category and the focus of this work, are stretchable structures, which are highly deformable materials. There are two types of stretchable structures: elastomers and auxetic metamaterials. Elastomers are polymers with inherent elastic properties and therefore are easily deformed (rubber, silicone, thermoplastic elastomer). Auxetic metamaterials are engineered materials with unique qualities that typically do not exist in natural materials (Z. Wang et al., 2020). One unique property is their ability to morph their shape in unusual ways. Specifically, while most natural materials shrink perpendicular to an

CONTACT Tamar Levi tamar.levy@milab.idc.ac.il Media Innovation Lab, School of Communications, Reichman University, Ha'universita Street 8, Herzliya 4610101, Israel

applied force when pulled, auxetic metamaterials are engineered to expand (Z. Wang et al., 2020). Our work shows that auxetic metamaterials hold great potential for shape-changing experiences, since they empower material designers to accurately define the metamaterial's shape morphing using parametric design of material properties, without changing the shape-changing actuation force.

Combining fabrication methods like 3D printing and laser cutting with parametric design paves the way for novel morphing metamaterials. Designers can use parametric design to precisely and systematically customize material structures, resulting in predictable and easy to fabricate morphing behaviors. This integrated approach offers greater freedom to develop innovative shape-changing interfaces (Ion & Baudisch, 2019). As a result, HCI research started adopting morphing metamaterials (Gong et al., 2021; Ion et al., 2018; Jiang et al., 2023).

Programmable morphing materials are at the core of shape-changing experience design. They involve two main aspects: a stimulus applied to the material and a deformed material (Qamar et al., 2018; Van Manen et al., 2018). The stimuli can be heat, electromagnetism, light, humidity, and air pressure. The material change is usually a physical change in internal structure that results in visible shape deformation, which influences the perceived user experience.

When an interface morphs its shape people react in different ways. Alexander et al. (2018) highlighted the need to understand how shape change influences the perceived user experience. They emphasized the lack of in-depth user studies on shape-changing experiences, and identified two main challenges: (A) technical implementation issues; (B) evaluation study concerns. The technical implementation challenges they define are: (A1) Creating a robust prototype that can withstand repeated shape change; (A2) Precisely controlling the experience; (A3) Developing a simple and replicable design. The user evaluation challenges they define include: (B1) Studying the independent effect of different modalities; (B2) Insulating and evaluating the effect of specific design aspects.

In recent years, researchers started to address this knowledge gap, some with review papers (Rasmussen et al., 2012), some with design taxonomies (Kim et al., 2018; Roudaut et al., 2013), and others with empirical user studies (Hu & Hoffman, 2019; Kwak et al., 2014; Tan et al., 2016).

A noted review paper by Rasmussen et al. (2012) distinguished between two types of movement characteristics in shape-changing interfaces, defined as kinetic parameters and expressive parameters. Kinetic parameters account for the physical movement, including path, speed, and frequency. Expressive parameters account for humans' perception, including association (metaphors such as mechanical or organic) and adjectives (the perceived personality traits or qualities).

In the Related Work section, we detail the relevant empirical user studies (Hu & Hoffman, 2019; Kwak et al., 2014; Tan et al., 2016). In sum, they reveal new knowledge regarding the correlation between specific movement characteristics (kinetic properties and form) and the perceived experience (including emotional valence, emotional arousal, and personality traits).

Building upon Alexander et al.'s call for a better understanding of how a shape's change influences the perceived user experience, our work contributes by studying the influence of morphing metamaterials, which are gaining popularity in the shape-changing community. Through an empirical user study, we reveal the correlation between specific design properties of morphing materials and the emotional experiences they evoke.

Our research extends prior work by closing the gap between the structural design of morphing metamaterials and the emotional experiences their shape-changing behavior produces. More specifically, we address the following research questions:

(1) How do specific metamaterial design properties affect the morphing of the metamaterial?
(2) What is the mapping between the morphing metamaterial and the observer's perceived emotional experience?

To answer these questions, we use parametric design to control two key metamaterial design properties: *Density* and *Geometry*. These patterns are then laser-cut onto inelastic textiles, transforming them into morphing metamaterials. To actuate the metamaterial, we hand stitch an Arduino-based electromagnetic solenoid, achieving accurate programmatic control over the shape morphing.

In our user study, we manipulate *Density* level (Dense compared to Sparse) and *Geometry* (Angular compared to Curved), while keeping all other aspects constant, including actuation. Using this experimental design, we effectively isolated the effect of each morphing metamaterial design property on the material movement and, in turn, on the perceived emotional experience.

Our contribution is twofold:

(1) A methodology for systematic design and implementation of morphing metamaterial using parametric design, enabling controlled evaluation of specific metamaterial design properties.
(2) An emotional evaluation of morphing metamaterial as a function of changes in design properties. By keeping the actuation force constant across conditions, we reveal key insights into how changes in *Density* and *Geometry* impact emotions, mood, associations, and preferences.

2. Related work

Works related to our research include morphing metamaterials (focused on rotating rigid units auxetic metamaterial), shape-changing mechanisms for soft materials (specifically electromagnetic solenoid actuators), and user studies regarding the emotional perception of shape-changing experiences.

2.1. *Morphing metamaterials*

Metamaterials encompass a range of engineered materials with unforeseen properties and functionalities that make them attractive in diverse applications (Krushynska et al., 2023; Papadopoulou et al., 2017). Mechanical metamaterials are artificial structures with unusual properties that originate in their internal architecture rather than in the specific material from which they are made (Ion & Baudisch, 2019; Zadpoor et al., 2023). Such unique characteristics include programmable morphing metamaterials that support tunable stiffness, adjustable texture, and more (Jiang et al., 2023). Mechanical metamaterials are particularly significant for shape-changing interfaces due to their unique mechanical properties. Various industries, such as wearable technology and robotics, have started to utilize mechanical metamaterials in their designs (Zhang & Krushynska, 2022). The Human-Computer Interaction community has also embraced such materials to create interactive experiences (Ion & Baudisch, 2019; Jiang et al., 2023).

Auxetic metamaterials, a specific type of mechanical metamaterials, provide a novel opportunity to create new significant volume distortion while maintaining high resistance (Qamar et al., 2018). Auxetic metamaterials coupled with parametric design offer an excellent opportunity to design shape-changing experiences. Among the techniques used to produce a predefined morphing behavior are controlling the design of the auxetic hinges (Dudek et al., 2022; Konaković et al., 2016; Ou et al., 2018; Zhang & Krushynska, 2022), incorporating non-auxetic building units (Konaković et al., 2016; Ou et al., 2018), using irregular shapes or sizes of building blocks (G. Choi et al., 2019; Eguchi et al., 2022; Grima et al., 2005; Jin et al., 2020; Sedal et al., 2018), and using a fixed perimeter to allow only the central area to expand (Jain et al., 2021; Liu et al., 2018).

In our work, we focused on auxetic metamaterial enclosed in a circular shape (with fixed positioning of the perimeter) that can transform from a 2D sheet to a dome-like volumetric shape (see Figure 1).

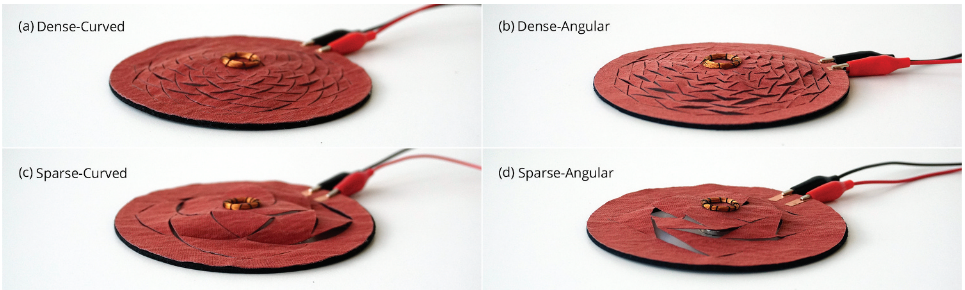

Figure 1. The four morphing metamaterials were created using parametric design changes of *Density* and *Geometry* design properties. When actuated using the same electromagnetic force, each metamaterial design exhibits different movements that lead to varied emotional shape-changing experiences due to their distinct designs.

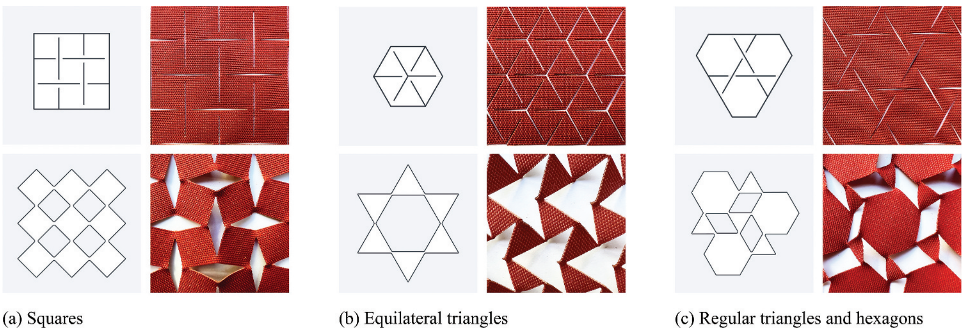

Figure 2. Example designs of auxetic metamaterial cutting patterns in the rotating grid unit method, transformed from parametric design to physical textile using laser cutting.

There are several types of auxetic metamaterials. Our work focused on a specific type called "rotating rigid units". Rotating rigid units are constructed from rigid shapes connected by hinges in their corners. When stretched, the units revolve around the connecting hinges, generating material expansion (Z. Wang et al., 2020). A common method for creating rotating rigid units is to apply a cutting pattern to a flexible material sheet, leaving material between each pair of neighboring units to act as an axis, see Figure 2 (Cheng et al., 2020; Groeger & Steimle, 2019; Qamar et al., 2018; Zhai et al., 2021; Zheng et al., 2019). Previous HCI studies leveraged this technique to produce interfaces such as sensors (Zheng et al., 2019), flexible circuits (Groeger & Steimle, 2019), morphing hydro material (Jain et al., 2021), and inflatable materials (Eguchi et al., 2022; Jin et al., 2020).

Our work differs from prior studies on hydrogel and pneumatic auxetic metamaterials by leveraging electromagnetic force for actuation. This offers precise, programmable control and fast response times. In contrast, hydrogel actuators are slower and less durable, and pneumatic auxetics require more complex manufacturing and control systems.

2.2. *Shape-changing mechanism for morphing materials*

The HCI community has explored various technologies for actuating morphing materials. The main four include (1) Humidity-responsive materials (Rivera et al., 2020; Yao et al., 2015); (2) Hydraulic (Kilic Afsar et al., 2021) and pneumatic mechanisms (Hu & Hoffman, 2019; Zhu et al., 2020); (3) Heat-responsive materials, including both shape-memory materials (Coelho & Maes, 2009; Muthukumarana et al., 2021; G. Wang et al., 2018) and materials with thermal expansion (Du et al., 2018; Heibeck et al., 2015); and (4) Electromagnetic actuation using solenoid, usually a helical coil of wire (Bau et al., 2009; Preindl et al., 2020). Each technique has advantages and disadvantages regarding the robustness of the actuated material and the actuator's fabrication complexity (Alexander et al., 2018).

Our work focuses on electromagnetic actuation using solenoids. These actuators consist of two layers that attract or repel each other: one with a solenoid coil and the other with a Neodymium magnet (Bau et al., 2009; K. Y. Choi & Ishii, 2020; Mazursky et al., 2021). Electromagnetic actuators are easy to fabricate, durable, and controlled with high accuracy using a simple electronic circuit, but have low force. We overcame this disadvantage by actuating lightweight textiles.

Academic research about electromagnetic solenoid actuators in interactive experiences can be divided into four categories: (1) Tactile feedback (Bau et al., 2009; K. Y. Choi & Ishii, 2020; Mazursky et al., 2021); (2) Speaker (Preindl et al., 2020); (3) Wireless power source (Micus et al., 2021; Takahashi et al., 2022); and (4) Shape-changing experiences, which is the focus of our work. The Crafted Logic project by Posch and Kurbak (2016) used solenoid actuators to create an interactive installation. They handcrafted textile "logic gates" that alter state in response to electromagnetic control. Two related artworks include the Flip-dot dress by Pauline van Dongen (2012), a sound-responsive garment with dots that flip between two colors when an electromagnetic field is applied, and the Flapping Textile Wing project, a DIY project by Perner-Wilson and Satomi (2015) that actuates a piece of fabric to create a wing-like movement.

Our work differs in goal and focus. We utilize the electromagnetic force to generate a consistent signal that leads to predictable material morphing, enabling systematic evaluation of the perceived shape-changing experience.

2.3. *Perception of emotional aspects in shape-changing experiences*

Related work regarding the perception of movement includes works from the HRI (Erel et al., 2019, 2021) and shape-changing communities (Hu & Hoffman, 2019; Kwak et al., 2014; Tan et al., 2016; Van Oosterhout et al., 2018). Within the shape-changing community, works include video simulations and empirical studies with prototypes, looking at the perceived experience.

Strohmeier et al.'s video simulation research (2016) explored how the kinetic parameters of a flexible shape-changing surface influence the emotional experience. They presented simulations of a surface shape morphing and evaluated perceived emotions using valence and arousal dimensions. Their results suggest that motion properties (speed, amplitude, and area) accounted for arousal, while the shape's convexity (concave vs. convex) and curvature influenced valence.

An empirical study by Kwak et al. (2014) evaluated the perception of a shape-changing experience with six shape-changing interfaces with varied visual and tactile feedback. They used a qualitative repertory-grid interview technique to identify how people interpret the experience. Their results revealed various personal constructs including personality traits (e.g., stubborn, energy, territorial, and open vs. closed), state of mind (e.g. happy, sad, downhearted, and hopeful), appearance, and product properties (e.g. sturdy vs. fragile and mechanical vs. organic).

Research by Tan et al. (2016) applied theories of biological motion to shape-changing interfaces to create emotional experiences. They developed a shape-changing interface made of a cylindrical bellow that emerged from a small box using motors. By adjusting kinetic properties such as velocity, fluidity, and orientation, they created various movement patterns based on biological motion. Their results suggest that speed, direction, and orientation significantly impact emotions and are consistent with theories about the relationship between biological motion and affect.

Hu and Hoffman (2019) conducted a study to examine how participants perceive a pneumatic "skin-like" texture that can transform into goosebumps or spikes when actuated. They evaluated the emotional experience generated by the skin texture, considering both the texture design (goosebumps and spikes) and its kinetic properties (frequency and amplitude patterns). The study also evaluated the experience of visual and tactile modalities in a separate and controlled manner. The results suggest that the material texture affects emotional valence, while the frequency of the movement influences emotional arousal.

Our work stands apart from prior research in several key ways. While other studies have focused on the emotional effects of shape-changing interface movements, we specifically examine the impact of morphing material design properties. We focus particularly on how the density and geometry of morphing metamaterials influence material movement and, consequently, the user experience. Moreover, unlike works that leverage changing actuating forces to produce different shape-changing experiences, we use a constant force and modify only the material design. This ensures a distinct difference in the material's movement, caused solely by the change in the material design properties.

3. Design & implementation

3.1. *Design principles*

Our design process started by drawing inspiration from cognitive psychology literature, exploring how design properties can potentially impact the perceived experience. We continued with an initial design of four cutting patterns tested in a design pilot study. Following clear insights from the design pilot, we focused on two metamaterial design properties: *Density* and *Geometry*.

3.1.1. *Design inspiration from cognitive psychology literature*

We reviewed cognitive psychology literature that addressed the aesthetic preference and emotional impact of interactive objects, including varying textures, shapes (sphere vs. cube), and feedback (Soranzo et al., 2018); the emotional expression of abstract forms (De Rooij et al., 2013); and the emotional impact of geometry, specifically curve and angular geometries (Corradi & Munar, 2020). We also reviewed literature that explored the correlation between human emotions and Laban Movement Analysis (Fdili Alaoui et al., 2017; Gross et al., 2012; Shafir et al., 2016), a framework used to analyze movement qualities and patterns using properties such as body, effort, space, and shape. Laban studies include the effect of specific movement properties during walking (Gross et al., 2012) or dancing (Shafir et al., 2016), or in interactive objects such as robotic swarms (Santos & Egerstedt, 2021) and flying drones (Sharma et al., 2013).

From the relationship between Laban Movement Analysis and emotional perception, we learned that expended, stretched, and growing movement patterns raise joyful feelings. In contrast, smaller, more shrunk movement trails lead to sad feelings (Gross et al., 2012). Direct and short movement trails create negative valence, while indirect movement generates positive valence (Sharma et al., 2013). Smooth movement trace generates pleasant feelings and calmness, while angular trace generates negative emotions (Santos & Egerstedt, 2021).

Additionally, we learned that geometry plays an important role in emotion recognition, particularly curved vs. angular geometry (Corradi & Munar, 2020; De Rooij et al., 2013; Soranzo et al., 2018). Former research introduced the “Curvature Effect”, a primal biological tendency of people's positive feelings toward curved shapes compared to angular ones. This phenomenon occurs in various mediums, including graphics, everyday objects, interior designs, interactive objects, and art (Corradi & Munar, 2020). Another relevant phenomenon is the “Threat Hypothesis”, which argues that people's tendency to prefer curved geometry originates from the unpleasant arousing feelings (i.e. fear) caused by angular geometry (Corradi & Munar, 2020). Lastly, the ”Smooth Curvature” effect claims that objects with smooth curved textures are more aesthetically pleasant and relaxing than those with rough textures.

From the relationship between Laban Shape Analysis and affect, we learned that expended, stretched, and growing movement patterns raise joyful feelings, while smaller, more shrunk movement trails lead to sad feelings (Gross et al., 2012). In correlation, direct and short movement trails create negative valence, while indirect movement generates positive valence (Sharma et al., 2013).

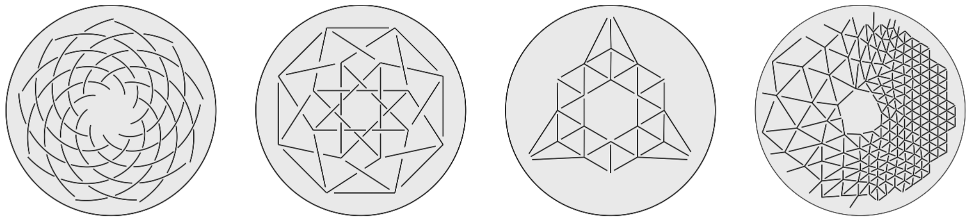

Figure 3. Four parametric-design cutting patterns that were evaluated during the design pilot study, to better understand the role geometry and density play in a shape-changing experience.

Finally, we learned that observing movement traces can impact both emotional valence and mood. Smooth movement trace generates pleasant feelings and calmness, while angular trace generates negative emotions (Santos & Egerstedt, 2021).

3.1.2. *Design pilot study*

Based on inspiration from psychology literature, we designed four different cutting patterns with various design properties, including curvature, density, asymmetry, and geometry tiling. Our pilot study aimed to reveal general insights using these diverse patterns. This helped us choose specific design properties for further exploration in the in-depth user study. To explore the impact of the curvature effect, we included curved and angular elements, and to explore the movement trace and ability to expand, we explored different densities. After several iterations, we created a set of four distinct designs (see Figure 3): (a) Curved-Dense; (b) Angular-dense; (c) Angular-Sparse; (d) Varied density.

We fabricated and actuated four different cutting patterns according to the fabrication process presented in section 3.2. We conducted a design pilot session, in which we presented them to six participants in a lab setting (age range 22–50, 3 females, 3 males). We placed the four designs on a table and actuated them one by one. We conducted an informal interview for each morphing metamaterial, asking participants to describe their impressions openly. The insights helped us understand the role geometry and density play in the shape-changing experience. For example, participants showed clear interest in the dense patterns. They reported a considerable difference in experiencing the patterns with high density (Figure 3a,b and those with low density (Figure 3c). Moreover, when describing the varied density pattern, they addressed how the material's pattern is inconsistent. They pointed out that the dense areas expand more than the sparse, and emphasized how the experience felt different when viewed from various perspectives.

After reviewing the literature and conducting a pilot study, we have decided to focus on two design properties: *Density* (Dense vs. Sparse) and *Geometry* (Angular vs. Curved). Based on the curvature effect and threat hypothesis, we assume that curved patterns will result in more positive emotions, mood, and be more aesthetically pleasing compared to angular patterns. Furthermore, based on the Laban Shape Analysis, we predict that dense patterns with a larger movement trace will create a more positive emotional experience and mood than sparse patterns.

3.2. *Technical implementation*

3.2.1. *Parametric design of the auxetic metamaterial*

We implemented a parametric design methodology to create precise geometric patterns that vary according to our defined design properties (*Density* and *Geometry*). We used Rhinoceros 6 and Grasshopper software to create a radial Fibonacci spiral pattern for the curved patterns, evenly spaced along the circumference of a circle (see Figure 4a,c). To create the Straight pattern, we

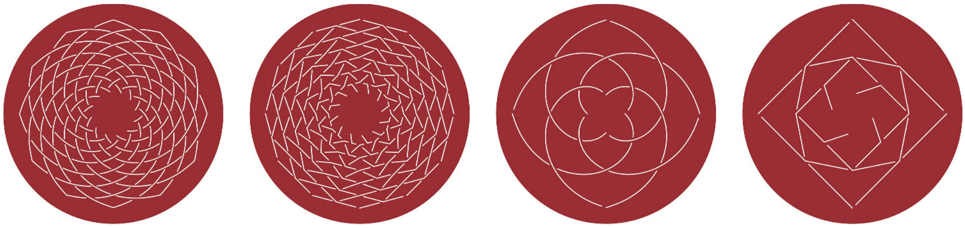

Figure 4. The four auxetic metamaterial cutting patterns used in the evaluation study, combining *Density* (dense vs. Sparse) and *Geometry* (curved vs. Angular) design properties.

followed the same intersection points of the curved pattern, with straight lines connecting between the dots instead of curved lines (see Figure 4b,d). Then, we transformed the designs into rotating rigid units' cutting patterns by connecting neighbor geometries with hinges in their corners. The rigid units rotate around the hinges when stretched, generating expansion in both axes (see Figure 2). Since each unit within the pattern had four neighbor shapes, it can be considered a deformed variation of the typical rotating squares cutting pattern shown in Figure 2a, which is known for demonstrating auxetic behavior. Therefore, the resulting cutting patterns can transform materials into stretchable metamaterials.

3.2.2. *Textile fabrication*

The type of material selected heavily influences the behavior of rotating rigid units in auxetic metamaterial (Grima et al., 2007). The rigidity of the material is a crucial factor in determining its behavior. Elastic materials tend to contract perpendicularly to the applied force. Therefore, elastic material can result in non-uniform shape deformation and biased study results. To ensure consistent morphing behavior, we applied the cutting pattern on an inelastic material, specifically a synthetic woven textile. The synthetic textile granted robustness, as the laser beam's heat sealed the fibers around the cuts, making the morphing metamaterial durable for repeated actuation cycles. Furthermore, the focus on textiles opens a door for seamless integration of the actuator into the fabric (see section 6.2) due to the similarity between electromagnetic solenoid copper wire and a textile's thread.

We fabricated four morphing metamaterials by integrating two textile layers into a single multi-layered textile. The multilayered textile included an expandable top layer and a rigid base layer stabilizing the metamaterial structure. We used a standard laser-cutter (Universal Laser VLS3.50) to fabricate both textile layers in a circular shape of 12 cm in diameter, according to the patterns defined in Figure 4. The base layer is made of a 1.5 mm thick rigid artificial leather, while the top layer is a non-stretchable woven polyester textile, 0.4 mm thin. We utilized a thicker and heavier base layer to maintain consistent morphing behavior during repeated iterations, ensuring that the metamaterial boundary remains stable during actuation. To fabricate the stretchable layer, we implemented a cutting pattern over the woven polyester textile, which granted the auxetic behavior that made the shape morphing possible.

3.2.3. *Technical implementation of the hand-stitched electromagnetic actuator*

We fabricated an electromagnetic solenoid by coiling 150 turns of insulated 34 AWG copper wire around a 12 mm diameter pole. We kept loose copper threads at both coil ends for later control. The result was a coil with a 12.5 mm inner diameter and 19 mm outer diameter. Next, we removed the coating from both wire ends, to prepare the power source connection. The hand-stitched solenoid had 12 Ohm resistance. We used an Arduino microcontroller and a 6 V at 0.5 Amp transistor to

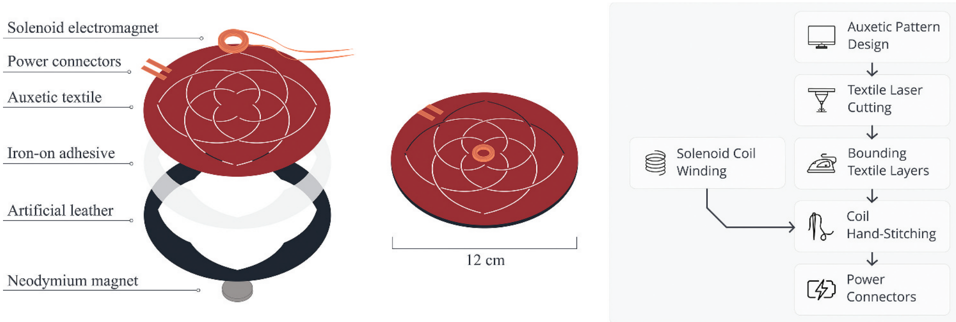

Figure 5. Left: the morphing metamaterial layers with solenoid electromagnet and power connectors at the top. Stretchable auxetic textile layer, made of a woven polyester textile, 0.4 mm thin, parametrically designed and fabricated using a laser cutter. An interfacing fabric as adhesive, glued to the rigid artificial leather that holds the structure in place, 1.5 mm thick. On the bottom, the magnet that repels the top solenoid electromagnet. Right: the design, fabrication, and assembly process.

power the solenoid actuators. We used digital Pulse Width Modulation (PWM) signals to drive each actuator via the power transistor. The result was accurate control over the magnetic field intensity, ranging from zero to 6.2 mT. The magnetic field intensity directly impacts the metamaterial's height. This allowed us to control the auxetic textile's shape morphing and evaluate the material movement's effect.

3.2.4. *Assembly*

We deliberately chose to expose the electromagnetic coil since we wanted users to understand the manipulating force rather than become overly focused on the "magic" of the movement. To that end, we explained at the beginning of the study how the exposed coil attracts or repels the magnet beneath to generate movement.

Our assembly process drew inspiration from standard textile fabrication techniques to achieve material-level design. We assembled the morphing metamaterials by first stitching the solenoid electromagnet to the top auxetic textile layer, followed by bounding the two textile layers to a multilayered textile (the rigid base and the auxetic layers) together by ironing them with a fusible interfacing fabric layer in between. Next, we attached two pieces of conductive textile tape to create power connectors, and soldered the two copper wire ends to the conductive tapes. Lastly, we placed a round neodymium magnet (19 mm in diameter and 2.8 mm in thickness) beneath the copper solenoid. The result was a metamaterial with two textile layers (see Figure 5), with a top layer that can move thanks to the fabricated cutting pattern and the solenoid actuator. At rest, the height of the metamaterial is 2.5 mm. When activated to the maximum magnetic field intensity, the textile's height can reach up to 28 mm. We actuated all the textiles using the same Arduino code, meaning that the actuation force (change in PWM cycles and strength) was identical across all experiences. We used constant and slow animation cycles to allow users to observe the experience without being rushed. The actuated PWM cycle generated the following movement: Two seconds going upwards; Two seconds going downwards; and Two seconds at rest state at the bottom;

4. Evaluation

We conducted a 2×2 within-participants study to evaluate whether different morphing metamaterial properties (*Density* and *Geometry*) affect how participants emotionally perceive the metamaterial's movement while focusing on how the experience is perceived through visual modality solely. The ethics committee of the research institute approved the study.

The manipulation of morphing metamaterials' *Density* and *Geometry* directly altered the material's stretchability, which in turn influenced the nature of the movement. We evaluated whether the resulting movements generated varied emotions. This causation relationship is established by consistently manipulating the effect of *Density* and *Geometry* while keeping all other aspects of the experience constant across conditions (material, shape, color, size, electromagnetic PWM cycle, and strength). We evaluated the experience with repeated minimal movement to show that even minimal manipulation of metamaterials can lead to clearly distinctive emotional experiences. Moreover, the movement was deliberately not connected to a real-world use-case to not limit the generalization of the effect to a specific context.

4.1. *Participants*

Twelve adults participated in the study (age range 22–33, 8 females, 4 males). The participants received course credit or a coupon for a coffee and pastry in a local coffee shop chain. Before the experiment began, they signed a consent form. We informed them that the experiment would be video recorded and that we would erase all recorded materials after the data analysis.

4.2. *Experimental design*

The within-participants experimental design involved two properties: *Density* (Sparse vs. Dense) and *Geometry* (Angular vs. Curved). Participants observed all four combinations of the morphing metamaterial properties' levels: Sparse-Curved, Sparse-Angular, Dense-Curved, and Dense-Angular (see Figure 1). We presented the four metamaterial designs to participants in a counterbalanced order to avoid order effects. Specifically, we create all possible permutations of presentation orders (24 in total) and randomly select a unique condition sequence for each participant (12 sequences).

4.3. *Measurements*

Both qualitative and quantitative measures were utilized to better understand participants' experience with each morphing metamaterial design. Qualitative measures included semi-structured interviews, analyzed using the thematic coding approach (Boyatzis, 1998). Quantitative measures included a set of scales assessing the observers' emotional experience and perception of the textile movement. The subscales included the Affective Sliders Questionnaire, Valence and Arousal subscales (Betella et al., 2016), Mood scale (Wolf et al., 2015), and Godspeed Questionnaire, Animacy and Likability subscales (Bartneck et al., 2009).

4.3.1. *Qualitative interviews*

Two types of interviews were conducted: a within-condition interview immediately after each interaction, and a post-study interview at the end of the four conditions. The goal of the within-condition interview was to evaluate each shape-changing experience separately. For each condition, we asked the following questions: (1) "How would you describe the experience to a friend?"; (2) "Please try to name it"; (3) "What did you like and dislike?." The second (post-study interview) was conducted at the end of the study after the participants had chosen one condition they would like to experience again. The interview included the following questions: (1) "Why did you choose this object?"; (2) "Do you see any differences between the objects?"; (3) "What is your general impression of this technology?".

4.3.2. *Quantitative questionnaires*

After interacting with each of the four morphing metamaterials, the participants filled out three short quantitative questionnaires that evaluated each metamaterial separately.

(1) Affective Sliders Questionnaire (Betella & Verschure, 2016): a self-reporting tool of human emotions. Composed of two sliders that assess the participant's perception of the experience, measuring levels of perceived emotional valence and arousal. The questionnaire is based on Russell's Circumplex Model of Affect Russell (1980). This model maps emotions in a two-dimensional space defined by arousal and valence and is commonly used to evaluate emotional experiences in response to different stimuli.
(2) Godspeed Questionnaire (Bartneck et al., 2009): a questionnaire designed to evaluate robot perception. The two subscales relevant to the study were: Animacy and Likability.
(3) Mood scale (Wolf et al., 2015): an instrument developed to assess the impact of interaction on the participant's mood. The participants rate their mood on a 5 point Likert scale (1 = not at all, 5 = extremely) reporting to what extent they felt good, bad, friendly, unfriendly, angry, pleasant, happy, and sad.

4.4. *Experimental settings*

The experiment took place in a dedicated research lab room. We placed the four metamaterial designs on a round table, opposite the participant's seat (see Figure 6). Arduino hardware was attached underneath, with a 4.5 V power source ready for quick swaps between conditions. A magnet in front of the participant's seat marked the designated location for the metamaterial design that would be activated next.

4.5. *Procedure*

Participants arrived at the lab, signed a consent form, and completed a demographic questionnaire. They were informed that the experiment would be video recorded, and that they could quit participating at any time. Then the participants entered the experimental room and sat opposite the textiles. A research assistant (RA) guided them through the conditions, provided questionnaires, and conducted interviews. To minimize the novelty effect, the RA explained how the exposed electromagnetic coil attracts or repels the magnet beneath it to form movement. This also reduced differences in participants' level of understanding of the technology and minimized technology-focused questions during the discussion.

To start the study, the RA activated a textile based on the counterbalance order (see Figure 6). While the metamaterial moved, participants completed questionnaires about their experience,

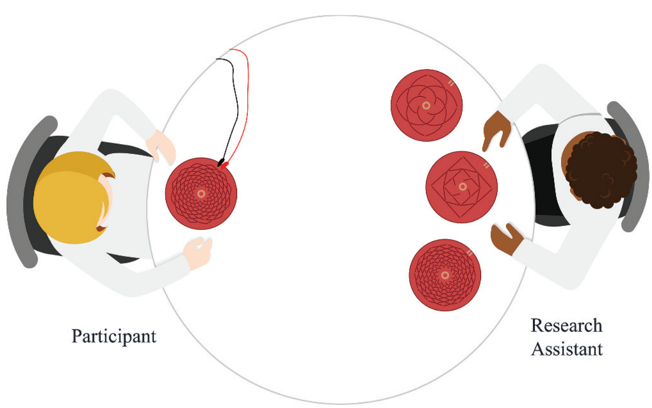

Figure 6. The experiment in the experiment room. The active morphing metamaterial is in front of the participants to allow close observation, while the other three metamaterials are not active, and located next to the research assistant.

followed by a brief interview. The RA then connected the next metamaterial and repeated the process for all four conditions. After all interactions, the RA conducted a concluding interview and discussed all experiences.

5. Findings

We analyzed the participants' perceived experience gathered using qualitative and quantitative measures. The qualitative interview data were analyzed by two individual raters using the Thematic Coding method (Boyatzis, 1998), a common methodology for identifying repeating themes in qualitative data. In addition, we performed a qualitative analysis of personal preference by asking participants (after they experienced all four conditions) which morphing metamaterial they would like to experience again, and why. The quantitative data were analyzed using a 2-way ANOVA conducted for each scale separately: Affective Sliders Questionnaire (Valence and Arousal subscales), Godspeed Questionnaire (Animacy and Likability subscales), and Mood scale.

5.1. *Qualitative analysis*

The interviews were transcribed (795 quotes) and analyzed using Thematic Coding. The analysis involved four stages: (1) One rater transcribed all interviews; (2) Two raters reviewed a quarter of the interviews independently, identifying initial themes; (3) The raters presented the initial themes to a third researcher, discussed inconsistencies and defined list of mutually-agreed themes; (4) The two raters analyzed all interviews independently, and inter-rater reliability was verified (Kappa = 80%). The analysis resulted in two main themes: Emotional Interpretation and Entity Associations. Emotional Interpretation had three sub-themes: Metaphors, Aesthetics, and Mood, and each emotion was defined as ”positive”, ”negative”, or ”neutral”. Entity Associations had three sub-themes: Living, Objects, and Free-will.

5.1.1. *Theme A: emotional interpretation*

All participants (12/12) expressed emotions for at least one of the four morphing metamaterials they experienced. The two Dense conditions had the strongest effect and triggered more positive interpretations (Dense-Curved 9/12 and Dense-Angular 5/12) than the Sparse conditions (Sparse-Curved 4/12 and Sparse-Angular 2/12). Respectively, the two Sparse conditions generated more negative interpretations (Sparse-Curved 6/12 and Sparse-Angular 9/12) compared to the Dense conditions (Dense-Curved 1/12 and Dense-Angular 1/12).

Further analysis of the emotional interpretations in all four conditions revealed three sub-themes: Metaphors, Aesthetics, and Mood (see Figure 7).

Metaphors included both ”positive” and ”negative” interpretations. All the ”negative” metaphors were in the two Sparse conditions, with participants describing ”negative” personality traits like submission, *”The motion feels like someone trying to catch something, but giving up.”* (P3, Sparse-Curved); restrained, *”It feels that he wants to give a part of himself but not to give everything.”* (P4, Sparse-Angular); and reserved, *”He looks sad to me, I feel that he has a lot of barriers.”* (P3, Sparse-Angular). More emotionally intense Metaphors included death, *”I feel that he is dying and crying for help.”* (P11, Sparse-Curved); *”It's like someone connected to a ventilator machine.”* (P13, Sparse-Angular), and dying organs, *”I see a slow heartbeat. On the brink of dying. A dying heart.”* (P9, Sparse-Angular). Participants' positive Metaphors included object associations and were evident in all conditions, *”He reminds me of a kite. He is perfect. Pleasant, and friendly.”* (P5, Dense-Curved). They suggested associations related to animals, *”It looks like many ants doing an action together”* (P12, Dense-Angular) and plants, *“It reminds me of a tree, it feels alive.”* (P10, Dense-Angular).

Another sub-theme of Emotional Interpretation was Aesthetics related attributes. Participants found the two Sparse conditions stuck and nonfluent, *”Only the center moves and the borders are in place, it does not inflate”* (P4, Sparse-Curved); and *”It bothers me that not everything rises…it is not*

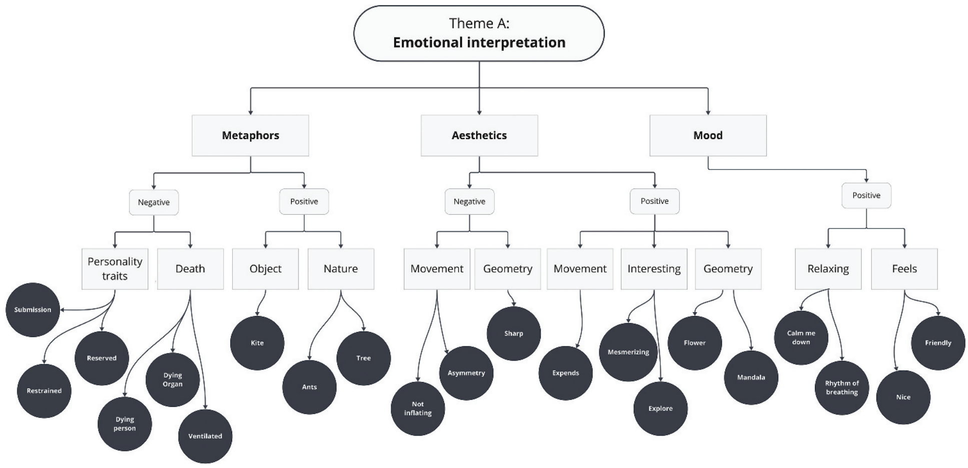

Figure 7. The emotional interpretation theme qualitative analysis (performed using thematic coding), including the sub-themes, the ”positive” and ”negative” interpretations, and the clusters of topics revealed from participants' quotes.

satisfying enough” (P7, Sparse-Angular); they also noted a lack of symmetry, *”It doesn't look good that everything doesn't go up symmetrically. It's irritating.”* (P2, Sparse-Curved). In contrast, the Dense conditions were described more favorably, described as a whole movement, *”It's beautiful the way it expands”* (P9, Dense-Curved); interesting, *”There is a lot to explore here. A lot of things happen.”* (P12, Dense-Angular); and even fascinating, *”I looked at it a lot, it's so mesmerizing.”* (P2, Dense-Curved). Additionally, the curved geometry was seen as more attractive, with specific design associations *”I like it better. Maybe because it reminds me of Mandala”* (P8, Dense-Curved); or flower *”Visually it is the most beautiful, it moves like a flower.”* (P9, Sparse-Curved) while the Angular geometry was described as unappealing, *”Its shape bothers me a bit – the square, sharpness, and triangles.”* (P7, Sparse-Angular).

A less dominant yet notable sub-theme was the impact on participants' Mood. The two Dense conditions generated more positive feelings compared to the Sparse ones. Participants described the experience of the two Dense conditions as relaxing *”There's something soothing about it. If I was in an anxiety attack, it would calm me down.”* (P11, Dense-Angular); *”It takes me into the same rhythm of breathing. and it's just soothing.”* (P6, Dense-Curved), and as friendly, *”I really liked the shape, the movement, it feels nice and friendly.”* (P5, Dense-Curved).

In sum, the theme of emotional interpretation reveals a range of metaphors. Sparse metamaterials are strongly associated with negative emotions and mood, while Dense metamaterials are linked to positive ones. Additionally, *Geometry* plays a role in aesthetic preference, with Curved designs perceived as visually pleasing and Angular designs perceived as unappealing.

5.1.2. *Theme B: entity*

All participants (12/12) associated the morphing metamaterial with a type of entity in at least one of the conditions they experienced. Further analysis revealed three entity sub-themes: Object, Living, and Free-will (see Figure 8).

The Objects sub-theme included familiar objects (e.g. window, balloon, kite, and a ninja knife), unfamiliar/alien objects (extraterrestrial, futuristic, virtual reality, spaceship), and use-case specific objects (learning aid, breathing exercise, and Imagination stimulation). The two Angular conditions led to more Object metaphors (Dense-Angular 10/12 and Sparse-Angular 9/12) than the two Curved conditions (Dense-Curved 6/12 and Sparse-Curved 4/12).

The two Curved conditions led to associations of familiar objects, while the two Angular conditions led to unfamiliar ones. Familiar objects quotes include: *“a child's game. Like some kind*

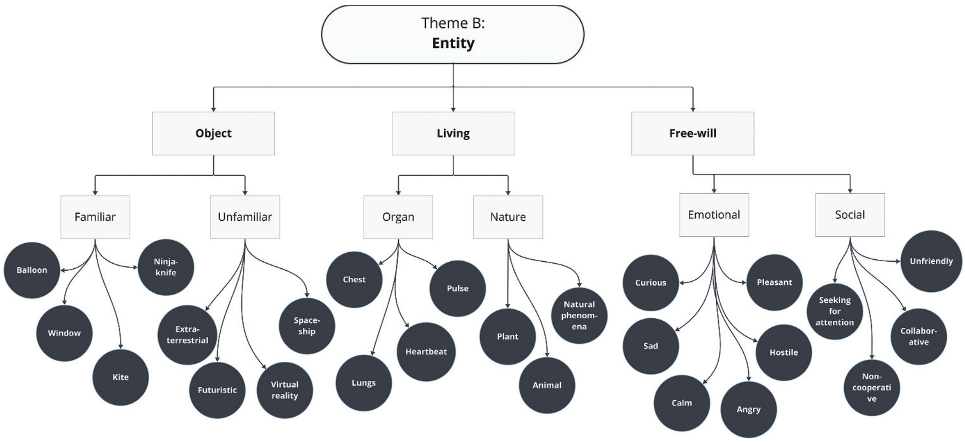

Figure 8. The entity theme qualitative analysis (performed using thematic coding), including the sub-themes and the clusters of topics revealed from participants' quotes.

of rubber." (P2, Dense-Curved); *"a sponge that absorbs and releases water"* (P10, Dense-Curved). Unfamiliar objects quotes include: *"an alien object; as if I was taken to a mission in space"* (P13, Dense-Angular); *"something futuristic"* (P2, Sparse-Angular). A less prominent type of Object association was use-case such as *"It is for someone a little anxious. It lets him concentrate on one thing to relax, by synchronizing the breath."* (P6, Dense-Curved); and *"I would use it to teach kids geometry"* (P8, Sparse-Angular).

The Living sub-theme included associations of an organ (e.g. chest, lungs, heartbeat, and pulse) or a nature-related entity (e.g. plants, animals). The two Curved conditions were more frequently perceived as a nature-related entity (Dense-Curved 6/12 and Sparse-Curved 5/12) than the Angular conditions (Dense-Angular 3/12 and Sparse-Angular 1/12). The most frequent curved nature-related association was a flower *"It has life, it's not something still, it grows."* (P4, Curved-Dense); *"It moves like a flower. It's just like a flower. A breathing flower."* (P9, Sparse-Curved). Other Curved associations included summer, sun, pet, and turtle shell. Sparse conditions led to organ associations, with a specific negative interpretation of a dying organ *"a heart, but not one that functions well, because a heartbeat is usually fast."* (P9, Sparse-Angular); *"a heart, with an irregular heartbeat...like a damaged heart."* (P2, Sparse-Curved). Dense conditions received functioning organ descriptions: *"breath, even lungs because it inflates, and then it goes down"* (P7, Dense-Angular) and *"someone sitting, and his chest goes up and down"* (P13, Dense-Curved).

Free-will associations were the least prominent, associated almost equally in all conditions. There were mostly "negative" free-will associations *"all the edges don't want to cooperate."* (P4, Sparse-Curved), with a minority of "neutral" associations *"He feels very confused and intrigued."* (P3, Dense-Curved).

In summary, the Entity theme reveals that curved metamaterials are linked to nature and perceived as familiar, whereas angular metamaterials are associated with objects and seen as unfamiliar. Additionally, dense metamaterials are connected with functioning organs, while sparse metamaterials relate to dying organs.

5.1.3. *Personal preference analysis*

As part of our experiment, we conducted a post-condition interview to measure the participants' personal preferences. After experiencing all four conditions, they selected a metamaterial to experience again and explained their choice. The majority preferred the Dense-Curved design (9/12), describing its movement as fluent, soothing, and natural, like a growing, or breathing entity. The

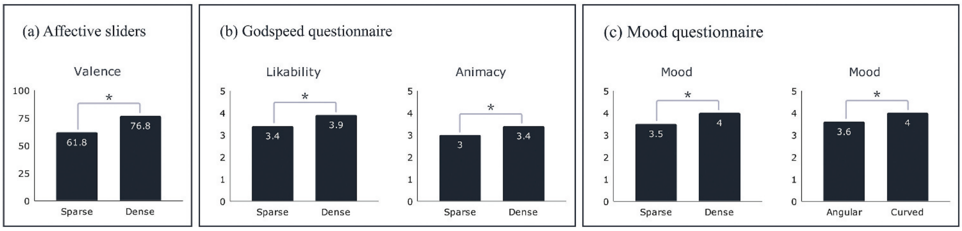

Figure 9. Quantitative analysis of the perceived user experience, including (a) Valence subscale (affective sliders questionnaire); (b) likability and animacy subscales (godspeed questionnaire); (c) mood scale.

least preferred design was the Sparse-Angular metamaterial, with 4/12 participants describing it as alien, mechanical, distressing, and threatening.

5.2. *Quantitative analysis*

Using two-way ANOVA we compared the main effects of *Density* (Dense vs. Sparse) and *Geometry* (Curve vs. Angular) as well as the interaction between them for the quantitative measures. A separate two-way analysis was performed for each dependent measure: Affective Sliders (Arousal and Valence subscales); Mood questionnaire; and Godspeed questionnaire (Likability and Animacy subscales).

5.2.1. *Affective sliders scale*

A separate two-way ANOVA analysis was performed for each circumplex model factor: Valence and Arousal. The valence analysis revealed a significant main effect of *Density* $F(1,11) = 7.818$, $p = 0.017$. Dense metamaterials generated more positive Valence ($M = 76.8\%$, $SD = 20.7\%$) compared to Sparse textiles ($M = 61.7\%$, $SD = 20.7\%$), see Figure 9a. The Curved main effect and the interaction were not significant. The Arousal analysis did not reveal any significant effects.

5.2.2. *Godspeed questionnaire*

We performed a separate analysis for the Likability and Animacy subscales of the Godspeed questionnaire. A *Density* main effect was found for both the Likability $F(1,11) = 8.559$, $p = 0.014$ and Animacy $F(1,11) = 5.751$, $p = 0.037$ subscales. Dense metamaterials were more likable and perceived as more animated compared to Sparse textiles (see Figure 9b).

5.2.3. *Mood questionnaire*

The mood analysis revealed main effects for both morphing metamaterial properties (*Density* and *Geometry*) and no interaction effect, *Density*: $F(1,11) = 8.176$, $p = 0.016$; *Geometry*: $F(1,11) = 6.105$, $p = .031$ (see Figure 9c). Dense metamaterials created a better mood compared to Sparse textile designs. Curved textile designs resulted in higher Mood scores ($M = 4.016$, $SD = 0.67$) than Angular designs.

6. Discussion

We introduced an innovative approach for studying the perceived human experience elicited by morphing metamaterials. We believe that morphing metamaterial will play a pivotal role in developing novel shape-changing experiences. Our work shows that metamaterials enable interaction designers to determine the shape morphing behavior using changes in the material-level design, rather than manipulating the external force. The change in design properties directly and systematically affects the metamaterial movement, which in turn impacts the observer's experience. More specifically, we show that the parametric design of the *Density* and *Geometry* properties results in a range of emotional experiences.

Our findings extend prior work by systematically mapping how design properties impact the user experience of morphing metamaterials. Previous work studied the effect of motion and shape properties but not metamaterial design properties. We extend this literature by focusing on the material design itself. As our findings show, changes in metamaterial design properties significantly and consistently influence the perceived human experience. This underscores the importance of including material design considerations into design guidelines for shape-changing experiences. Therefore, our work opens a new space for the creative exploration of expressive shape-changing experiences by material designers.

We kept consistent slow and repetitive movement across all conditions to isolate the effect of morphing metamaterial design. Our findings show that metamaterial design significantly influenced valence and mood. Previous studies by Hu and Hoffman (2019) and Kwak et al. (2014) suggest that movement properties have a notable impact on arousal levels. Thus, exploring motion properties in future work opens an opportunity to enrich morphing metamaterial experiences.

Our findings extend the existing body of work on the emotional perception of movement. Previous works revealed that diverse motion properties (velocity, frequency, amplitude, acceleration, time, and direction) impact arousal levels (Gross et al., 2012; Hu & Hoffman, 2019; Kwak et al., 2014; Strohmeier et al., 2016; Tan et al., 2016), that movement trail and its smoothness account for valence and mood (Sharma et al., 2013; Tan et al., 2016), and that shape-related properties also impact emotional valence (Hu & Hoffman, 2019; Strohmeier et al., 2016). Our unique contribution is the mapping of the independent effect *Density* and *Geometry* design properties have on participants' valence, mood, associations, and preferences.

Below, we unpack the impact material properties have on the perceived emotional experience (Section 6.1), followed by technical insights regarding metamaterial actuation (Section 6.2), and conclude with a set of design guidelines mapping the effect *Density* and *Geometry* properties have on the perceived shape-changing experience (Section 6.3).

6.1. *How material properties influence the emotional experience*

6.1.1. *The effect on participants' emotions and mood*

Material Density and *Geometry* have a separate and significant effect on participants' emotional valence and mood. Dense and Curved metamaterials generate positive valence and mood, and Sparse and Angular metamaterials generate negative valence and mood, with *Density* having the most noticeable impact on emotional experience.

Our findings may be explained by the morphing metamaterial movement traces, considering that angular and sparse designs produce more angular movement traces, and Curved and Dense designs produce smoother movement. P3 explained the Curved design movement *"The movement feels more fluent. There are no edges, so it is much smoother."*; and P5 described how *Density* impacts movement trace *"the cuts are smaller, and as a result, it goes down more gradually."* Santos and Egerstedt (2021) suggest that smooth movement traces tend to be associated with positive valence, while angular traces to negative valence, and De Rooij et al. (2013) argue that the smoothness of a movement is an indicator of pleasantness. Corradi and Munar (2020) propose that the preference for curved movement trace originates from movement in nature, where curved lines indicate normal behavior.

6.1.2. *The effect on participants' associations*

The qualitative analysis revealed that *Density* and *Geometry* were associated with specific metaphors, and *Density* alone significantly influences animacy levels.

Regarding associations, Curved metamaterials were linked with natural entities, while angular metamaterials were seen as objects. The angular metamaterials, in particular, were perceived as unfamiliar and even alien objects. A possible explanation may be that the Curved design movement is familiar and lifelike, while the angular design movement is unexpected. As P11 said, "*It doesn't make sense that such a square shape would rise and fall*" (Angular-Sparse).

Another entity association was living organs. Sparse designs led to negative associations such as dying organs, while Dense led to a positive and neutral living organ association. These qualitative results were reinforced by the quantitative analysis of the Animacy subscale (Bartneck et al., 2009), showing that Dense metamaterials were rated as more life-like than Sparse metamaterials. These findings align with previous research showing that the perception of instability generates associations of fear and suffering (Strohmeier et al., 2016). It may be that negative or positive organ associations result from the perceived instability or stability of the movement, as Dense designs lead to consistent and gradual movement, while sparse designs lead to abrupt movement.

6.1.3. *Participants' preference*

The qualitative analysis revealed participants' preferences, which resonated in the analysis of the Likability subscale (Bartneck et al., 2009). The most preferred experiences were Dense and Curved designs, while Sparse and Angular were the least preferred or even disliked. This tendency aligns with prior findings about the smooth curvature phenomenon studied on objects with curvature shape and contour (Corradi & Munar, 2020; De Rooij et al., 2013; Soranzo et al., 2018). The qualitative analysis reveals participants' explanations for their preferences. For example, P5 explained his preference toward the Dense-Curved *"It rises seamlessly and reminds me of a kite. It is really perfect. It feels natural, comfortable, pleasant, and friendly." and P10* described her preference for the Dense-Curved design *"I feel that the shape and the texture allow us to see the small nuances of the movement."*.

6.2. *Technical insights*

Our primary focus was designing a metamaterial capable of consistent morphing to support systematic evaluation. Building on the work of Qamar et al. (2018), who highlighted the stretch-ability of auxetic metamaterials as a key characteristic for morphing materials, we decided to focus on morphing metamaterials. We extended prior work, which showed how the rotating rigid unit technique leads to a diverse range of morphing metamaterials (Cheng et al., 2020; Groeger & Steimle, 2019; Qamar et al., 2018; Zhai et al., 2021; Zheng et al., 2019), and decided to leverage auxetic structures in the design of metamaterials, allowing us to produce diverse shape-changing experiences. The next challenge involved creating a uniform shape-changing experience for evaluation, which we addressed by first applying cutting patterns to a non-stretchable woven textile using a laser cutter (shown by prior work), followed by actuating the material with electromagnetic solenoids. This approach granted programmatic control over metamaterial movement, making it suitable for consistent shape-changing experiences. Importantly, our technique is not limited to the specific synthetic textile and auxetic metamaterial we focused on. Future studies can similarly evaluate a wide range of auxetic structures and properties, as well as other non-stretchable materials.

From the actuation force perspective, we found electromagnetic solenoids to be an extremely suitable actuation for textile-based metamaterials, for two main reasons. First, the insulated wire can be woven into the textile just like a standard textile thread. This enables material designers to leverage their domain-specific know-how, such as embroidering the wire as a decorative element or using a circular loom or knitting machine to weave or knit the wire as part of the material. Second, the electromagnetic force can be accurately and steadily controlled by a simple Arduino microcontroller. Additionally, its force is adjustable by varying the length of the conductive wire (longer wire results in a stronger electromagnetic field), and the solenoid perimeter (smaller perimeter leads to a stronger electromagnetic field). Additional relevant factors are that solenoid actuators are safe to use since they leverage low electrical current and are cheap and easy to fabricate (Figure 10).

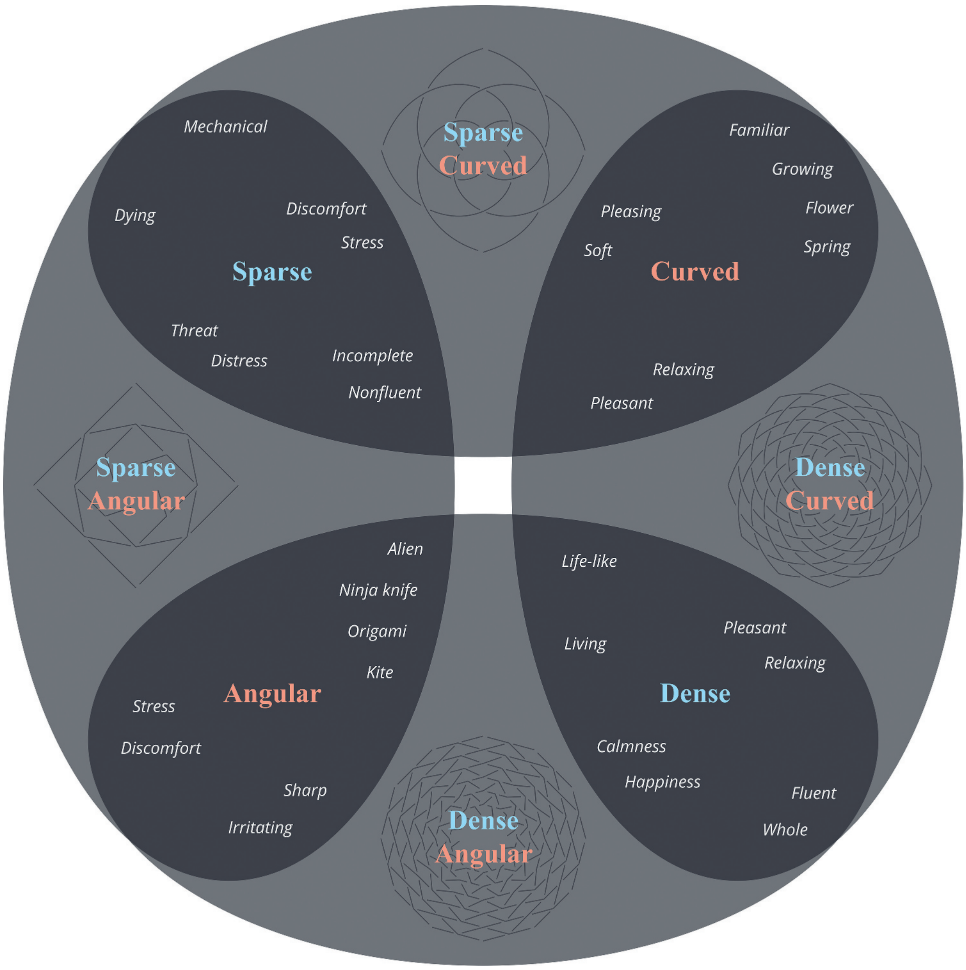

Figure 10. A visual representation of our design guidelines, including the design condition (i.e. "Angular", "curved", "dense", and "sparse") and a selection of themes and sub-themes revealed in the qualitative user study. We did not list all themes, but focused on the ones providing actionable insights for designers. See the findings section 5 for a full list of themes and sub-themes.

6.3. *Design guidelines: how metamaterial design properties impact perceived experience*

We clustered our findings into several design-focused recommendations, focusing on actionable insights aimed at designers of morphing metamaterials.

6.3.1. *The effect on perceived emotions*

In our morphing metamaterial experience, *Density* level had the most significant effect on emotional valence, evoking positive emotions with the most frequent ones being happiness and calmness. Sparse metamaterials evoked negative emotions, such as distress and threat.

6.3.2. *The effect on perceived aesthetics*

Curved designs were perceived as aesthetically pleasing, evoking soft associations like pets or flowers. In contrast, Angular designs were described as unappealing and sharp. Dense metamaterials were seen as aesthetic, described as fluent and cohesive, while Sparse tend to be unsatisfying, described as non-fluent, and incomplete.

6.3.3. *The effect on mood*

Dense morphing metamaterials generated a positive mood that was expressed as relaxing and pleasant, while Sparse led to a negative mood that included stress and discomfort. Although less prominent, Curved designs also impacted mood, evoking a nature-related relaxing experience, such as "A flower evoking freedom and calmness" and "happy sun, full of life." In contrast, angular patterns were associated with mechanical objects such as propeller, metronome, and wheel.

6.3.4. *The effect on metaphors*

Curved morphing metamaterials often generate nature-related associations like flowers, trees, and animals and phenomena-related associations like spring, wind, and growing. Angular metamaterials tend to generate object-related associations, including origami, balloon, and kite. In addition, Curved designs are usually perceived as familiar natural entities or known objects, while Angular designs are perceived as unfamiliar entities such as alien, futuristic, and virtual reality. In addition, Sparse designs are often linked to dying organ associations, while Dense designs are linked to living entities.

6.3.5. *The effect on Animacy*

Density level seems to influence whether morphing metamaterial is perceived as animated. Dense metamaterials are more likely to be perceived as life-like, while Sparse designs tend to be seen as mechanical objects.

We hope our design guidelines can inspire shape-changing materials designers and researchers to embrace material design properties as a relevant and meaningful factor impacting the final shape-changing experience. By recognizing the mapping between material design properties such as *Density* and *Geometry* on the end user's perceived emotion, designers can create more engaging and expressive experiences. Our findings emphasize the importance of thoughtful design decisions when forming an experience with a morphing metamaterial. We particularly look forward to continued exploration of metamaterial design properties, as they offer exciting possibilities for developing novel and expressive shape-changing experiences.

7. Conclusion

In this paper, we conducted a study to evaluate how morphing metamaterial design properties affect people's emotions during shape-changing experiences. Our study found a clear correlation between the *Density* and *Geometry* design properties and users' perceived emotions. Our contribution is a methodology for systematic morphing metamaterial design and implementation that enables a controlled evaluation of specific metamaterial design properties, uncovering their independent impact on the observer's perceived emotions. Our study's findings provide design guidelines on how changes in *Density* and *Geometry* of morphing metamaterial impact emotions, mood, associations, and preferences. In line with Alexander et al.'s call for more systematic research in the shape-changing research community, our work not only contributes new understanding and guidelines about the emotional impact of morphing materials, but also provides a method for material designers to create new morphing materials using parametric design and evaluate their impact on end users. We hope our work will open up new possibilities for metamaterials-focused shape-changing experiences, contributing to more expressive and evocative designs, as well as new understandings of the impact such morphing metamaterial have on perceived experience.

8. Limitations

This work has several limitations. Since the electromagnetic solenoid produces a low force, we were limited to using lightweight materials for the morphing metamaterial, as its weight determines the maximum actuation height possible. Additionally, solenoids can overheat quickly, especially when working with synthetic materials. Therefore, we included breaks in the actuator motion cycle to let it cool down. We acknowledge that the rhythmic movement may lead to a bias toward associations of breath and heartbeat. However, our qualitative findings reveal a wide variety of associations, suggesting that such a possible bias is not strong. Other limitations concern the user study. The study had a small sample size of 12 participants (8 females, 4 males) to enable a detailed qualitative analysis, however it limits the ability to draw statistically significant quantitative conclusions (Castro et al., 2010). We recognize this limitation, which may explain insignificant results in certain measures. Therefore, future studies should use larger samples to evaluate quantitative measures more accurately. Regarding the uneven gender sample (8 females, 4 males), we assume it does not affect the results since previous research has indicated that participant gender does not affect emotion recognition of visual stimulation (Lambrecht et al., 2014; Santos & Egerstedt, 2021).

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Tamar Levy (http://tamar.levy@milab.idc.ac.il) is a graduate of the MA in HCI program at Reichman University, interested in shape-morphing materials, parametric design, and human perception of interactive experiences. She has a dual undergraduate degree from the Hebrew University, a B.Sc in Computer science and a B.Des in Industrial design. This paper summarizes her MA thesis at Reichman University. Tamar also works as a research associate at the university's Media Innovation Lab, leading several research projects on interactive materials and wearable technology.

Hadas Erel (http://hadas.erel@milab.idc.ac.il) is an assistant professor at Reichman University's Media Innovation Lab, a Human-Robot Interaction (HRI) researcher and a cognitive psychologist, leading the social HRI research at the lab, with special focus on basic research with non-humanoid robots.

Oren Zuckerman (http://oren.zuckerman@milab.idc.ac.il) is an associate professor at Reichman University's Media Innovation Lab, an HCI researcher focusing on tangible collaboration and shape-changing interfaces. He is the founder and director of the Media Innovation Lab (miLAB), and head of the MA in HCI program at Reichman University.

ORCID

Tamar Levy http://orcid.org/0009-0006-4684-8420
Hadas Erel http://orcid.org/0000-0001-7099-6104
Oren Zuckerman http://orcid.org/0000-0003-1310-6499

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