

Felt Sound: A Shared Musical Experience for the Deaf and Hard of Hearing

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ABSTRACT

We present a musical interface specifically designed for inclusive performance that offers a shared experience for both individuals who are hard of hearing as well as those who are not. This interface borrows gestures (with or without their overt meaning) from American Sign Language (ASL), rendered using low-frequency sounds that can be *felt* by everyone in the performance. The Hard of Hearing cannot experience the sound in the same way. Instead, they are able to physically experience the vibrations, nuances, contours, as well as their correspondences with the hand gestures. Those who are not hard of hearing can experience the sound, but also feel it just the same, with the knowledge that the same physical vibrations are shared by everyone. The employment of sign language adds another aesthetic dimension to the instrument—a nuanced borrowing of a functional communication medium for an artistic end.

Author Keywords

accessible musical interface design, inclusive performance

CCS Concepts

•Applied computing → Sound and Music Computing; Performing arts; •Human-centered computing → Interface design prototyping; Accessibility design and evaluation methods;

1. INTRODUCTION

Music performers and audiences perceive sound not only through the auditory system but also with the assistance of their bodies in the space. This kind of embodied sensation offers non-auditory ways of perceiving sound and music. For instance, Shibata reports that vibrations transmitted through physical objects excite the same regions in the brain as hearing them [24]. In this paper, we discuss a wearable musical interface, Felt Sound, specifically designed to create inclusive performances for individuals who are deaf and hard of hearing, as well as those who are not. Deaf and Hard of Hearing individuals cannot experience sound fully or, in some cases, at all; however, they can sense low-frequency, high-amplitude sound vibrations through their bodies. Felt Sound exploits these qualities of low-frequency sound through gestural interaction inspired by American Sign Language (ASL) gestures.

Outside the musical domain, gestures often carry communicative functions with well-defined meanings. Unlike other musical gestures, communicative gestures tend to appear less commonly and more ambiguously in music performance [7]. Such non-obvious communicative gestures express loosely defined meanings in music that leaves more room for expressiveness and bodily communication compared to speech-based languages [27]. Interestingly, ASL embodies the qualities of both gesture and language. Gestures in sign language have clear communicative functions while they also resemble expressive musical movements. By thinking about ASL in this way—as a combination of communicative and musical gestures—our interface design seeks to provide a different kind of gesture-based vocabulary and vibrotactile musical experience.

In Felt Sound, we present a musical interface (see Figure 2) that incorporates non-musical communicative gestures (as input) and connects such gestures to low-frequency



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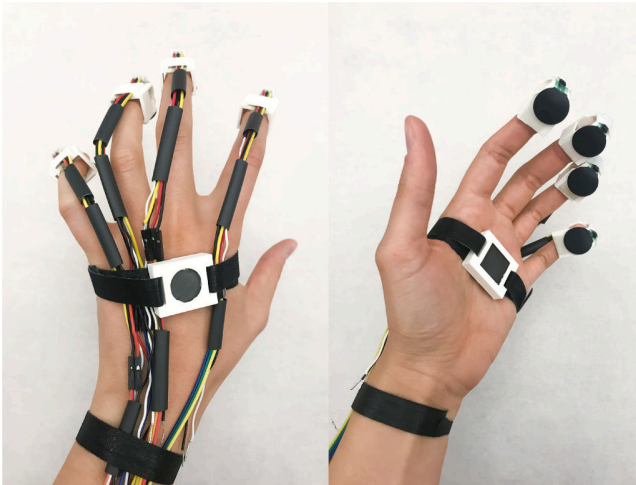


Figure 2: The prototype of Felt Sound’s interface

sounds designed to produce physical sensations (as output). This work borrows from American Sign Language (ASL) gestures, potentially with or without their overt meaning.

We derive our inspiration from Dana Murphy’s original performance titled *Resonance* (2018) (see Figure 3) [19]. She states that her inspiration is from “ASL song interpretations and the experience of music for those who are Deaf and Hard of Hearing.” Her performance challenges the practice of music as a solely auditory experience.

A roadmap for the rest of this paper: Section 2 reviews existing accessible digital musical instruments (ADMIs) for Deaf and Hard of Hearing individuals, these instruments’ feedback mechanisms, and their interfaces. Section 3 describes Felt Sound’s interaction, sound, and inclusive performance design. It also discusses the concept of borrowing non-musical gestures for this type of music performance. Section 4 provides a qualitative report on the audience’s experience based on preliminary performance sessions using Felt Sound.

2. BACKGROUND

Among DMIs, instruments addressing the needs of musicians with hearing impairment are limited. Frid’s survey on ADMIs reports that DMI designers more frequently address users’ complex needs in terms of physical and cognitive disabilities, rather than users experiencing vision and hearing impairments. The majority of ADMIs are targeted to individuals with physical disabilities or children with health conditions and impairments [6]. She further states that these instruments’ target groups reach beyond disabled users. They are designed not only for people with disabilities but also for musicians in general, a design objective that we also value and adopt for deaf and hard of hearing musicians and audiences as well as those who are not. Her survey shows that only a few DMIs designed for deaf and hard of hearing individuals explore visual, haptic, or visuo-haptic bi-feedback mechanisms.

An example of ADMIs that provide visual feedback is Fourney and Fels’s research. They use visuals to inform “deaf, deafened, and hard of hearing music consumers” about the musical emotions conveyed in the performance. Unlike assistive visual devices, their interfaces extend Deaf and Hard of Hearing users’ experience of accessing the music of the larger hearing culture [5]. Similarly, the vibrotactile feedback encourages designers to augment and/or substitute the auditory feedback. The efforts toward augmenting

or completely replacing the auditory feedback with vibrotactile feedback remain limited in musical instrument design. Researchers generally study sensory feedback for disabled users outside the musical instrument design context. Novich and Eagleman explore vibrotactile sensations to help the Deaf hear the human voice using a dynamic haptic vest [21]. Their method includes vibrational motor arrays to deliver spatiotemporal information of the speech. Compared to assistive musical interfaces that provide vibrotactile sensations, their device places little emphasis on music signals and focuses more on communicating speech and environmental sound information through a wearable device.

In addition to tactile feedback, Burn extends haptics with visual feedback in his DMIs to replicate the missing auditory sensation for deaf musicians [1]. His instruments target “the deaf musicians who wish to play virtual instruments and expand their range of live performance opportunities.” He emphasizes the difference between deaf and hearing musicians’ interpretation of the multi-sensory feedback received from acoustical instruments and compares them to feedback from virtual instruments. From the interviews and workshops with Deaf musicians, he reports that electronic instruments pose difficulties to resolve certain characteristics of sound, such as pitch and harmonics. Similar to Burn, Narayakkara’s haptic chair also combines vibrotactile sensation with visuals using a vibrating chair with a computer display to convey musical information. While the visual effects display musical features such as note onset, duration, pitch, loudness, and instrument type, the haptic chair physically amplifies the in-air acoustic vibrations. They leverage many partially deaf individuals’ ability to hear sounds via “in-air conduction through the ‘conventional’ hearing route: an air-filled external ear canal” [20].

Additionally, Soderberg et al. design musical interfaces for hard of hearing musicians using visual and haptic feedback [25]. They extend this focus by studying communication and collaboration between hearing and deaf musicians. Their study reveals how body language plays a crucial role in music creation and performance between the two groups. They state that these efforts to offer inclusive musical instruments and performance spaces could help hard of hearing and hearing musicians share a similar musical context.

Some researchers focus more on the interaction mechanism than the feedback. Hansen et al. explore inclusive music creation by employing adaptable sensor data for gestural control with instruments designed for deaf and hard



Figure 3: Dana Murphy is performing her piece, *Resonance*.

of hearing children. Their interface, Soundscape, includes detachable sensor units to place on clothing or external objects. These sensors allow the system to detect users' movement with the aid of the arm, wrist, and headbands [11, 10]. So far, we have not seen an accessible musical instrument incorporating ASL gestures. The research on sign language is generally directed at developing recognition and translation systems [22]. For ASL gesture recognition, gestural controllers, widely sensor gloves, are adapted either to analyze their gestures or to aid sign communication [12, 18, 22, 14].

In these related works, we have not found ADMIs that directly use sound as tactile means of musical conveyance, nor have we seen interactions that directly use ASL and ASL-inspired gestures for musical expression. The only prior example embodying both aspects was Dana Murphy's *Resonance*, which is a direct precursor to this work. *Resonance* utilizes ASL gestures and low-frequency vibrations to create a piece that is seen and felt. By creating this piece, she reflects her inspiration from ASL song interpretations into the physical performance and challenges the idea of music as a solely auditory experience [19].

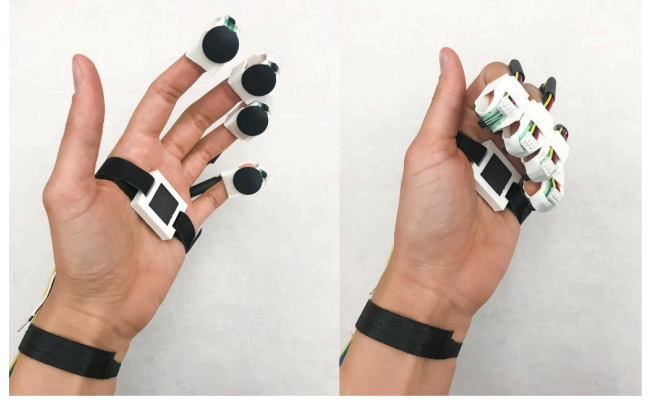
3. DESIGN

3.1 Interaction

In Felt Sound, we adopted a modular design approach to allow designers and performers to customize the interaction and the gestural composition [23, 4]. The instrument is composed of separate modules to capture varying levels of gestures; nuanced finger gestures, single-hand gestures, and small arm gestures from both hands interacting with each other. The overall interface includes fingertip modules, passive elements like magnets for magnetic sensing, an accelerometer, and a controller module. These elements can be combined as desired on the left and right hand, wrist, and fingers. Figure 4b shows all four fingertip sensors and two magnetic modules that are worn on one hand.

The finger gestures are detected with custom-made wearable sensors shown in Figure 4b. This sensor includes a hall effect sensor triggered by a wearable magnet and force-sensitive resistors (FSR) for continuous control. While the FSR and hall effect sensors are fixed on the 3D printed fingertip structure, the wearable magnet can be placed either on the palm, on the back of the palm, or worn on the wrist depending on the desired gestures. Similarly, the fingertip sensors can be worn all on one hand or distributed to both hands to capture the interaction between the two hands and larger scale gestures between them. Since the detection mechanism is limited to available sensors, this modality creates flexibility to customize gesture-to-sound mapping. For example, single finger interaction can be extended to multiple fingers to create fist opening and closing gestures (Figure 4a). ASL gestures appear as static and dynamic hand gestures where the gestures are based on movement and hold model [26]. We focus on capturing the nuanced gestures with pressure sensing on fingertips (Figure 4b - iii), fingers' closing (Figure 4b - ii), fingers' tapping to the palm, and the fist closing and opening gesture (Figure 4a), as well as their dynamic motion using an accelerometer.

All the modules are prototyped by 3D printing the sensor enclosing and base structures. The accelerometer and magnets are embedded during the 3D printing process. This approach called the hybrid additive manufacturing method exceeds the scope of this paper [15]. Its application for musical instruments is discussed as part of another research. For this initial prototype, we used a Teensy 3.5 controller for its number of analog input options, a three-axis accelerometer,



(a) The hall effect sensors and the magnet placed on the palm allow detecting first closing and opening gestures.



(b) Fingertip sensor and a magnet module can be seen in the first image (i); as the finger is bent and approaches the magnet, the hall effect sensor changes state (ii); the FSR sensors output continuous data to control frequency, gain, and filter and effect parameters (iii).

Figure 4: Gesture-sensing mechanism

FSRs, and non-latching linear hall effect sensors.

3.2 Designing "Felt" Sound

The main design objective of Felt Sound draws from creating music as a shared experience for deaf, hard of hearing musicians and audiences, and those who are not. This experience consists of a gestural performance and physical sensations of sound. The gestural composition is designed to control sound events with movements that are inspired by ASL gestures and song interpretations. Listeners during the performance can sit next to the subwoofers and are encouraged to touch and sense the beat. ASL gestures in the composition are mapped to low-frequency, high amplitude multichannel subwoofer sound system to amplify physical sensations of the in-air acoustic waves. This kind of mapping to the sound objects is based on static and dynamic gestures of one or both hands. These gestures are supported with nuanced finger gestures for fine-tuning of the sound engines. For example, ASL word for music triggers the low-frequency beating sound engine where the tone frequency is adjusted by pressure sensing on the fingertip sensors and beating frequency based on the acceleration data (Figure 5). The sine oscillators are connected to a Faust ¹ distortion object and to the beating effect. Similarly, the low-frequency drones are triggered with the hall effect sensor based on the proximity of the magnets that are positioned on the palm or the back of the palm depending on the defined gesture. These drone tones are modulated using LFO objects in ChuckK ² to control the amplitude modulation. The poetry gesture is based on pressure sensing to capture the index finger and thumb's closing gesture. Acceleration

¹<https://faust.grame.fr/>

²<https://chuck.cs.princeton.edu/>

indicates note onsets.

The table 1 shows a sample set of gestures used in the composition and their associated sound objects along with their detection mechanisms. The most commonly employed gestures are music and poetry words. In addition to their meaning, the choice of these gestures is due to their rich controller mechanisms, expressive nature, and ability to combine nuanced gestures—finger interaction—with larger-scale gestures—hand and arm interactions. These gestures imitate their ASL correspondence but they are not intended to have a direct translation into language. The sound objects, shown in Table 1, are designed using FaucK [28].

3.3 Borrowed Gestures

McNeill states that the gestures occur not only in communication with others but also in thinking [16]. Jamalian, Giardino, and Tversky study this modality of gestural communication in thinking and conceptualizing spatial environments to understand how gestures reflect mental representations [13]. Their study reveals that the gestures reflect the content of the thought, lighten the memory load, and establish embodied representation of the performance ecosystems. In music, this increasingly studied topic of musical gestures tries to distinguish various functionalities of musical gestures as well as their corresponding meanings [7, 27]. Although the functions of musical gestures—sound producing, communicative, sound facilitating, and accompanying gestures—are distinctly categorized, the communicative gestures frequently overlap with the other gestures when musicians communicate with co-performers, interpret expressive and emotional musical elements, convey their own experiences, and interact with the audience. In other words, we observe that spontaneous gestural expressions co-occur during the performance, either intentionally or unintentionally. Our design of gestural interaction draws from communicative nature of gestural use in music performance, which is similar to speech and thinking, as well as transforming these gestures into sound-producing gestures.

The gestures we borrow from ASL have well-defined communicative functions. McNeill emphasizes that the gestures are components of the language and not an accompaniment or an add-on [17]. These concurrently occurring gestures still carry communicative functions; however, they are not organized based on spoken languages of hearing communities unlike ASL [8]. Goldin-Meadow and Brentari explain how sign languages adopt elements from the two:

Table 1: Gesture-to-Sound Mapping





ASL Gesture	Meaning	Sound Engine	Detection
	Music	Low-frequency beating	Acceleration
	Show	Trigger drones	Magnetic sensing
	Poetry	Frequency change	Pressure sensing and acceleration
	Empty	Clear all the sound engines	Magnetic and pressure sensing



Figure 5: ASL music gesture creates beating effects with waving the hand captured through accelerometer worn on the right hand.

categorical components from speech-plus-gesture and imagistic components from gestures [9]. On the other hand, we observe that musicians, too, adopt gestures’ functionality and communicative and expressive components [7]. Like in music, the gestures in sign languages appear intuitively to understand and express. From language to music performance, gestures from numerous domains overlap in expression, functionality, and communication. In Felt Sound, we explore the expressive and communicative nature of gestures—not limited to their meanings—by adopting movement into DMI performance. Our main purpose is to draw the performer’s focus to bodily movement with an unconventional gestural vocabulary.

We introduce the concept of “borrowing” (incorporating) gestures from non-musical domains into DMI design and performance. Borrowing actions of others as a research concept of bodily movement is studied by McNeill [17]. The author discusses how mimicry—recreating a gesture, movement, or an expression not through simple imitation but by carrying its meaning—helps communicators unravel the contexts of other speakers. We believe a similar translation is possible in music performance by adopting non-musical gestures. Non-musical gestures discussed in this paper are different than ancillary or sound-accompanying gestures which occur spontaneously or unintentionally in music performance. Instead, these are the gestures that carry different functionalities and meanings in non-musical domains. For example, BodyHarp incorporates dance gestures into musical interface which allows musicians to mimic dance-like gestures and improvise with dancers and musicians in the same performance [2]. Similarly, Armtop and Blowtop include co-occurring gestures in speech as well as traditional musical instrumental gestures [3]. As a continuation of this idea, Felt Sound borrows sign language gestures by interpreting their inherent meanings from an artistic point of view.

3.4 Inclusion and Accessibility

Our approach does not necessarily try to overcome the disabling factor using new technology or interfaces but rather we aim to craft practices that recognize these factors and create spaces in which different communities can be brought together. Although deaf and hard of hearing listeners’ experience of music varies from each other and hearing listeners, many can still perceive and enjoy rhythm, vibrations, and sounds at lower registers. In Felt Sound, we focused on the physical sensations of the in-air acoustic waves to offer equal entry-points to everyone in the performance.

Soderberg et al. emphasize that the differences in music perception and experience between hearing and deaf musicians create social barriers [25]. According to the authors, these barriers are overcome through the visual and physical

channels such as body language. Their research raises some important questions such as hard of hearing community's choice of music, the threshold where some musical elements overwhelm them, and eliminating the unequal entry-points in music creation and performance. We focus on these three main objectives in designing an inclusive performance space with Felt Sound, creating a shared experience for both deaf and hard of hearing and hearing communities to reduce the sense of isolation.

The vibrotactile sensation through in-air waves introduces another medium that the sound can be perceived. We leverage the use of vibrotactile sensation, which deaf and hard of hearing listeners develop a higher sensitivity for. The vibrations are delivered using beating patterns in the in-air sound waves through a surround subwoofer system. Low-frequency sound composition allows deaf and hard of hearing listeners to perceive music in similar ways with hearing listeners while the physical sensations move hearing listeners' attention from solely auditory music appreciation to a more physical one. Another objective of our design to create a common ground between two communities is gestural performance. By incorporating ASL gestures into DMI performance, listeners can experience the communication carried by a gestural vocabulary borrowed from a non-musical domain. The performer carries their meanings through expressive movement qualities—the qualities perceived through kinesthetic sensations by both the performer and the audience. Low-frequency content in the composition also takes part in the kinesthetic experience since their range resembles the frequency range of body movement, 10 Hz and below.

4. PERFORMANCE

In 2018, Murphy's *Resonance* explored performance with low-frequency vibrations for the Deaf and Hard of Hearing to a mixed audience with varying musical training, age, and hearing. More recently, using Felt Sound, we performed in three sessions in a surround speaker setup with eight subwoofers. After Murphy's performance (which was presented on a program with other, more "conventional" computer music), one of the audience members expressed that he was losing his hearing with age and her piece was the one he could hear just as well as anyone else. His comments reflect our design objectives: 1) creating expressive physical sensations through in-air sound waves, 2) offering a shared experience for all audience members with or without hearing impairment, and 3) aesthetically coupling the sound-mediated kinesthetic sensations with gestural communication. In our performance and qualitative assessment sessions, we mainly explored these three design considerations.

Eight audience members volunteer their thoughts on their physical, aural, visual, and tactile experience of Felt Sound in an open-ended qualitative questionnaire. Audience members had considerable music training with an average of 18+ years and familiarity with DMI performance. Seven members communicated with spoken English (none of the seven knew sign English) and only one communicated primarily with both speaking and signing.

All listeners reported some physical sensations through low-frequency sounds,

- "I felt like I was using my torso to listen to music rather than my ears. The vibration seemed to be felt in and out of the torso."
- "The felt sound highlighted moments of silence for me more so than traditional sound. I felt light and free in those moments and active in the moments of more intense vibration."

- "The premise of the piece felt like a physical expression of music through low-frequency sounds. Combining it with gestural elements created a powerful body to body connection."

The audience commented on the relationship of kinesthetic (movement) sensation and audio-visual feedback received from Felt Sound. They further expressed how the interface and the performance affected the communication between the performer and the audience.

- "I felt like the sounds are not perceived through pinpointed sources, but rather through the entire body. The sounds definitely embraced the bodies within the audience. However, rather than feeling connected with other members of the audience, the connection was more one-to-one between the performer and myself. I am also curious how this is felt to actual members who use ASL."
- "I felt like physical and auditory movement were definitely related and emerging from the glove as the main controller. Responsive!"

Some audience members reported their aesthetic evaluation based on the ASL gestures as sound-producing gestures.

- "I very much like the fluidity of the gestures and the way it looked like you were pulling the sound out of your left hand."
- "As a non-sign-language speaker it felt more like a choreography rather than a gesture."

Meanwhile, one listener noted that Felt Sound did not consistently deliver physical sensations to him and he found the mapping confusing. For this listener, the most effective part of the performance was,

- "Moments when an emphatic gesture had a corresponding emphatic result in the sound".

He suggested,

- "... the piece could benefit from involving more whole-body and face-expression interpretations of the intended gestural aesthetics. Maybe drawing inspiration from theater and dance would help. ..."

Two listeners expressed that their unfamiliarity with the sign language affected their understanding of the premise of the piece and they experienced the performance from a third-person perspective. Although non-sign-language speakers experienced challenges with the context, they noted that they tried to put themselves into ASL signers' and Deaf and Hard of Hearing listeners' place. Although we collaborated with and consulted an ASL signer and a Hard of Hearing musician/composer, admittedly, our assessment would benefit from gathering more feedback from the Deaf and Hard of Hearing community.

5. CONCLUSIONS

In this work, we present a movement-based digital musical instrument, Felt Sound, specifically designed for inclusive performance. It aims to provide a shared musical experience for both deaf and hard of hearing individuals and those who are not. This instrument's gestural interaction is inspired by American Sign Language (ASL) and its sound design from physical sensations of low-frequency sounds. The performance unites the visual-gestural with the vibrotactile sensations from the in-air sound.

We qualitatively evaluated three performance sessions with Felt Sound. The audience feedback spoke to the potential of creating performance contexts that not only offered shared experiences for audiences with different hearing – but also invited each group to experience the music from the standpoint of the other. Although Felt Sound and *Resonance* provided promise, we experienced some limitations. As future work to follow up this first instantiation of Felt Sound, we plan to gather impressions from Deaf and Hard of Hearing audience and to continue our collaboration with Deaf and Hard of Hearing individuals and ASL signers.

5.1 Links

An excerpt from the performance sessions is linked here: <https://youtu.be/HwVBk2Mr-1g>. Please, note that this piece is intended to be performed with subwoofers. If you have access, please, use an appropriate setup; if not, make sure to use headphones.

6. REFERENCES

- [1] R. Burn. Music-making for the deaf: Exploring new ways of enhancing musical experience with visual and haptic feedback systems.
- [2] D. Cavdir, R. Michon, and G. Wang. The BodyHarp: Designing the Intersection Between the Instrument and the Body. In *Proceedings of 15th Sound and Music Computing Conference (SMC2018)*. Zenodo, 2018.
- [3] D. Cavdir, J. Sierra, and G. Wang. Taptop, armtop, blowtop: Evolving the physical laptop instrument. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, pages 53–58, Porto Alegre, Brazil, 2019.
- [4] A. Ericsson and G. Erixon. *Controlling design variants: modular product platforms*. Society of Manufacturing Engineers, 1999.
- [5] D. W. Fournery and D. I. Fels. Creating access to music through visualization. In *2009 IEEE Toronto International Conference Science and Technology for Humanity (TIC-STH)*, pages 939–944. IEEE, 2009.
- [6] E. Frid. Accessible digital musical instruments—a survey of inclusive instruments. In *Proceedings of the International Computer Music Conference. The International Computer Music Association, San Francisco*, pages 53–59, 2018.
- [7] R. I. Godøy and M. Leman. *Musical gestures: Sound, movement, and meaning*. Routledge, 2010.
- [8] S. Goldin-Meadow. The role of gesture in communication and thinking. *Trends in cognitive sciences*, 3(11):419–429, 1999.
- [9] S. Goldin-Meadow and D. Brentari. Gesture, sign, and language: The coming of age of sign language and gesture studies. *Behavioral and Brain Sciences*, 40, 2017.
- [10] K. F. Hansen, C. Dravins, and R. Bresin. Ljudskrapan/the soundscraper: Sound exploration for children with complex needs, accommodating hearing aids and cochlear implants. In *Proceedings of the Sound and Music Computing Conference, Padova, Italy*, pages 70–76. Padova University Press Padova, 2011.
- [11] K. F. Hansen, G. Dubus, and R. Bresin. Using modern smartphones to create interactive listening experiences for hearing impaired. *Proceedings of Sound and Music Computing Sweden, ser. TMH-QPSR, R. Bresin and KF Hansen, Eds*, 52(1):42, 2012.
- [12] J. Hernandez-Rebollar. Asl glove with 3-axis accelerometers, Jan. 28 2010. US Patent App. 11/836,136.
- [13] A. Jamalain, V. Giardino, and B. Tversky. Gestures for thinking. In *Proceedings of the Annual Meeting of the Cognitive Science Society*, volume 35, 2013.
- [14] W. Kadous et al. Grasp: Recognition of australian sign language using instrumented gloves. 1995.
- [15] E. Macdonald, R. Salas, D. Espalin, M. Perez, E. Aguilera, D. Muse, and R. B. Wicker. 3d printing for the rapid prototyping of structural electronics. *IEEE access*, 2:234–242, 2014.
- [16] D. McNeill. *Hand and mind: What gestures reveal about thought*. University of Chicago press, 1992.
- [17] D. McNeill. Gestures of power and the power of gestures. In *Proceedings of the Berlin Ritual-Conference. Berlín: Fischer-Lichte y Wulf*, pages 1–13, 2008.
- [18] S. A. Mehdi and Y. N. Khan. Sign language recognition using sensor gloves. In *Proceedings of the 9th International Conference on Neural Information Processing, 2002. ICONIP’02.*, volume 5, pages 2204–2206. IEEE, 2002.
- [19] D. Murphy. *Resonance*. Stanford University, Mar 2018.
- [20] S. Nanayakkara, E. Taylor, L. Wyse, and S. H. Ong. An enhanced musical experience for the deaf: design and evaluation of a music display and a haptic chair. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 337–346. ACM, 2009.
- [21] S. D. Novich and D. M. Eagleman. [d79] a vibrotactile sensory substitution device for the deaf and profoundly hearing impaired. In *2014 IEEE Haptics Symposium (HAPTICS)*, pages 1–1. IEEE, 2014.
- [22] C. Oz and M. C. Leu. American sign language word recognition with a sensory glove using artificial neural networks. *Engineering Applications of Artificial Intelligence*, 24(7):1204–1213, 2011.
- [23] N. Rasamimanana, F. Bevilacqua, N. Schnell, F. Guedy, E. Flety, C. Maestracci, B. Zamborlin, J.-L. Frechin, and U. Petrevski. Modular musical objects towards embodied control of digital music. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*, pages 9–12. ACM, 2011.
- [24] D. Shibata. Brains of deaf people “hear” music. *International Arts-Medicine Association Newsletter*, 16(4):1–2, 2001.
- [25] E. A. Søderberg, R. E. Odgaard, S. Bitsch, O. Høeg-Jensen, N. Schildt, S. D. P. Christensen, and S. Gelineck. Music aid-towards a collaborative experience for deaf and hearing people in creating music. In *New Interfaces for Musical Expression. New Interfaces for Musical Expression*, 2016.
- [26] C. Valli and C. Lucas. *Linguistics of American sign language: an introduction*. Gallaudet University Press, 2000.
- [27] M. M. Wanderley. Non-obvious performer gestures in instrumental music. In *International Gesture Workshop*, pages 37–48. Springer, 1999.
- [28] G. Wang and R. Michon. Fauck!! hybridizing the faust and chuck audio programming languages. In *Proceedings of the 16th international conference on New interfaces for musical expression*, 2016.