Soft Speakers: Digital Embroidering of DIY Customizable Fabric Actuators

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Figure 1: Soft Speakers: digitally embroidered audio and haptic actuators on fabrics in three steps: 1) Digital design of the speaker pattern using Adobe Illustrator or Artistic Digitizer Software, 2) Digital fabrication using conductive thread in a digital embroidery machine; 3) Implementation into soft interfaces and wearables

ABSTRACT

We introduce Soft Speakers, a systematic approach for designing custom fabric actuators that can be used as audio speakers and vibro-haptic actuators. Digitally-embroidered with e-textiles, we implement Soft Speakers as tactile, malleable and aesthetic designs to be part of wearables, soft furnishing and fabric objects. We present a rapid technique for the DIY fabrication of audio feedback into soft interfaces. We also discuss and evaluate 7 factors for their parametric design in additive and constructive methods. To demonstrate the feasibility of our approach and the breadth of new designs that it enables, we developed 5 prototypes: 3 wearables, a piece of furniture and a soft toy. Studying Soft Speakers with maker-users expanded the design space, empowering users and supporting inclusive design. Our study includes insights on user experience of real-world interactive applications for remote communication, e-learning, entertainment, navigation and gaming, enabled by Soft Speakers' customizable and scalable form factor.

CCS CONCEPTS

• **Human-centered computing → Human-computer interaction**.

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KEYWORDS

e-textiles; research through design; digital-embroidery; digital fabrication; wearable computing; inclusive design; interactive furniture.

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1 INTRODUCTION

This motivation stems from the notions of ubiquitous environments [52], Radical Atoms [15] and the design of everyday computational objects [43]. As technology increasingly blends into the fabric of our environment, the gap between 'devices' and other physical objects will disappear and the boundaries between seamless and seamful interaction will no longer be perceived [24]. For example, virtual assistants such as Alexa could be integrated into devices with various form factors to suit different soft objects that match various aesthetics and interior or fashion styles, rather than aiming to look like a 'smart speaker'. We could soon be listening and talking to garments, bags, cushions, throw blankets and curtains. Figure 2 shows the scope of Soft Speakers versus conventional speakers in expanding audio and haptic feedback to soft interfaces, wearables and soft furnishing.

Soft Speakers –versus rigid/bulky speakers– could be more suitable for soft objects, lightweight for wearables and relatively appropriate for washability. Moreover, the proposed fabrication method supports DIY, makerspace culture, low-cost and accessible scalability and customization.

We believe this gap is a missed opportunity that could benefit from research through design. Our approach to design, fabricate and implement such speakers was based on learning through making, where our making and observation of over a 100 swatches and samples form insights for the future research of e-textiles, soft interfaces and wearables' design. Herein, we will discuss the design and fabrication of Soft Speakers, as well as five applications that demonstrate the potentials for fashion, interior and product design of soft interfaces.

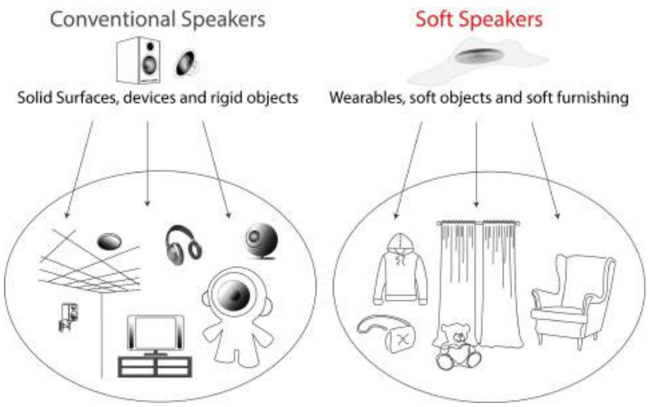

Figure 2: The motivation for Soft Speakers is to expand audio and haptic feedback to the scope of soft interfaces, wearables and soft furnishing.

The key contributions of this paper are:

i. Introducing a systematic approach in 3 steps for designing, fabricating and implementing fabric speakers into everyday soft objects.

ii. Identifying 7 technical and design parameters and properties as well as results of our experimental evaluation of Soft Speakers.

iii. Prototyping 5 real-world applications that demonstrate the benefits and limitations of Soft Speakers (including wearables, furniture and domestic objects) focusing on in-the-wild user experience.

2 RELATED WORK

This paper builds on research in e-textiles and wearable fabrication techniques, interactive furniture and domestic decorative speakers.

2.1 Speakers and e-textiles

The fabrication of real-world applications using e-textiles at scale still remains a problem that is not yet fully solved [47]. Although a good deal of research has looked into wearables and e-textiles [3, 16, 31, 40, 56], it predominantly focuses on soft sensors [2, 30, 34, 50, 55], lighting LEDs [12, 36] and morphological actuators [19, 25, 39, 51], despite the potentials anticipated from full soft circuits [4, 33]. Limited research on audio feedback only considered 'sound sequin' [55] as piezoelectric actuators and interactive headphones [29], both in rigid form factors.

The concept of designing fabric speakers has been recently explored by artists [17, 44, 45] and textile designers [18, 27, 54], engaging the DIY community (via instructables [32]) and workshops' participants [13] in hand-embroidering conductive yarns, screen-printing conductive inks and ironing-on conductive tapes on different fabrics. Recent work on laser-cutting conductive sheets [11] can be similarly utilized to create replicable and scalable paper speakers [5, 45]. Moreover, prior work on fabricating e-textile speakers either relies on specialized hand-crafting skills, cannot be rapidly or accurately replicated or is not systematically predictable. Digital embroidery machines can be used to automate embellishment design and add layered dynamic aesthetics to wearables and soft objects [20]. Concurrent research utilized digital embroidery to create conductive coil shapes for induction sensing [10] and fabric speakers [41]. Despite this recent work, little focus has been situated around accessible and inclusive design, and user experience of such a concept.

In part, the reason could be due to the sophisticated design process of aforementioned examples depending on professional training, intricate creative practice and specialized textile machines (such as the Tajima) [18, 20]. Such expensive equipment (ranging from \$12,000 to \$60,000) limits exploration to exclusive specialized centers around the world. We aim to enable similar fabrication results as textile designers, with affordable means and off-the-shelf equipment and tools (e.g. using less sophisticated digital embroidery machines starting at \$550), to make the design of fabric speakers accessible to a vast array of researchers, designers and even users.

2.2 Speakers in Interactive Furniture

Researchers have explored the potential of interactive furniture and soft furnishing at home, with examples ranging from hard objects such as tables [9], chairs [42] and lamps [21] to soft furnishing such as upholstered chairs [28], sofas [22], carpets [46], table-cloths [23, 49] and curtains [48]. Instead of introducing new gadgets and devices to our living spaces, such interactive designs augmented pre-existing home objects with sensing and/or actuation within the fabric of our surrounding environment itself.

Such prior work on interactive furniture focused on exploring user experience in interacting and/or living with such everyday things as computational objects. Findings showed how embedding interactivity within everyday artifacts can support social engagement [21, 23, 48], self-reflection [9, 22, 46] and self-expression [49]. The interactivity embedded included soft sensing [23] and feedback in the form of display of information [42, 48] or actuation (such as motion, colour-change [22, 46], pattern-change [9] and shape-change [23]). However, previous work on embedding audio and haptic feedback in interactive furniture and soft homeware is yet to be explored. This is partially because rigid speakers (i.e. the predominant form factor for audible output) are not appropriate for soft furnishing in terms of living comfort and material affordance.

2.3 Speakers in Homeware

From a product design perspective, the design of home speakers is moving towards aesthetic appeal and more decorative stylish designs than ever before. The latest products that are now available in the market are designed to blend into interior spaces, and often disappear in the background of our environments, rather than stand out as 'digital devices'. For instance, Bang & Olufsen has recently released different powerful wireless sound speakers [1] that are entirely user-customizable and scalable into any forms, patterns and colours to match users’ aesthetic and acoustic preferences. With a large array of designs, patterns and form factors to suit people, tomorrow’s speakers will go beyond efficiency and allow users to express themselves in new ways. As Weiser envisioned decades ago, technology will recess into the background of our lives [52] and will become far less obtrusive.

This, in part, answers the question of: ‘Why speakers should look aesthetically pleasing and be an integral part of our spaces and wearables?’ while also carefully considering the user needs in a rather more ‘personalized’ and ‘customizable’ approach. In this sense, Ishiguro and Poupyrev [14] have proposed the design and fabrication of 3D printed speakers, suggesting that: “*The speaker can take the shape of anything from an abstract spiral to a rubber duck, opening new opportunities in product design.*” [14, p. 1]. However, rigid and non-malleable form factors remain dominant in this case, excluding applications in wearables and soft furnishing.

3 SOFT SPEAKERS

Inspired by machine-embroidered sensors [10, 12], paper speakers [5, 45] and their e-textile version [38], we wanted to establish digitally-embroidered fabric speakers as a means of interactivity that can be embedded seamlessly into soft artefacts. To digitally-design fabric speakers, we first need to break speakers down into their basic components.

variations.jpg

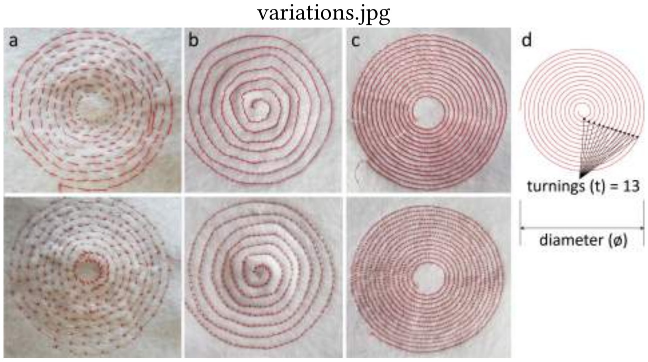

Figure 3: Soft Speakers using: a) hand-embroidery (1-4 hours); b) mechanical sewing machine (20-40 min); and c) digital sewing machine (2-4 min); and d) the arithmetic spiral pattern

Basic Principles: The basic idea of a dynamic speaker is that a coil of a highly conductive material is wrapped around in proximity to a magnet producing an electromagnetic field when electric current flows through. This electromagnetic field translates the electrical signal into an audible sound. Therefore, the stronger the magnet and the more conductive the coil material is, the higher the volume of the speaker.

Hand-Embroidered Speakers: Crafting a soft speaker can be hand-embroidered using the couching technique of conductive thread in a plane spiral shape instead of a 3D coil. The fabric speaker is then placed on top of a magnet (placed in the centre of the stitched coil) and connected to an audio amplifier. The embroidered speaker is as thin as the fabric membrane it is stitched to and can be used in everyday soft interfaces which will act as both an embellishment and a speaker. The drawback of creating soft speakers with hand-embroidery is that it is both time consuming and needs experience and exquisite precision to hand-stitch the conductive thread neatly in a spiral path close together but without touching each other (Figure 3.a). Although a sewing machine can be used to enhance this process [37], it is still not ideal and relies heavily on training for manual maneuvering of the fabric to achieve the desired condensed curves (Figure 3.b).

Digital Embroidering Soft Speakers (Our Approach): Taking the previous technique further, fabric speakers can also be crafted using a digital sewing machine. By designing the coil shape on a digitizer illustration software, and uploading the machine’s bobbin case with conductive thread, we can obtain precise stitches that create better quality soft speakers custom-made to the size and sound volume in a more usable, replicable, and efficient technique (Figure 3.c). Figure 1 shows this process in three steps: design, fabrication and implementation.

patterns.jpg

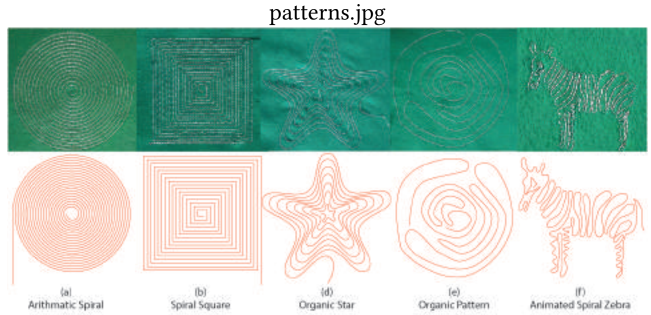

Figure 4: Examples of geometric, organic and animated spiral patterns for soft speakers and vibro-haptic actuators

3.1 Design

Our approach is based on digitally designing soft speakers using illustrator software programs, e.g. Adobe Illustrator, EmbroideryEditor or Janome Artistic Digitizer. Using such tools, not only can we create parametric designs, but we can also convert digital images and patterns into spiral composites that function as fabric actuators. To use conductive patterns as DIY speakers with off-the-shelf amplifiers, the resistance of the material used should be equal to 4 Ω, 8 Ω or 12 Ω. The conductive materials we relied on during our experimentation and designs were the Karl-Grimm[1] high-flex 3981 Cu threads (with 7×1 ply-twisting and synthetic core) due to their high conductivity, low resistance (2.3 Ω/m) and reliability (breaking strength at 2.8 kg) in comparison to other off-the-shelf conductive threads. We used both the copper and silver-platted threads that have unique features of being solderable, less fraying, stronger and more reliable.

[1] http://www.karl-grimm.de/

Conductive Thread	Karl-Grimm High-Flex		Adafruit Stainless Steel	
	Copper	Silver-plated	2 Ply	3 Ply
Resistance (Ω/m)	2.3	1.7	4.9	3.0
Diameter (mm)	0.42	0.42	0.2	0.25
Breaking Strength	2.8 Kg	2.8 Kg	-	-
Length of 4 Ω (m)	1.74	2.35	0.82	1.31
Length of 8 Ω (m)	3.48	4.71	1.64	2.62
Length of 12 Ω (m)	5.22	7.06	2.46	3.94
Price (USD/m)	$0.02	$0.02	$0.34	$0.49
Solderable	Yes	Yes	No	No

Table 1: Comparing off-the-shelf conductive threads.

3.1.1 Arithmetic Spirals. We explored different spiral shapes and found the arithmetic spirals to be the most efficient in terms of functionality. The arithmetic spiral, also known as the Archimedean spiral, is characterized by a spiral pattern of n loops (or turns) where each turn expands uniformly at equal gaps (Figure 3). The arithmetic spiral starts at the origin where r and φ denote the distance and angle from the start point respectively. To determine the resistance of the entire spiral, the unit resistance of the spiral's material should be multiplied by the total length (l) of the spiral, calculated by the equation below:

$$l = \frac{a}{2} \times \left[\varphi \times \sqrt{(1+\varphi^2)} + ln \left(\varphi + \sqrt{(1+\varphi^2)} \right) \right] \quad (1)$$

Where a and φ can be calculated (for $n > 0$) as below:

$$a = \frac{r}{\varphi} \text{ and } \varphi = 2\pi n$$

For reference, Table 1 compares different types of off-the-shelf conductive threads and the relationship between the resistance and length of arithmetic spiral Soft Speakers.

3.1.2 Arbitrary Patterns. Through experimentation and observation, we learned that Soft Speakers can be also designed in other non-spiral patterns. This is an interesting design factor in applications that do not require high quality sound and focuses more on aesthetic qualities. Examples of such designs (see Figure 4) can be geometric (e.g. squares, stars, triangles), organic (e.g. ovals, curves, swirls) and other motif patterns (e.g. floral, animal, abstract, etc). The latter can be designed by spiraling a digital image or digitizing a spiral continuous drawing. Examples of applications that can benefit from such arbitrary patterns include vibro-haptic feedback and microphones as visible embroidered patches onto wearables and soft objects. The challenge of such designs remains in constructing the embroidery with the accurate thread length i.e. resistance.

3.2 Fabrication

Machine Settings: We used the professional home-sewer Janome Memory Craft 500E Embroidery Machine ($1400 USD). We set the machine on auto-tension with maximum sewing speed of 600spm (i.e. stitch per minute). The "thread cutting command" should be switched off and excess conductive thread at the start and end of every embroidery job should not be trimmed to accommodate for electronic connection to the circuit. The "resume mode" is helpful to enable aggregation of parts of the embroidered circuit particularly in the case of 2-channel speakers with other embroidery elements.

Software Settings: To create a parametric design of an arithmetic spiral on Adobe Illustrator, these steps can be followed: 1) Create 2 circles with the same center (the smallest determines φ and the largest with radius r); 2) Blend them with specified steps = $[2t-2]$; 3) Expand the object, ungroup, cut half of it and paste in place; 4) Drag them to align together and delete every other arc; 5) Join the shape and save the image file. Then, the Trace Image option can be used to import the design into an embroidery editor. Depending on the software options, a vector or a raster graphic can be used, where the former is preferred for precision. In either cases, fills and backgrounds –caused by imported images- should be deleted from the design or skipped during embroidery.

Practical Tips: Conductive thread breaks through the pathways when placed in the spool pin, but works properly in the bobbin case. Careful balanced winding of the conductive thread in the bobbin helps achieve neat seams and prevent knots, breaks and crossovers. Spool holders and bobbin huggers can be used to store conductive thread in place and prevent them from unwinding. For sustainable design, we encourage good practice of saving all extra trimmed thread (both conductive and passive) to upcycle later into conductive yarn fill (useful for making squeeze sensors for instance).

We provide examples of speaker patterns on Github[2] (designs, embroidery files and data files). These designs are not an exhaustive list but are rather validated instances and guidelines. In section Applications, we scale, combine, and modify these Soft Speakers to better satisfy the requirements of different applications and use cases.

3.3 Implementation

After embroidering the Soft Speaker, we can connect it to other electronic components required for the sound to be audible. Figure 5 shows an illustration of the circuit with the embroidered pattern being the top, and optionally-visible, layer adjacent to a magnet and connected to an audio cable through a miniature 4-8 Ω amplifier. Other amplifiers (e.g. 12 Ω) can be also used for larger embroidered speakers. Such a circuit would function on-demand, i.e. whenever the audio cable is connected to an audio source of any device (such as a computer, tablet or mobile phone), the speaker will operate. We recommend using Class D amplifiers as they only draw power when there is an audio signal connected. Alternatively, (sewable) microcontrollers can be added to allow for programmed input-output control. In all cases, the circuit can be powered with either a rechargeable 3.7 V LiPo battery that can be removed as needed or a 5 V DC adapter.

There are a number of parameters that determine the performance of Soft Speakers. Below we present each of these parameters to enable the understanding and replication of such scalable actuators.

3.3.1 Design Parameters (DP).

(1) Membrane (DP1): The stiffness and (other) properties of the fabric influence the amount of sound produced or causing the

[2]Available at: https://github.com/snabil2/Soft-Speakers

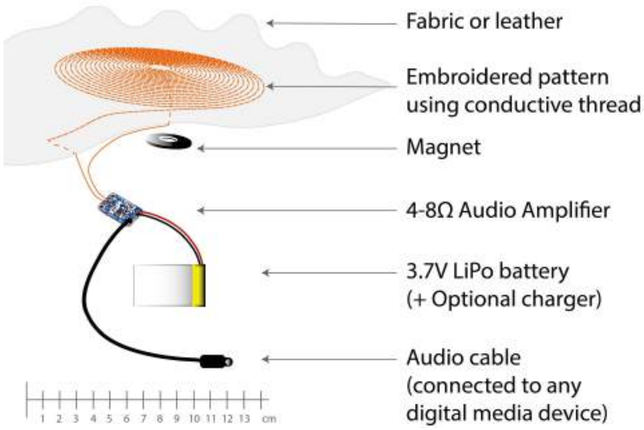

Figure 5: Illustration of the Soft Speaker circuit consisting of the embroidered layer hiding a magnet underneath and connected to an audio cable through an amplifier that is powered by a rechargeable LiPo battery.

fabric to vibrate. We experimented mostly with felt fabric for low-cost plentiful samples, however craft felt is less efficient than thicker types (3-5 mm). A work around to strengthen the fabric is to add an adhesive interface layer (i.e. stabilizer) before embroidering the speaker pattern to give it the firmness required for the bounce of audio waves. Lightweight fabrics such as chiffons, satins and tulle can then be used for both audio and haptic feedback as the fabric vibrates with no audible sound. On the contrary, leather, vinyl and skin are ideal materials for embroidering high-volume speakers due to the material affordance.

(2) Thread Type (DP2): The thread used for embroidering Soft Speakers should be of a highly conductive material. Examples of conductive threads include copper, silver-plated copper and stainless-steel; the latter being the least conductive. Thus, speakers designed with Cu-core conductive thread can be of highest performance. Table 1 shows a comparison between different off-the-shelf conductive threads.

(3) Embroidery Pattern (DP3): The pattern of the embroidered speaker has significant influence on the quality of the produced sound. Theoretically, spiral speakers function better than random patterns but our experimentation shows that non-geometric, organic and arbitrary patterns of spiral fill can also generate an audible sound. The more the pattern consists of turns in a smaller surface area, the more it is efficient as an actuator. However, this is highly affected by DP2 where the type of thread used determines the resistance (Ω) per unit length.

(4) Embroidery Stitch (DP4): Conductive thread should be embroidered with a basic running stitch on a balanced tension, then extra embroidery details can be layered on top. In fact, lowering the needle thread tension causes many issues that affect the performance of the speaker. However, inserting the conductive thread through the tension-adjusting spring (or notch) of the bobbin case should be skipped to avoid short circuiting the speaker. To form a strong balanced stitch, the tension knob (or digital setting) can be turned up and down until perfect seams are tested. Ideally, stitches should be evenly spaced on both sides of the fabric with each thread lying flat against its side of the fabric. Conductive fuzz residing along the pathways or inside the bobbin case may also cause imperfections.

(5) Magnet Strength (DP5): Soft Speakers are electromagnetic speakers, meaning that they rely on the force of a magnet and its movement towards and away from an electromagnetic coil to make the vibrations and audible output [14]. The stronger the permanent magnet, the larger the movement, which results in louder sounds. Neodymium rare earth magnets are the strongest magnets currently available [8], and with Soft Speakers they produced the most movement and loudest sounds. Designers and users can also change the volume with magnet proximity, giving users control over the volume and the ability to adjust it to their own needs. The magnet strength should be proportional to the surface area of the embroidered pattern (e.g. spiral), so the overall dimensions of the pattern should be within the range of the magnetic field.

(6) Pattern variables (DP6): Both the diameter of the spiral and the number of turns determine the gap between arcs and how tightly the spiral is wrapped; therefore the quality of the generated sound. The more turns can fit in a smaller area, the louder the speaker will be [38]. The most crucial parameter is the total length of the spiral that depend on the used amplifier (typically 4 Ω, 8 Ω or 12 Ω) for the speaker to function properly. This length can be calculated through equation (1).

(7) Audio file (DP7): It is understandable that sound quality of the audio output would depend on the audio quality displayed. However, it is also crucial to consider the frequency and volume of the original audio with respect to the application. For example, if an application employs vibration with no audible output, an audio file of 20 Hz can achieve the desired actuation. Techno music also vibrates the fabric membrane but with accompanying loud audio output.

4 TECHNICAL EVALUATION

General evaluation and quantitative analysis of fabric embroidered speakers is discussed in details by Preindl et al [41]. Since our study focuses on user experience and DIY making, it was vital to provide maker-users with accessible and easy-to-read graphs to help them design their Soft Speakers. To deduce the variables of speaker diameter and turns (DP6), we used equation (1) to identify the ideal values for generating effective speakers for off-the-self amplifiers. This analysis created charts (see Figure 6) that helps understand the relationship between spiral variables and speaker resistance. These charts show three graphs representing 4 Ω, 8 Ω and 12 Ω Soft Speakers (embroidered with 2.3 Ω/m conductive thread) respectively. Figure 6 also shows a heatmap of the resistance (Ω) of arithmetic spirals depending on the diameter (ø) and number of turns (*n*).

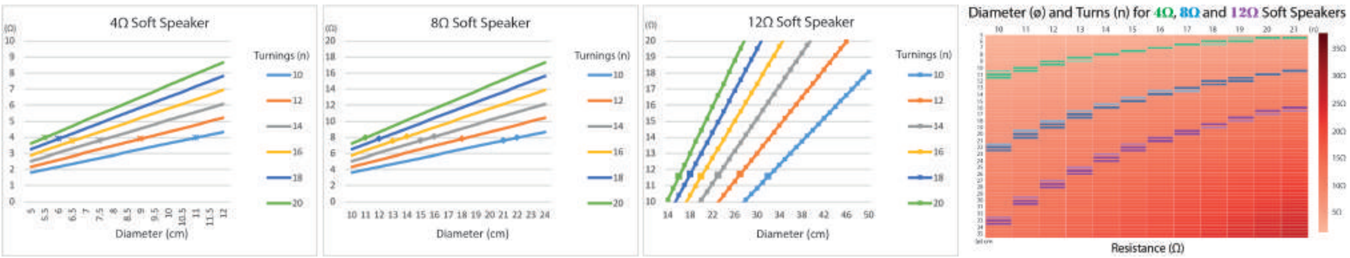

Figure 6: (Left) Measuring the resistance of Soft Speakers designed as arithmetic spirals based on their diameters and turns. (Right) Heatmap of the resistance (Ω) of arithmetic spirals based on the diameter (ø) and turns (*n*) for the fabrication of 4 Ω (green), 8 Ω (blue) and 12 Ω (purple) Soft Speakers.

To evaluate the sound quality of Soft Speakers, we used the Audacity Software's frequency spectrum analysis with a spectrum algorithm (size: 512), Hann window function and a linear frequency axis. This spectrum plot algorithm allowed us to sequentially input different samples, which we experimented to compare variable parameters. By fixing all other parameters as controlled variables (e.g. DP3, 4, 6 and 7), we can plot comparative charts of other variable parameters such as membranes (DP1), thread types (DP2) and magnets (DP5). Figure 7 shows these audio spectrums and the impact of different types of fabric membranes, threads and magnet strengths on the sound (in dB) of Soft Speakers.

During our experiments, we used a mono channel amplifier and 4 Ω arithmetic spirals with 16 turns and ø=73mm embroidered with silver-plated Cu thread (Karl-Grimm high-flex 3981 7×1) as fixed parameters to measure audio dB with respect to a 0 to 20 KHz audio sample. The results indicate that leather forms the best membrane for clear loud speaker sound while the thin delicate fabrics such as tulle, chiffon and lace as the least efficient (yet utilizable for haptic feedback). Analysis results also show the impact of magnet strength on the output in a directly proportional relationship.

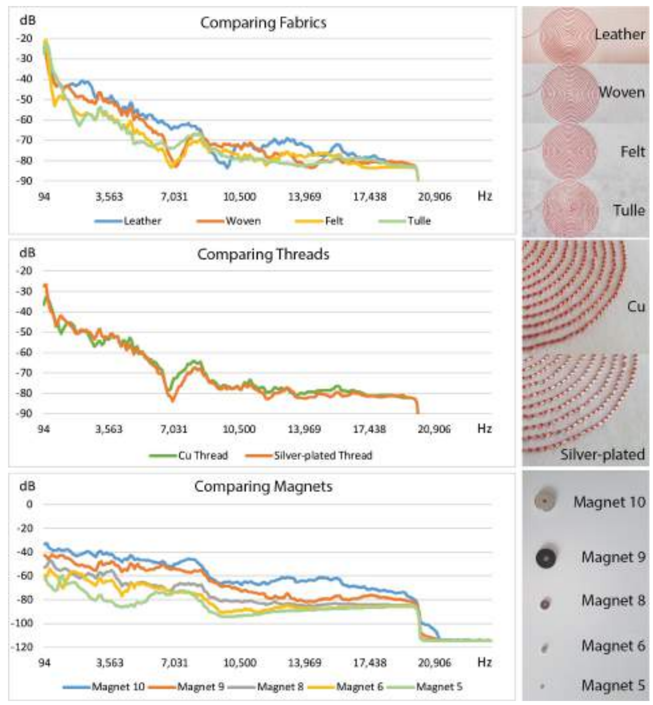

Figure 7: Frequency spectrum analysis of Soft Speakers audio dB comparing different fabrics, threads and magnets.

5 APPLICATIONS

To demonstrate Soft Speakers, we elaborate on what applications may benefit from the use of the proposed fabrication method. We discuss potential applications and present the design, fabrication and user experience of living with: a wearable winter hat (the Talking-Tuque), a haptic-audio t-shirt (the tectonic-tshirt), a headscarf (the Sound-Scarf), a piece of furniture (the Listening-Chair), and a soft object (the Teacher-Teddy). Our design decisions to realize each prototype are informed by the Design Parameters (DPx) learnt and discussed in the previous section. Our prototypes employ some aesthetic customization of Soft Speakers with coloured threads and the use of magnets as embellishment in addition to other non-functional decorative elements.

5.1 Methodology

To explore the in-situ potentials of deploying Soft Speakers in-the-wild, we used autobiographical design [7, 26] as a methodology to reflect on the lived experience with Soft Speakers, and to better understand how users might want to customize them. Autobiographical design research draws on extensive genuine usage by the designer of the system [26]. Moreover, our evaluations included the key features of this design method including: genuine needs, real systems, fast tinkering, record keeping, and long-term usage [6].

Through 3 weeks of study, the first author and their family designed, built and lived with these prototypes of Soft Speakers. Because the first author lived with the prototypes, any tinkering needed or adjustments to the design that family members requested could happen immediately in real time. We captured field notes throughout and users' names were mapped to aliases for anonymity. The family consists of 4 participants (3F, 1M): the first author (alias: Sally), her husband (alias: Adam) both within age range 30-40, and two children (aliases: Judy(12) and Mary(7)). Through the ethnographic account below, the first-person tense is used, to denote the experience of the first author's family.

5.2 Talking Tuque (Accessible Design)

The Talking-Tuque is a winter hat with two embedded Soft Speakers embroidered within: one on each earflap. Figure 8 shows the design process and making of the Talking-Tuque from the pattern and digitally embroidering Soft Speakers to testing and stitching the audio amplifier circuit.

Figure 8: The making of the Talking-Tuque: a) Sketching the design; b) Digital embroidering Soft Speakers; c) Stitching the audio amplifier circuit to the fabric; d) Sewing the layers together with zippers and some embellishment; and e) The hat worn in winter on either face.

5.2.1 User Experience. Judy couldn't use earphones that fit her ear size and with 6 months of winter where she lives, she had a need to combine her winter hat with headphones explaining: "*you can't really walk around in headphones in winter, and you can't wear it on top of your tuque. Some people use earphones but I don't find them comfortable*". She sketched her design with a colour palette inspired from her winter suit. We used a matching wool yarn to add some embellishment (in the form of: couched seams, 2 dangling braids, and a pompom on top) for the aesthetic desirability of the hat. Finally, we added an invisible zipper with a matching colour to allow easy access to the sewn circuit. When Judy wore it during her outdoor walks, she used it to listen to her favourite sound track and navigate Google-Maps. She was happy and excited to be able to clearly hear the directions, while staying warm and without headphones, just by plugging the audio jack in her hat's braided chin tie: "*I love how it's easy to use and easy to access the electronics inside*". Mary elaborated: "*This is way better than headphones, because you can walk with it without anyone noticing that you're listening to anything… It's more comfortable because it's soft and fabric so it is much better because it warms my ears, covers my head and a speaker… [but] nobody else can hear, then I can have something [private] playing and no one else would say oh what's that?*"

5.2.2 Design and Fabrication. We made the hat using three layers: the embroidered Soft Speakers circuit layer, an insolation layer and a second external layer. The two external layers form a reversible design to allow personalization whether the wearer wants to show the embroidered Soft Speakers or not (the speaker can be on the inside or outside of the hat). The circuit could be wirelessly connected to a smart phone or iPod in the user's pocket (using a Bluetooth connector sewn to the hat), but for this prototype we designed the audio jack in the decorating dangling braid to be connected to the phone's audio cable. We used felt fabric as the membrane material (DP1) of the Soft Speakers to support warmth and sturdiness durable for frequent wearing in cold days, yet low-cost. The two embroidered speakers on both sides are 4 Ω arithmetic spirals (DP3) with turns(n)=15 and diameter(ø)=73mm (DP6) using silver-plated conductive thread (DP2). We connected both spirals to a two-channel Adafruit stereo 3.7W Class D Audio Amplifier. We also stitched a sewable circular magnet (ø=15 mm, H=3 mm with 5 mm hole) to the center of each spiral (DP5). To power the circuit, we connected the amplifier to a 3.7 V 150mA LiPo battery (20×26×3.8 mm) with a micro-Lipo charger that can be used to recharge the LiPo battery with a MicroUSB cable. In this sense, the battery is not soldered to the circuit, but is connected to it (through a 2-pin JST-PH connector) and can be removed for washability and safety purposes.

5.3 Tectonic-Tshirt (Gaming Application)

The Tectonic-Tshirt is a t-shirt with two embedded Soft Speakers embroidered on the upper back. Figure 9 shows the design process and making of the Tectonic-Tshirt.

Figure 9: The making of the Tectonic-Tshirt: a) user sketch; b) pattern design; c) and d) digital-embroidery of Soft Speakers as part of the whole design; and e) wearing the t-shirt with Soft Speakers while gaming for personalized sounds and vibrations.

5.3.1 User Experience. Adam expressed curiosity to create a gaming application that suits his interests. He enjoys video games but has to mute the sound while playing among his family to avoid disrupting them. He also refrains from wearing headphones that are perceived by his family members as offensive and isolating from their shared aural space. His idea was to embed vibro-haptic Soft Speakers in his T-shirt to be connected to his mobile gaming apps generating private audio feedback and on-skin vibration with the games' sound effects. He expressed the value of personalized designs and customization by elaborating that: "*It's a nice fancy idea. People like to choose what they wear, and the designs that appeals to them. Designing my own clothes in addition to the functionality that I want as well, this is really cool. Instead of shopping around between ready-made designs that I like or don't because it is missing something, I wish it just had this or didn't have that, this is better… I chose this pattern because it matches my personality. I like these designs in general. I really like [it]… has speakers without headphones, and you're comfortable walking around, [it] is way better of course*". Adam also explained the limitations by stating that: "*The only drawback in this, is the wire to the phone. It needs to be wireless or Bluetooth. Then it will be even more flexible and totally separate from the device. Then* *one can walk around totally free from wires attached to his ears or clothes... In the future, it could be controlled via mobile app or smart watch, so you can mute, play, etc, that would be really nice.*"

5.3.2 Design and Fabrication. Seeking to make a T-shirt with speakers for video games (which also vibrates with the game interactions), Adam designed an embroidery pattern that incorporates Soft Speakers. Figure 9.a shows his sketch that together we imported into the embroidery editor software, adjusted the dimensions and added stitching details. The final design was 279×95 mm to cover his upper back muscles for haptic-audio sensation. One each side, we incorporated a Soft Speaker underneath the design as the first embroidery layer. As the digital machine embroidered his T-shirt, Adam commented: "*I love how my design turned out, I like the neat sharp edges and the contrast between red and black. I like how the speakers are not visibly clear in it.*" We used a white cotton t-shirt as the membrane material (DP1) for comfortable gaming and to emphasize the versatility of the design. As the application is for sound effects not for vocal communication, the use of an arithmetic spiral was not essential and we opted for a slightly alternative shape that better fits the design. The 4 Ω speakers were arithmetic spirals distorted to a 70×60 mm oval shape (DP3) with turns(n)=18 (DP6). We embroidered the spirals using silver-plated conductive thread (DP2) with white sewing thread for blend in the background of the design. We placed the circuit on the front of the t-shirt to highlight seamfulness: "*I want to show the electronics but still be able to wash it*". Therefore, Adam chose to use snaps for connections between the Soft Speakers' conductive thread and the amplifier circuit. He then soldered the electronic components on a 1 mm bendable circuit board that he cut to a matching shape of the embroidery design. He explained design decisions that enables not only easier fabrication but also better usability: "*it is better that I had put the circuit outside, so if anything happened, I can just snap it off my t-shirt anytime and put it back in easily… I was thinking of making the connections with magnets, but wondered whether it is healthy, but this [snapping] is better*".

5.4 Sound-Scarf (Inclusive Design)

The Sound-Scarf is a women's scarf with two embedded Soft Speakers embroidered within: one on each ear. Figure 10 shows the design process and making of the Sound-Scarf from digitally embroidering Soft Speakers to testing and stitching the audio amplifier circuit.

5.4.1 User Experience. Sally is an academic who likes to maintain a professional look and wears a scarf for religious reasons: "*While at work, I find it uncomfortable to use headphones on top of my scarf and even more challenging to use earpieces as it gets tangled with my covered hair*". Supporting diversity and inclusive design, Soft Speakers inspired a technically simple DIY solution to embed 'sound in a scarf': "*I used to think that no headphone designer ever considered a user with a headcovering. Now with this 2in1 scarf, I feel empowered.*"

5.4.2 Design and Fabrication. We made the scarf using a circular-pattern fabric that we cut into an appropriate size for a scarf. Using red sewing thread, we digitally embroidered two speakers to stand-out as part of the fabric pattern, to "*look like an embellishment on the fabric*". The connections between the two speakers and the circuit

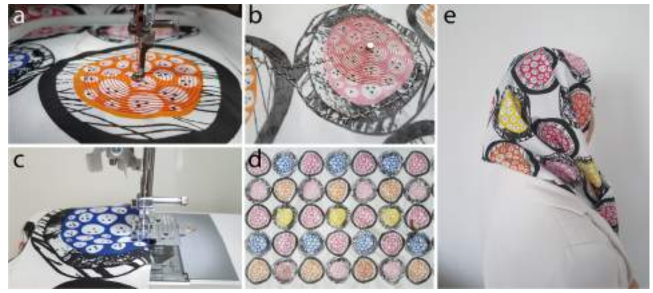

Figure 10: The making of the Sound-Scarf: a) digital embroidery of arithmetic spirals; b) attaching the magnets; c) sewing the scarf; d) stitching the amplifier circuit; and e) wearing the Sound-Scarf and listening to the Soft Speakers.

was sewn with the same continuous conductive thread of the speakers using a sewing machine's zigzag stitch to blend in the scarf pattern. The scarf can be connected to the audio device using an audio cable. We used woven fabric as the membrane material (DP1) of the scarf to support headcovering and sturdiness for frequent use. The two embroidered speakers on both sides are 4 Ω arithmetic spirals (DP3) with turns(n)=16 and diameter(ø)=65 mm (DP6) using silver-plated conductive thread (DP2). To eliminate electric wires, we soldered the conductive thread of the speakers directly to the two-channel auto-gain Adafruit stereo 3.7W Class D amplifier.

5.5 Listening Chair (Comfy Communication)

The listening-chair is an armchair with two embedded Soft Speakers embroidered within: one on each wing. Figure 11 shows the design process and making of the Listening-Chair from digital design and embroidery to the assembly and situation in the living room.

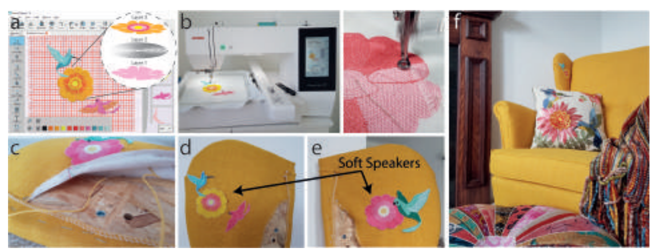

Figure 11: The making of the Listening-Chair: a) Digital design; b) Embroidering Soft Speakers; c) connecting the speakers to the circuit; d) and e) Testing left and right sides/channels; and f) Living with it at home.

5.5.1 User Experience. We, Sally and Adam, both work from home on our laptops attending several online meetings per day. "*We want to share the comfort of our living room as we work but our laptop speakers cause significant distraction to one another during every meeting. Alternatively, headphones are not respectful or comfortable for us*". Supporting privacy without isolation, we thought of a meetings' chair that could have soft speakers inside. The couple tried to schedule their meetings at non-conflicting times to each enjoy the comfort of the Listening-Chair.

After one of Sally's meetings, Adam stated: "*[The chair's speakers] did not disturb me at all or cause any noise*". After one of his meetings on it he commented: "*The sound is clear and I'm able to increase the volume and the more I increase it no one else seems to be hearing it or annoyed by the sound effects of my video game… only I can hear it clearly but at the same time I don't have to use annoying headphones on my head or in my ears*". Intrigued, Judy also asked if she can use it for her online lessons and felt empowered that she was the only person in the room that could hear the teacher: "*Really? You can't hear anything? I can hear it clearly!*".

5.5.2 Design and Fabrication. To make the Listening-Chair, we hacked an Ikea Strandmon armchair that we chose because: 1) it has two side wings that allows the speakers to be in proximity to the users ears; 2) it is easy to assemble and deconstruct (to embroider the speakers and troubleshoot the circuit); and 3) it matches the interior style of our living room. To blend in with other soft furnishing elements in the room, we designed the Soft Speakers as colourful flowers supplemented by flying birds for aesthetics. In this sense, each embroidered flower is, in essence, a soft speaker. Before assembling the chair together, we unstapled the upholstery of both wing sides to gain access to its inner layers. Ideally, in a constructive method, we should embroider the speaker to the chair's fabric. However, to simplify the process using an additive method, we made the embroidery into patches that were later stitched to the chair's fabric. Each patch incorporated a 4 Ω arithmetic spirals (DP3) Soft Speaker with turns(n)=18 and diameter(ø)=63 mm (DP6) hidden within its layers. We used a palette of colourful matching threads with silver-plated conductive thread (DP2) to embroider the two flower speakers using the digital embroidery machine. The conductive thread was then soldered to wires hidden with the upholstery of the wings and connecting them to a MAX9744 stereo 20W class-D audio amplifier and a 5 V DC power adapter. The class-D means that it is cool-running drawing power only when the audio cable connected is used.

5.6 Teacher Teddy (E-Learning Application)

The Teacher-Teddy is a DIY teddy bear with a Soft Speaker stuffed within. Figure 12 shows the design process and making of the Teacher-Teddy from embroidering the Soft Speaker to using it as a child's e-learning tangible device

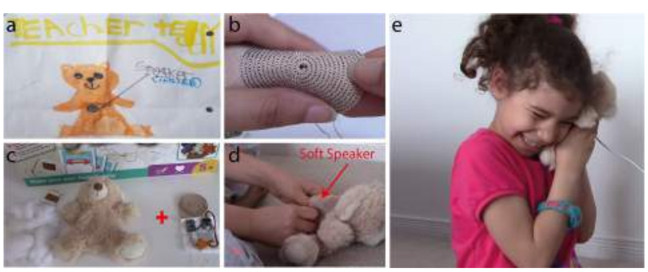

Figure 12: The making of Teacher-Teddy: a) Child sketch; b) Embroidering a Soft Speaker; c) Utilizing a DIY bear-making kit; d) Stuffing the circuit; e) e-learning with Teacher-Teddy.

5.6.1 User Experience. With the e-learning education methods taking over schools, Mary found it difficult to focus and engage in teacher-led online meetings. Virtual classrooms entail complex concepts to children who may need physicality and tangibility to be able to engage with their teachers and peers. Mary felt bored and disconnected during such online classroom meetings. Holding on to her teddy bear, she innocently asked whether it can similarly talk "*while still being fluffy and squishy*". She drew a sketch of how she wants the Soft Speaker hidden "*inside his belly*". The soft teddy has in fact been made by the 7-year-old girl herself with a DIY make-your-own-bear kit a few months earlier. She unstuffed it again and added the Soft Speaker inside herself. Mary then used it, not just as a speaker for her online classes, but as a proxy teacher that she listens to instead of the real (now virtual) one. When asked if Mr. Brown has now become like a robot she answered: "*No, I love that you can squish it and hug it all night*". Mary's lessons could now be heard from 1m range of the teddy but not further to avoid disrupting her sister during concurrent online classrooms.

5.6.2 Design and Fabrication. The diameter of the speaker needed to be no more than 7cm to fit in his belly, so we packed it with 16 turns (DP6), added a strong neodymium magnet (DP5) and we chose to make it from leather (DP1) to produce a clear audible sound. We then stitched the speaker's conductive thread into an Adafruit mono 2.5W class-D audio amplifier that is 15×24×2 mm in size. This soft toy now allowed the parents to supervise children's home schooling while listening to audio content or instructions as personal-sound without disruption or interference with shared space sound.

6 LIMITATIONS AND FUTURE WORK

Compared to common audio speakers, the main limitation of Soft Speakers is the volume and sound quality. The audible sound intensity is directly proportional to the strength of the magnet used (DP5) in addition to the impact of the other design parameters. In this sense, most Soft Speakers are audible in proximity of centimetres and start fading out beyond 1 2m distance. Significantly strong magnets can form a safety hazard for example if the user carries metallic objects, wears magnetic jewellery (especially earrings) or uses a pacemaker device. We plotted our frequency analysis spectrums based on audio recordings in a quiet room. In future work, we would like to evaluate the same comparisons while audio recording in an anechoic chamber for frequency and dB accuracy. We also suggest testing and considerations of constructive and destructive interference when using two or more channels of Soft Speakers in proximity to each other. Finally, long-term deployment in different users' homes will help gain deeper insight on the utility, usability and user experience of Soft Speakers. This should also help understand and highlight further benefits as well as limitations of embroidering speakers in everyday scenarios.

7 DISCUSSION

Our lives are dynamic and with Soft Speakers now our audio speakers can be equally dynamic and support our everyday life. In this paper, we bring DIY techniques to the research community and demonstrate how soft speakers can be customized to suit a wide variety of individual unique needs. We present applications for social and professional communication, entertainment, gaming, navigation, e-learning and inclusion. For example, a speaker within furniture and soft toys for families who co-work and co-study from home or a speaker that can be worn when walking in poor weather conditions, or by people who find it difficult or uncomfortable to wear headphones can all provide significant value.

7.1 Empowerment of DIY Fabrication

Previous work on Soft Speakers is not accessible or easily replicable for makers. Related work has used sophisticated textile fabrication methods [18, 27] or time-consuming and expertise-relying techniques [37, 38] to create fabric speakers and produce art installation [17, 44]. However, in our design research, we developed a low-cost DIY fabrication method with quantified parameters that can help embed fabric speakers in our real-world objects. We used an embroidery machine that is widely available at community Fab Lab spaces, and have provided the digital files (as supplementary material) to lower barriers to entry. The replicability of our speakers makes this customization easy to scale and our aim with this work is to provide the resources for makers to produce Soft Speakers to suit their own unique needs.

7.2 Toolkits and Toolkitless

From the lens of the fluidity of insights that occur during the experience of autobiographical design [7], we found benefits for Soft Speakers for both adults and children as well as for individuals and families. Once introduced to the concept, users from different ages and backgrounds can start sketching, designing and making their own e-textile speakers. Soft Speakers are basically a kit-of-no-parts as defined in related work [35]. Still, for those without access to an embroidery machine, or the necessary e-textile supplies, Soft Speakers could be easily developed into accessible *patch on and play* toolkits. This approach is best demonstrated in the Listening-Chair and Teacher-Teddy prototypes. Soft Speaker toolkits can take on the form of decorative embroidered patches and can provide individuals with ways to embed speakers around their home or to augment or patch up furnishing to cover up tears, rips or stains. In these ways, Soft Speakers have the potential to upcycle and augment our everyday objects and spaces.

7.3 Expanding Surfaces

Soft Speakers expand the possible locations for embedding sound and haptic vibration, and especially the opportunities for home and interior spaces. As demonstrated in the wide variety of prototypes developed for this study, embroidered Soft Speakers enable designers to choose the decorative design of the speaker so that it becomes either visible embellishment or invisible and blends into the environment. The digital design and fabrication enable rapid, replicable and scalable soft interfaces with audio feedback. Soft Speakers build on Weiser's vision of technologies that "*weave themselves into the fabric of everyday life until they are indistinguishable from it*" [53], and into our fashion design, interior design and product design.

7.4 Privitization without Isolation

The aural distance of Soft Speakers depend on the design parameters used. With common speakers, the sound is either public and may cause disruption to some, or private and isolates the user, both often causing social embarrassment in a shared space. On the contrary, Soft speakers are ideal for non-bubbling private interaction in both mobile and stationary scenarios. Only the individual(s) wanting/needing the audio output can hear/feel it, while still allowing the individual to be aware of the shared aural space of their surroundings. In this way, soft speakers are particularly suited to ambient applications in how they enable individuals to be aware of their immediate tasks as well as what is going on around them [53]. In terms of the design space, Soft Speakers act as the opposite of noise cancelling headphones as they augment our experiences with sound or vibration without cancelling other interactions out.

7.5 Assistive and Inclusive Design

Enabling customizable DIY of fabric actuators with both additive (e.g. Teacher-Teddy, Listening-Chair) and constructive (e.g. Talking-Tuque, Sound-Scarf, Tectonic-Shirt) methods, supports the diversity of users' gender, ability, needs and beliefs more than conventional speakers. Users, and their carers, who might feel left out from mass-produced speakers can develop their own designs that support their needs. For example, young people who find earpieces uncomfortable or people who wear headwear for cultural or religious reasons deeming their ears somewhat inaccessible for headphones in public. In addition, the tactility of its fabric membrane can inspire applications for accessibility and assistive technology such as hearing and vision impairment applications. Other applications can employ ultrasonic sounds such as baby in womb on a father's wearable or a mother's heart beat on a baby blanket. Other scenarios such as hygienic facemasks, biker-style headcovering, umbrellas and versatile hats can be also accommodated by Soft Speakers.

8 CONCLUSION

Soft Speakers are not comparable to conventional speakers, but present an alternative means for output interaction in non-rigid form factors. This allows audio and haptic feedback to be embedded in fabric, leather and textile objects, expanding the design space to include wearables, soft furnishing and soft objects. In our design research, we learned how to design, fabricate and implement Soft Speakers using digital embroidery in DIY accessible, aesthetic and low-cost means. Through living with a number of prototypes, we gained insight into different applications that could benefit from the Soft Speakers making. By analyzing the findings, we learned that Soft Speakers can empower users of different ages to create customized inclusive designs of e-textile actuators. Our study bridges the gap between DIY fabrication approaches and scalability for e-textiles within a range of deployable and replicable real-world applications. Whether it is for warmth, sanitation, culture or religion, people often cover their heads and ears with fabrics. Soft speakers stitched into their everyday wearables create diverse and inclusive designs for haptic-audio feedback as opposed to rigid form factors of common headphones that are inaccessible to many. Since DIY methods are integral to our approach, we emphasize on maintenance and making tactics –such as patching and upcycling– from a sustainability perspective. Our work contributes five examples of how everyday soft interfaces (an accessory, clothing, headcovering, furniture, and a pet toy) can accommodate such interactive capabilities, without compromising their affordances and aesthetics, creating great opportunities for this design space.

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REFERENCES

[1] Bang and Olufsen. 2019. Architectural Speaker - Beosound Shape. (2019). https://www.bang-olufsen.com/en/speakers/beosound-shape

[2] Joanna Berzowska and Marguerite Bromley. 2007. Soft computation through conductive textiles. In *Proceedings of the International Foundation of Fashion Technology Institutes Conference*. 12–15.

[3] Joanna Berzowska and Marcelo Coelho. 2005. Kukkia and vilkas: Kinetic electronic garments. In *Ninth IEEE International Symposium on Wearable Computers (ISWC'05)*. 82–85. https://doi.org/10.1109/ISWC.2005.29

[4] Leah Buechley and Michael Eisenberg. 2009. Fabric PCBs, Electronic Sequins, and Socket Buttons: Techniques for e-Textile Craft. *Personal Ubiquitous Comput.* 13, 2 (Feb. 2009), 133–150. https://doi.org/10.1007/s00779-007-0181-0

[5] Marcelo Coelho, Ivan Poupyrev, Sajid Sadi, Roel Vertegaal, Joanna Berzowska, Leah Buechley, Pattie Maes, and Neri Oxman. 2009. Programming Reality: From Transitive Materials to Organic User Interfaces. In *CHI '09 Extended Abstracts on Human Factors in Computing Systems* (Boston, MA, USA) *(CHI EA '09)*. Association for Computing Machinery, New York, NY, USA, 4759–4762. https://doi.org/10.1145/1520340.1520734

[6] Audrey Desjardins and Aubree Ball. 2018. Revealing Tensions in Autobiographical Design in HCI. In *Proceedings of the 2018 Designing Interactive Systems Conference* (Hong Kong, China) *(DIS '18)*. Association for Computing Machinery, New York, NY, USA, 753–764. https://doi.org/10.1145/3196709.3196781

[7] Audrey Desjardins and Ron Wakkary. 2016. Living In A Prototype: A Reconfigured Space. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 5274–5285. https://doi.org/10.1145/2858036.2858261

[8] Jacob Fraden. 2004. *Handbook of modern sensors: physics, designs, and applications.* Springer Science & Business Media.

[9] William Gaver, John Bowers, Andy Boucher, Andy Law, Sarah Pennington, and Nicholas Villar. 2006. The History Tablecloth: Illuminating Domestic Activity. In *Proceedings of the 6th Conference on Designing Interactive Systems* (University Park, PA, USA) *(DIS '06)*. Association for Computing Machinery, New York, NY, USA, 199–208. https://doi.org/10.1145/1142405.1142437

[10] Jun Gong, Yu Wu, Lei Yan, Teddy Seyed, and Xing-Dong Yang. 2019. Tessutivo: Contextual Interactions on Interactive Fabrics with Inductive Sensing. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 29–41. https://doi.org/10.1145/3332165.3347897

[11] Daniel Groeger and Jürgen Steimle. 2019. LASEC: Instant Fabrication of Stretchable Circuits Using a Laser Cutter. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3290605.3300929

[12] Nur Al-huda Hamdan, Simon Voelker, and Jan Borchers. 2018. *Sketch & Stitch: Interactive Embroidery for E-Textiles.* Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173656

[13] Anja Hertenberger, Barbro Scholz, Beam Contrechoc, Becky Stewart, Ebru Kurbak, Hannah Perner-Wilson, Irene Posch, Isabel Cabral, Jie Qi, Katharina Childs, Kristi Kuusk, Lynsey Calder, Marina Toeters, Marta Kisand, Martijn ten Bhömer, Maurin Donneaud, Meg Grant, Melissa Coleman, Mika Satomi, Mili Tharakan, Pauline Vierne, Sara Robertson, Sarah Taylor, and Troy Robert Nachtigall. 2014. 2013 E-Textile Swatchbook Exchange: The Importance of Sharing Physical Work. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers: Adjunct Program* (Seattle, Washington) *(ISWC '14 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 77–81. https://doi.org/10.1145/2641248.2641276

[14] Yoshio Ishiguro and Ivan Poupyrev. 2014. 3D Printed Interactive Speakers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 1733–1742. https://doi.org/10.1145/2556288.2557046

[15] Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical Atoms: Beyond Tangible Bits, toward Transformable Materials. *Interactions* 19, 1 (Jan. 2012), 38–51. https://doi.org/10.1145/2065327.2065337

[16] Lee Jones, Sara Nabil, Amanda McLeod, and Audrey Girouard. 2020. Wearable Bits: Scaffolding Creativity with a Prototyping Toolkit for Wearable E-Textiles. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 165–177. https://doi.org/10.1145/3374920.3374954

[17] Judit Eszter Karpati. 2019. Draping Sound - EJTECH. (2019). http://ejtech.cc/?page_id=1379

[18] Rytha Kesselring. 2019. MilieuxMake Workshop Series presents: Tactile Sound | Milieux. (2019). https://milieux.concordia.ca/event/milieuxmake-workshop-series-presents-tactile-sound/?fbclid=IwAR0ocyaUxSrfYqZc2YT02-pM8ohI10HJ-Yrq5ye5BpJIRl8vSxLPpVzlapQ

[19] Tomomi Kono and Keita Watanabe. 2017. Filum: A Sewing Technique to Alter Textile Shapes. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 39–41. https://doi.org/10.1145/3131785.3131797

[20] Anne Lamers, Evy Murraij, Elze Schers, and Armando Rodríguez Pérez. 2019. Layered Embroidery for Dynamic Aesthetics. In *Proceedings of the 23rd International Symposium on Wearable Computers* (London, United Kingdom) *(ISWC '19)*. Association for Computing Machinery, New York, NY, USA, 302–305. https://doi.org/10.1145/3341163.3346942

[21] Hung-Sheng Lin, Yi-Tung Shen, Tzu-Han Lin, and Pei-Chun Lin. 2014. Disco lamp: An interactive robot lamp. In *2014 IEEE International Conference on Automation Science and Engineering (CASE)*. IEEE, 1214–1219.

[22] Sarah Mennicken, A. J. Bernheim Brush, Asta Roseway, and James Scott. 2014. Finding Roles for Interactive Furniture in Homes with EmotoCouch. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication* (Seattle, Washington) *(UbiComp '14 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 923–930. https://doi.org/10.1145/2638728.2641547

[23] Sara Nabil, Aluna Everitt, Miriam Sturdee, Jason Alexander, Simon Bowen, Peter Wright, and David Kirk. 2018. ActuEating: Designing, Studying and Exploring Actuating Decorative Artefacts. In *Proceedings of the 2018 Designing Interactive Systems Conference* (Hong Kong, China) *(DIS '18)*. Association for Computing Machinery, New York, NY, USA, 327–339. https://doi.org/10.1145/3196709.3196761

[24] Sara Nabil and David Kirk. 2019. Interactive Interior Design and Personal Data. In *People, Personal Data and the Built Environment*. Springer, 103–122.

[25] Sara Nabil, Jan Kučera, Nikoletta Karastathi, David S. Kirk, and Peter Wright. 2019. Seamless Seams: Crafting Techniques for Embedding Fabrics with Interactive Actuation. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 987–999. https://doi.org/10.1145/3322276.3322369

[26] Carman Neustaedter and Phoebe Sengers. 2012. Autobiographical Design in HCI Research: Designing and Learning through Use-It-Yourself. In *Proceedings of the Designing Interactive Systems Conference* (Newcastle Upon Tyne, United Kingdom) *(DIS '12)*. Association for Computing Machinery, New York, NY, USA, 514–523. https://doi.org/10.1145/2317956.2318034

[27] The Swedish School of Textiles. 2013. Smart Textiles Design Lab Blog: Goldwork techniques for E-embroidering. (2013). https://stdl.se/?p=3193

[28] Takeshi Oozu, Aki Yamada, Yuki Enzaki, and Hiroo Iwata. 2017. Escaping Chair: Furniture-Shaped Device Art. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction* (Yokohama, Japan) *(TEI '17)*. Association for Computing Machinery, New York, NY, USA, 403–407. https://doi.org/10.1145/3024969.3025064

[29] Syuzi Pakhchyan. 2008. *Fashioning technology: A DIY intro to smart crafting.* O'Reilly Media, Inc.

[30] Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner, Siegfried Bauer, and Michael Haller. 2018. RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 745–756. https://doi.org/10.1145/3242587.3242664

[31] Patrick Parzer, Adwait Sharma, Anita Vogl, Jürgen Steimle, Alex Olwal, and Michael Haller. 2017. SmartSleeve: Real-Time Sensing of Surface and Deformation Gestures on Flexible, Interactive Textiles, Using a Hybrid Gesture Detection Pipeline. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 565–577. https://doi.org/10.1145/3126594.3126652

[32] Hannah Perner-Wilson. 2012. Embroidered Fabric Speaker - Instructables. (2012). https://www.instructables.com/id/Embroidered-Fabric-Speaker/

[33] Hannah Perner-Wilson and Leah Buechley. 2010. Handcrafting Textile Mice. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems* (Aarhus, Denmark) *(DIS '10)*. Association for Computing Machinery, New York, NY, USA, 434–435. https://doi.org/10.1145/1858171.1858257

[34] Hannah Perner-Wilson and Leah Buechley. 2010. Making Textile Sensors from Scratch. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction* (Cambridge, Massachusetts, USA) *(TEI '10)*. Association for Computing Machinery, New York, NY, USA, 349–352. https://doi.org/10.1145/1709886.1709972

[35] Hannah Perner-Wilson, Leah Buechley, and Mika Satomi. 2010. Handcrafting Textile Interfaces from a Kit-of-No-Parts. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction* (Funchal, Portugal) *(TEI '11)*. Association for Computing Machinery, New York, NY, USA, 61–68. https://doi.org/10.1145/1935701.1935715

[36] Hannah Perner-Wilson and Mika Satomi. 2009. DIY Wearable technology. In *ISEA 15th International Symposium on Electronic Art*.

[37] Hannah Perner-Wilson and Mika Satomi. 2015. How To Get What You Want | Machine Embroidering. (2015). https://www.kobakant.at/DIY/?p=5501

[38] Hannah Perner-Wilson and Mika Satomi. 2020. How To Get What You Want. (2020). https://www.kobakant.at/

[39] Anna Persson. 2013. Exploring textiles as materials for interaction design. (2013). http://urn.kb.se

[40] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson. 2016. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 4216–4227. https://doi.org/10.1145/2858036.2858176

[41] Thomas Preindl, Cedric Honnet, Andreas Pointner, Roland Aigner, Joseph A. Paradiso, and Michael Haller. 2020. Sonoflex: Embroidered Speakers Without Permanent Magnets. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 675–685. https://doi.org/10.1145/3379337.3415888

[42] Larissa Pschetz and Richard Banks. 2013. Long Living Chair. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems* (Paris, France) *(CHI EA '13)*. Association for Computing Machinery, New York, NY, USA, 2983–2986. https://doi.org/10.1145/2468356.2479590

[43] Johan Redström. 2001. Designing everyday computational things. *rapport nr.: Gothenburg studies in Informatics* 20 (2001).

[44] Jess Rowland. 2013. Flexible audio speakers for composition and art practice. *Leonardo Music Journal* (2013), 33–36.

[45] Jess Rowland and Adrian Freed. 2012. Flexible Surfaces for Interactive Audio. In *Proceedings of the 2012 ACM International Conference on Interactive Tabletops and Surfaces* (Cambridge, Massachusetts, USA) *(ITS '12)*. Association for Computing Machinery, New York, NY, USA, 315–318. https://doi.org/10.1145/2396636.2396688

[46] Daniel Saakes, Takahiro Tsujii, Kohei Nishimura, Tomoko Hashida, and Takeshi Naemura. 2013. Photochromic carpet: Playful floor canvas with color-changing footprints. In *International Conference on Advances in Computer Entertainment Technology*. Springer, 622–625.

[47] Rebecca Stewart. 2019. Cords and Chords: Exploring the Role of E-Textiles in Computational Audio. *Frontiers in ICT* 6 (2019), 2.

[48] Tomomi Takashina, Kotaro Aoki, Akiya Maekawa, Chihiro Tsukamoto, Hitoshi Kawai, Yoshiyuki Yamariku, Kaori Tsuruta, Marie Shimokawa, Yuji Kokumai, and Hideki Koike. 2015. Smart Curtain as Interactive Display in Living Space. In *SIGGRAPH Asia 2015 Posters* (Kobe, Japan) *(SA '15)*. Association for Computing Machinery, New York, NY, USA, Article 32, 1 pages. https://doi.org/10.1145/2820926.2820971

[49] Sarah Taylor and Sara Robertson. 2014. Digital Lace: A Collision of Responsive Technologies. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers: Adjunct Program* (Seattle, Washington) *(ISWC '14 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 93–97. https://doi.org/10.1145/2641248.2641280

[50] Anita Vogl, Patrick Parzer, Teo Babic, Joanne Leong, Alex Olwal, and Michael Haller. 2017. StretchEBand: Enabling Fabric-Based Interactions through Rapid Fabrication of Textile Stretch Sensors. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 2617–2627. https://doi.org/10.1145/3025453.3025938

[51] Akira Wakita and Midori Shibutani. 2006. Mosaic Textile: Wearable Ambient Display with Non-Emissive Color-Changing Modules. In *Proceedings of the 2006 ACM SIGCHI International Conference on Advances in Computer Entertainment Technology* (Hollywood, California, USA) *(ACE '06)*. Association for Computing Machinery, New York, NY, USA, 48–es. https://doi.org/10.1145/1178823.1178880

[52] Mark Weiser. 1999. The computer for the 21st century. *ACM SIGMOBILE mobile computing and communications review* 3, 3 (1999), 3–11.

[53] Mark Weiser and John Seely Brown. 1997. The coming age of calm technology. In *Beyond calculation*. Springer, 75–85.

[54] Claire Williams. 2016. Sound Embroidery. (2016). http://www.xxx-clairewilliams-xxx.com/projets/sound-embroidery/

[55] Clint Zeagler, Scott Gilliland, Halley Profita, and Thad Starner. 2012. Textile interfaces: Embroidered jog-wheel, beaded tilt sensor, twisted pair ribbon, and sound sequins. In *2012 16th International Symposium on Wearable Computers*. IEEE, 60–63.

[56] Bo Zhou, Harald Koerger, Markus Wirth, Constantin Zwick, Christine Martindale, Heber Cruz, Bjoern Eskofier, and Paul Lukowicz. 2016. Smart Soccer Shoe: Monitoring Foot-Ball Interaction with Shoe Integrated Textile Pressure Sensor Matrix. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers* (Heidelberg, Germany) *(ISWC '16)*. Association for Computing Machinery, New York, NY, USA, 64–71. https://doi.org/10.1145/2971763.2971784