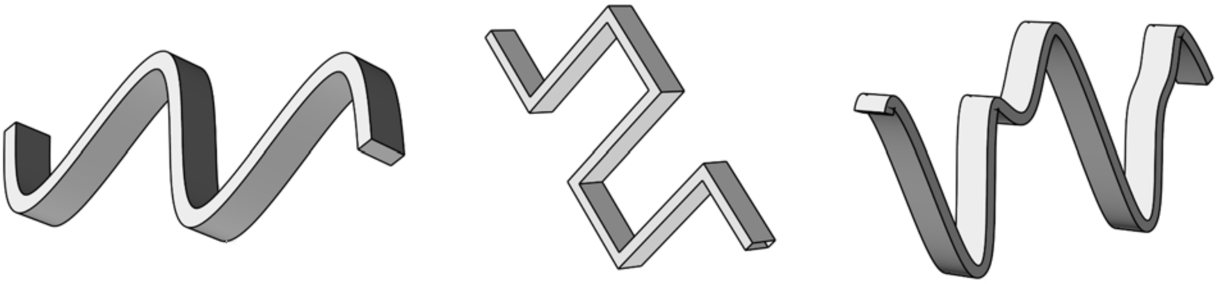
Jens Vetter

Tangible Signals



2025

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Tangible Signals

Physical Representation of Sound and Embodied Control Feedback.

Doctoral Thesis

This dissertation is submitted for the degree of Doctor of Philosophy.

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Abstract

Music brings joy, enables artistic self-expression and stimulates human connections. This thesis explores the physicality of computer music and digital music-making in the context of accessibility and assistive technologies for visually impaired and blind musicians. Using artistic research methods, the project aims to overcome the limitations of vision-centric music software by coupling digital data with the physical domain, creating a more tactile and accessible physical music computing experience. In collaboration with visually impaired and blind experts from the Institute for the Blind in Vienna, this research project investigates whether tangible musical interaction as a human-computer interaction (HCI) modality is a suitable approach towards accessible digital music-making and whether it can inspire creativity and enhance artistic stage performance.

This thesis presents the research project in detail, including an overview of the research context and background, a description of the practical work, and a presentation of the final results. Related topics are introduced, including artistic research, universal design, human–computer interaction, assistive technology, digital music-making and tangible interaction design. The practical section of the thesis outlines the iterative development of accessible text-based music software and multiple tangible musical interfaces. The artistic exploration of these interfaces and their use in stage-based live performances by visually impaired and blind experts is summarized to provide insight into their potential as tools for the practice of accessible computer music. Finally, the insights gained from the practical work, user inquiries, interviews, artistic explorations, stage performances and observations are evaluated and summarized. The research project shows that tangible musical interaction can be a valuable approach for visually impaired and blind musicians to use the computer for digital music-making, it can improve artistic expression and inspire musical creativity.

Acknowledgments

I would like to thank my supervisor, Martin Kaltenbrunner, for his support and constructive feedback throughout the research project. I would also like to thank Erich Schmid from the Institute for the Blind in Vienna for the inspiring collaboration and for his trust and artistic insights. Likewise, I am very grateful for the curiosity and feedback of Martin Mayerhofer, Ben Hofer, Mario Lang, and Angela Videbis. Thank you to all the students who participated in the workshops and lectures at BBI Vienna and OCC summer camps. Furthermore, I would like to thank my colleague, Enrique Tomás, for his feedback and insights. I also thank Hansi Raber and Johannes Unger for discussing the Welle music environment and providing helpful feedback. Many thanks to Rainer Gamsjäger for his support with the metalwork. Thanks also to all those who provide and share knowledge online via various websites, forums and mailing lists. Much of the practical work in this thesis has benefited greatly from their input on topics such as programming, electronics, and sound synthesis. This project would not have been possible without the support of the Austrian Academy of Sciences (ÖAW) in Vienna and the DOC Fellowship funding, for which I am deeply grateful. Many thanks to Barbara Seyerl for proofreading the publications.

I would like to express my gratitude to Elisa Unger for her unwavering patience and continuous support over the years, her constant encouragement and feedback, as well as her professional work on video documentation and logo design. Most importantly, I would like to thank my mother for all her support and encouragement. I would have loved to reflect with you on the final research results and celebrate these results, just as we always discussed relevant topics and next steps in the early phase of the research project.

Contents

Publications

Throughout the research project, various aspects and developments have been published as academic papers at peer-reviewed conferences focusing on related topics such as new interfaces for musical expression (NIME), tangible interaction (TEI), and accessibility and special needs (ICCHP). These publications summarize the project's starting point, present the development of accessible music software and the design of interactive tangible prototypes, and summarize the project's results.

The following academic papers have been published:

Vetter, J. (2019). Tangible Signals - Physical Representation of Sound and Haptic Control Feedback. In: *TEI - Proceedings of the 13th International Conference on Tangible, Embedded, and Embodied Interaction*.

Vetter, J. (2020). WELLE - a web-based music environment for the blind. In: *NIME - Proceedings of the International Conference on New Interfaces for Musical Expression*.

Vetter, J. (2021). Tangible Signals - Prototyping Interactive Physical Sound Displays. In: *TEI - Proceedings of the 15th International Conference on Tangible, Embedded, and Embodied Interaction*.

Vetter, J., Kaltenbrunner, M., Schmid, E. (2024). Sonic Interactions - Towards Accessible Digital Music-Making. In: *ICCHP - Computers Helping People with Special Needs, 19th International Conference*.

Chapter 1

Introduction

The artistic creation of music and sound is an inspiring and poetic field of self-expression, art, research, and community. Like many artistic fields, the creation of sound and music incorporates technology to expand artistic expression and extend the human body's acoustic, percussive, and tonal capabilities. The human passion for musical expression has resulted in an enormous diversity of instruments, ranging from the earliest bone flutes and pipe organs to the *guqin*,[1] electric sine wave generators and digital granular synthesizers.

Today, computers are the most affordable, ubiquitous, and versatile platform for music-making. They offer a wide selection of music software and external hardware devices. Computers provide musical and sonic possibilities that traditional instruments cannot, such as advanced sound synthesis, algorithmic composition, multimodal interaction, and networked performances. To access these digital capabilities, musicians interact with human-computer interfaces, such as keyboards, mouse, and screens. Interactions are defined by paradigms such as the command-line interface (CLI), the Windows, Icons, Menus, and Pointers (WIMP) model, graphical user interfaces (GUIs), and multimodal interaction. These paradigms enable rich communication, allowing computers to be used as musical instruments.

However, digital technologies simultaneously enable and hinder artistic practice, depending on cultural, societal, and industrial perspectives, norms, and ethics. Users with disabilities are often overlooked and excluded regarding technological developments. It is not the computational power itself that excludes users with physical or cognitive disabilities, but rather access to and interaction with the technology. Visually impaired and blind musicians (VIBs) face access barriers when

[1] https://ich.unesco.org/en/RL/guqin-and-its-music-00061

interacting with computers regarding digital music technology due to vision-centric software design. Despite assistive technologies such as screen readers, text-to-speech synthesis, screen magnifiers, and refreshable Braille displays, many aspects of music software remain inaccessible, such as displaying audio waveforms or equalizer curves. Likewise, most external digital music hardware presents access barriers. MIDI controllers often rely on visual feedback, such as flashing LEDs or menu screens. The same is true for digital synthesizers, sequencers, and groove stations, which prevents VIB musicians from using them. To address these barriers, several research projects have explored haptic interaction as an approach to complement or replace visual interaction. Examples include the *Moose*, the *Haptic Wave*, and the *HaptEQ* [R. B. Gillespie and O'Modhrain 1997; Tanaka and Parkinson 2016; Karp and Pardo 2017]. However, this topic remains underexplored and requires further research.

One approach toward more tactile and physical computing is tangible interaction design, an interaction modality that is based on the representation of digital data in the physical domain, which in turn allows the physical reconfiguration of the underlying digital data. By linking the digital and physical domains, tangible interaction design enables expressive bodily access and is therefore well suited for musical interaction and designing new musical instruments, such as the *Reactable*, the *Tquencer* or the *Kanchay_Yupana//* [Jordà et al. 2006; Kaltenbrunner and Vetter 2018; Hinojosa 2022].

The physicality of tangible musical interaction seems to address the artistic practice of digital music-making for VIB musicians who rely on non-visual displays and benefit from tactile feedback. Their use of music software, composition, and stage-based live performances could benefit from tangible musical interaction. These possible implications of tangible interaction as a means for accessible digital music-making are the focus of this research project. In collaboration with VIB experts and based on artistic exploration and inquiry, the project will examine the benefits and effects of tangible interaction for accessible digital music-making. This includes developing suitable tangible musical interfaces, using them for artistic practice, and collecting expert feedback and observations. The findings will provide an overview and guidelines for future developments in accessible digital music-making and tangible musical interaction for VIB experts.

The thesis is organized into four main chapters that introduce, contextualize, document, and evaluate the research project. The thesis aims to present all the relevant topics, practical aspects, and insights necessary to follow, evaluate, and reproduce the research process. The first chapter introduces topics such as artistic research, universal design, and disability concepts to provide context for the research. It begins with the author's personal motivation and artistic background. The chapter addresses the three main research fields of human-computer interaction, new interfaces for musical expression, and assistive technology. The chapter also presents the academic institutions and collaboration partners involved in the project and lists the research questions and methods. Lastly, the chapter provides an overview of the project's chronology and main contributions.

The second chapter offers insights into the research context and key topics underlying the research project. It delves into the early days of computer technology to explore the use of computers as tools for artistic expression and musical composition. Focusing on visual impairments and blindness, the chapter discusses the limitations of visual representations and summarizes related human-computer interaction modalities, such as haptic and tangible interaction. Finally, it describes the creation of sound and music as artistic expressions and analyzes computers as suitable platforms for musical expression and digital music-making, particularly with regard to assistive technology and accessibility.

The third chapter presents the practical work realized throughout the research process. Starting with the initial proposals for musical prototypes, the chapter details the first phase of the research process, its findings, and the development of accessible music software. It also describes the exploration of various sonic features and the subsequent iterative development of three tangible musical interfaces. The chapter then summarizes the VIB experts' exploration of the tangible interfaces. Finally, it describes the preparation of an artistic musical piece based on the use of tangible musical interfaces and its stage-based live performance.

The fourth chapter evaluates the insights gained during the practical work. Beginning with a discussion of the study framework and its limitations, it categorizes the insights into four key topics. The various VIB expert feedback and observations are then evaluated in regard to the research questions. The thesis concludes with a summary of the research project and its contributions, a reflection on the research process and methods, and a discussion of future perspectives.

1.1 MOTIVATION AND ARTISTIC BACKGROUND

The following section will introduce the author's artistic background and motivation in relation to the research project. Prior to this project, the author had no experience collaborating with VIB musicians or developing assistive music technology.

The motivation for beginning this artistic research project stems from a passionate and professional background in musical practice and stage-based performance, as well as experience designing sound sculptures and new musical instruments. As a musician who plays various acoustic instruments, such as the piano, drums, and guitar, as well as electronic instruments such as samplers, synthesizers, and the theremin, the author has an intimate relationship with sound and music composition. Through collaborations with visual and performance artists, his concept of music shifted from instrumental music to the incorporation of artistic and performative elements, such as costumes, site-specific settings, and artistic interventions. This resulted in the development of various sound objects, sound installations, and wearable sound costumes with a focus on mechanical actuation and acoustic sound generation.

The artistic project *Homo Incognito*, created in collaboration with the German artist and sculptor Sarah Leimcke, demonstrates the development of interactive, sensor-based musical interfaces (see Fig.1.1.1).[2] For this artistic project, two costumes with corresponding interactive interfaces were developed. One costume's interface involved cymbals as acoustic sound generators, whereas the other costume's interface involved mechanical exciters and metal tubes. The cymbal-based interface used two DC motors, each with metal screws mounted on their rotating shafts, that excited the cymbals by mechanically scrubbing their surfaces, creating loud and noisy sounds. The movement and speed of the motors were controlled by ultrasonic distance sensors built into the gloves of the cymbal-based costume. When the wearer approached physical objects in the environment, such as walls, furniture, or other people, the sensors detected the changes and triggered the motors to move accordingly, accelerating their speed in relation to the decreasing distance of the physical objects. The interaction principle resembles the echolocation practice used by persons with VIB. This practice uses click-sonar sounds to orient oneself in the environment. A person can scan their surroundings and listen to the echoing signals that reflect back from objects, walls, and doors by producing loud and sharp

[2] https://jensvetter.de/inkognito/

Figure 1.1.1: Image of the performance project *Homo Incognito* by Sarah Leimcke and Jens Vetter.

clicking sounds with the tongue. With training and careful listening, this practice enables VIB persons to perceive their environment, orient themselves, and guide their steps. Some VIB practitioners, such as Erich Schmid, a cooperation partner in this research project, report that this technique enabled them to gain enough orientation to ride a bike. As will be presented and discussed later, Schmid composed an original piece of music involving audio samples of his click-sonar technique and performed it live on stage.

Another project that combines musical and performative aspects is *Homo Restis*, which uses a wearable, multi-channel instrument setup for performances in public spaces [Vetter and Leimcke 2017]. The project centers on two costumed performers who act and move in public spaces by interacting with a system of multiple long strings (see Fig.1.1.2). The strings are interactive parts of a mobile sonic system that generate sounds depending on the speed and amount of interaction. Each string produces a different sound. This interactive sonic system was developed to connect performers with their environment and challenge traditional musical instrument design concepts by exploring new musical and performative interaction approaches. This interdisciplinary perspective on musical interaction forms the foundation for exploring new musical concepts and sonic interfaces and motivated the investigation for the present research project.

Figure 1.1.2: Image of the performance project *Homo Restis* by Sarah Leimcke and Jens Vetter.

Further experience using computers as musical instruments based on music programming languages was gained during collaborative work with performance artist Patrik Huber. Together, they formed the music group *Vetter_Huber*.[3] To generate sound and enable musical interaction, the author used SuperCollider, a music programming language, as an environment for sound synthesis and music composition. A custom graphical user interface, combined with external MIDI controllers, served as an interactive platform for live performances (see Fig.1.1.3).[4]

Likewise, the sound installation *Netz 2.0* demonstrates an artistic approach to performative sonic interactions. It combines metaphors from nature — specifically, the structure of a spider's web — with digital sound synthesis to allow playful and intuitive sound explorations. The interface uses the stretching of elastic strings as an interaction method and functions as both an art installation and a musical instrument (see Fig.1.1.4) [Vetter 2019]. This interactive sound installation provided the author with experience and knowledge in developing string-based, interactive musical interfaces.

[3]Studio album: *Vetter_Huber - Eskalation im Paradies.* https://seayou.bandcamp.com/album/vetter-huber-eskalation-im-paradies

[4]https://supercollider.github.io/

Figure 1.1.3: Image of the graphical user interface made with SuperCollider for *Vetter_Huber*.

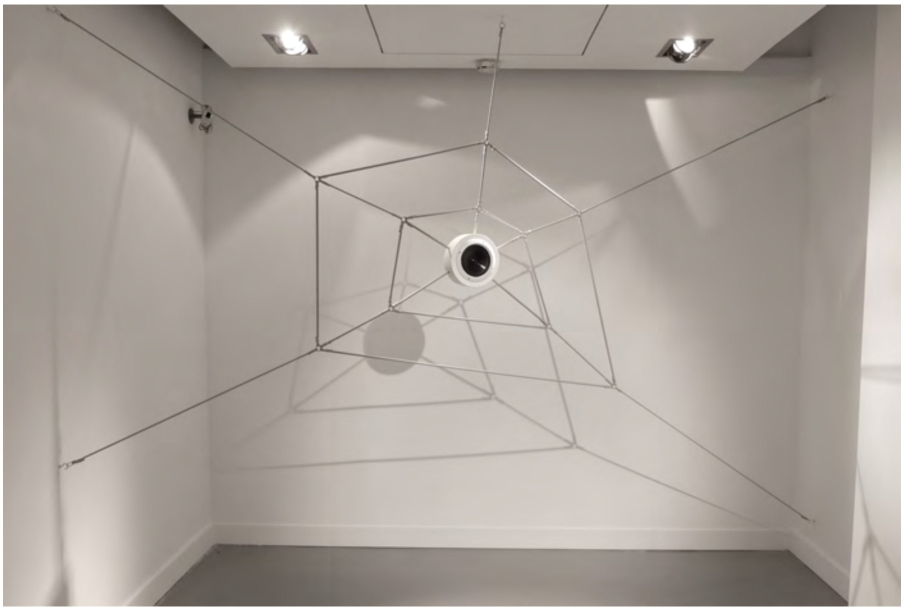

Figure 1.1.4: Image of the interactive sound object *Netz 2.0* at the Digital Design Weekend, ACF London 2018.

Another interactive musical device that was developed prior to the research project is the *Tquencer*, a standalone tangible sequencer that interacts with physical tokens and preset layers (see Fig.1.1.5) [Kaltenbrunner and Vetter 2018]. The device was developed in collaboration with Martin Kaltenbrunner (see Chapter 2.3.3). The design process provided further insight into creating tangible musical interactions.

The knowledge gained from developing musical instruments for stage performances, as well as expertise in music programming languages and sensor-based musical interactions, formed the basis for designing tangible musical interactions for VIB musicians. Focusing on interactive and tactile approaches and challenging the limitations of vision-centric software design from an artistic research perspective stimulated the author's creative imagination, despite having no prior experience or connections with the VIB community.

Figure 1.1.5: *Tquencer*, a tangible sequencer using overlays.

1.2 STATEMENT OF POSITIONALITY

The author is a forty-five-year-old middle-class white German man who identifies as non-disabled.[5] He is an experienced musician, performer, and media artist. He has a background in academic research in human-computer interaction, tangible interaction design, and new interfaces for musical expression (NIME), and aims to contribute his artistic experiences to these fields.

1.3 ARTISTIC RESEARCH

The present research project, *Tangible Signals*, combines aspects from various scientific and artistic disciplines, including human-computer in-

[5]The inclusion of the Author Statement of Positionality for research in the field of VIB people, assistive technology and music technology is inspired by Harrison [Shultz and C. Harrison 2023] as a disclosure of the researcher's identity and positionality.

teraction, tangible interaction design, assistive technologies, interactive sonic objects, and the artistic practice of digital music-making and stage-based live musical performances. Focusing on accessible digital music-making and the ideation and development of tangible musical interfaces, this project utilizes artistic research methods, particularly for the iterative development of musical interfaces and their practical exploration through artistic performance. The concept of artistic research will be presented below, including historical predecessors and various projects that were previously conducted at the Tangible Music Lab department at the University of Arts in Linz.

From Knowledge to Research

This research project is structured and carried out using methods and approaches from artistic research. But what exactly is artistic research, especially in relation to scientific research, and how can it be used to gain knowledge? According to Michael Schwab's essay "Contemporary Research" multiple variations of the term are in circulation. These variations differ primarily by geopolitical and linguistic particularities. Examples include artistic research, practice-based research, *recherche création*, and *Künstlerische Forschung*. Practice-based research is more associated with the United Kingdom, while artistic research is more associated with continental Europe [Schwab 2023]. To understand the meaning of artistic research, Schwab argues that focusing on its late twentieth century appearance and subsequent institutionalization is insufficient. He believes that there is a prehistory of the relationship between science, research and art that extends from Plato's exclusion of art from the state in his *Republic*, to non-ocular-centric discourses within religious and indigenous contexts during the Renaissance, to the impact of German Romanticism and Kant's critical work, which laid the groundwork for modern artistic research and contemporary art, to Beuys's *Jeder Mensch ist ein Künstler*. Similarly, Fernand Hörner states that historically, science and the arts were not strictly separated but underwent ongoing changes. The ancient free arts included music, rhetoric, arithmetic, geometry, astronomy, grammar, and dialectics. Scientists prepared artfully written and oral presentations. He mentions Leonardo da Vinci and Johann Wolfgang Goethe as exemplary figures who embodied both science and art. Hörner identifies the separation of art and science at the moment when the specialization of premodern science and art made universal genius impossible [Hörner 2018]. Michael Schwab uses the *Google Books Ngram Viewer* to illustrate the changing occurrence of words such as *artistic knowledge*, *creative research*, *art research*, *artistic research* and *practice-based research* in the literature over the last 200 years. The graph shows how the concept of knowledge, as seen in subjects such as artists, geniuses, artworks, and masterpieces, has evolved into a more fluid notion of research and the creation of knowledge. Traditional knowledge, which Schwab refers to as "conservative", was replaced by future unachieved knowledge through research, which he calls "progressive" and thus debatable [Schwab 2023].

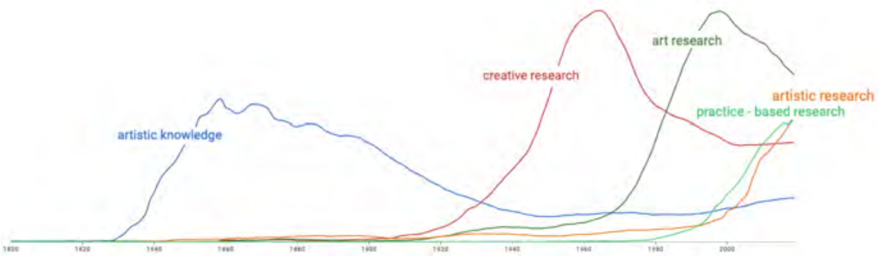

Figure 1.3.1: Result of *Google Books Ngram Viewer* on the shift of wordings around artistic research, informed by Michael Schwab.

However, as Schwab shows, the importance and concepts of artistic knowledge versus artistic research have changed over the last few centuries. Nevertheless, the current understanding of artistic research and its manifestations is still the subject of a controversial discussion that questions the scientific value and justification of the intersection of art and science [Butt 2017]. There are different heterogeneous forms and divergent goals that can be explored and categorized. These range "from the simple integration of philosophical or scientific knowledge to the establishment of artistic research as a form of institutionalized self–examination and scientification of artistic practice." [Busch 2009] Some authors even question whether academic artistic research exists and whether art and artistic practices can be considered scientific research [Mersch et al. 2020].

To provide perspective on the topic, it may be helpful to consider the following definition of research, which was formulated as part of the European Bologna process regarding doctorates as the third cycle of higher education (found in the 'Dublin descriptors'):

> *"The word 'research' is used to cover a wide variety of activities, with the context often related to a field of study; the term is used here to represent a careful study or investigation based on systematic understanding and critical*

> *awareness of knowledge. The word is used in an inclusive way to accommodate the range of activities that support original and innovative work in the whole range of academic, professional, and technological fields, including the humanities, and traditional, performing, and other creative arts. It is not used in any limited or restricted sense, or relating solely to a traditional 'scientific method'."* [6][7]

According to Henk Borgdorff, this definition of research represents a liberal perspective on the scientific focus and process. It is open to a wide variety of fields of interest, not just traditional scientific methods. It encompasses artistic practice as a legitimate subject of investigation and research [Borgdorff 2008].

Conversely, Julian Klein, director of the Institute for Artistic Research Berlin,[8] cites the more general UNESCO definition, that describes research as "any creative systematic activity undertaken in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this knowledge to devise new applications."[9] He states that research, as an activity, is not limited to the scientific community but is also practiced by artists through their systematic search for material, context, and knowledge. Artists perform this search constantly alongside their artistic practices. Research becomes artistic if it is conducted by artists with a certain quality, which he calls "the mode of artistic experience" [Klein 2017]. Using this "mode of artistic experience" as a basis for producing scientific knowledge at the intersection of artistic practices, research interests, and scientific methodologies places artists at the center of artistic research.

Despite all the controversy, today, artistic research is established at art schools and universities as a legitimate scientific practice. As James Elkins stated in 2013, there were around 280 institutions worldwide offering art-based PhD programs with diverse cultural backgrounds, historical traditions, and meanings of *research*, *assessment*, and *knowledge* [Borgdorff et al. 2013]. As Corina Caduff points out, the growing significance of artistic research can be measured by the number of funding agencies and their policies, the number of publications on the topic produced for conferences and anthologies, and the increasing institutionalization manifested by the foundation of research areas, research

[6] https://www.aqu.cat/doc/doc_24496811_1.pdf
[7] https://www.ehea.info/page-three-cycle-system
[8] https://www.artistic-research.de/
[9] https://read.oecd-ilibrary.org/economics/oecd-glossary-of-statistical-terms_9789264055087-en

institutes, doctoral programs, and teaching modules in master's programs [Caduff 2017]. She highlights places like the *Journal of Artistic Research* (JAR) as a central medium for academic publications on the topic, a platform that was founded in 2011 and since serves as a meeting point, network and archive or artistic research.[10] The journal is published by the *Society for Artistic Research*,[11] which also runs the *Research Catalogue*, an international database for artistic research projects and publications.[12] Caduff cites the Dutch art historian Henk Borgdorff who states that "artistic research does not have any one distinct, exclusive methodology" and therefore pleads for "methodological pluralism" [Caduff 2017]. Caduff continues by opposing scientific and artistic methods, where scientific methods are based on the explicit and therefore understandable sequence of question, path of knowledge and results. Artistic methods on the other hand are less traceable and focus more on the artistic result, that "speaks for itself". The combination of both methods is the melting point of artistic research. She agree's to Borgdorff by pointing out, that countless artistic research projects exhibited methodological pluralism, particularly because they are located in different artistic disciplines and therefore refer to different scientific contexts [Caduff 2017].

1.3.1 Artistic Research and Musical Interfaces

Regarding the present research project, which focuses on sonic interaction and artistic practice, how can artistic research be applied to the field of musical interfaces, digital music-making and accessibility? To the author, artistic research, particularly in the areas of human-computer interaction and NIMEs, is a form of scientific research conducted by an artist-researcher. This research is informed by the artist's perspective and includes artistic practice and results. The artist-researcher documents, verbalizes, contextualizes, and shares progress according to scientific methodologies. Or like Mike Hannula et al. put it in their basic formula of artistic research: "artistic research = artistic process (acts inside the practice) + arguing for a point of view (contextual, interpretive, conceptual, narrative work)" [Hannula et al. 2014].

This research project implements artistic research within an interdisciplinary, innovative, and collaborative project at the intersection of computer music, music technology, human-computer interaction, and

[10] https://www.jar-online.net/en
[11] https://societyforartisticresearch.org/
[12] https://www.researchcatalogue.net/

assistive technology. Applied methodologies are informed by scientific methods practiced in the HCI and, more specifically, the NIME communities. These methods include iterative design and development of musical interfaces, user inquiries, user feedback, observation, and qualitative interpretation. Artistic research methods are used to develop accessible music software, identify sonic features, and iteratively develop tangible musical interfaces. These methods also facilitate artistic practices such as composing a musical piece and performing it live on stage. Artistic decisions that were made during this research project, often resulted from an musical, artistic and performative knowledge of 'knowing how', which is opposed to the more conventional scholarly knowledge of 'knowing what', a differentiation that Henk Borgdorff describes as "non-conceptual knowledge embodied in art", that is "tacit, implicit knowledge" and "finds no direct discursive or conceptual expression" [Borgdorff 2012].

1.3.2 Artistic Research in the Tangible Music Lab

In the Tangible Music Lab (see Chapter 1.9), artistic research is employed as a methodology to explore topics such as novel musical interfaces, the physical embodiment of sound, and musical interfaces for animals. Artist-researchers, such as Reinhard Gupfinger and Enrique Tomás, apply their unique perspectives as media artists and musicians to conceptualize, design, and develop musical interfaces and sonic environments. As part of the scientific process, the collaboration with external partners enables co-design, and ensures authentic and unbiased expert feedback. The research process, including prototyping, design, collaborations and results is then published in scientific journals and conferences, in order to contribute new knowledge. Following below are two exemplary artistic research projects that were conducted at the Tangible Music Lab in recent years.

The Interface Score

Enrique Tomás, a sound artist and postdoc researcher, investigated new approaches to musical scores in his artistic research project *The Interface Score*. Interested in the extend to which musical instruments can be perceived as scores, he examines the cultural and technological nature of digital musical instruments and the artistic and philosophical consequences of understanding them as artifacts embodying a score [Tomás 2016]. Tomás proposed a compositional framework based on non-notational music systems, that is embodied and engraved into the musical instrument itself, as opposed to traditional graphical scores that are separated from the instrument and exist in a virtual or physical form that needs mediation and interpretation from the performer. The use of *inherent scores* therefore brings together performer, instrument and score, and thus reduces translational friction through its use of performative materiality. An artistic example for this notion of instrument-scores are Tomás' *Tangible Scores*, a new paradigm for musical instrument design centered around musical scores that are incorporated in the physical shape of the instrument (see Fig.1.3.2) [Tomás and Kaltenbrunner 2014].

Figure 1.3.2: Tangible Scores by Enrique Tomás.

Throughout his research process, Tomás artistically experimented with a wide range of materials, different approaches towards the fabrication of embodied and tangible music scores, the technological implementation of analysis and sound synthesis systems, and their performative adaptation and practice-based evaluation. He invited artists and musicians to use the instrument-scores for musical compositions, which even inspired a range of new digital musical instruments in the process. His *Tangible Scores* interfaces were exhibited at art and music festivals, and used in practice-based activities like workshops, artistic collaborations and stage-performances [Tomás 2018].

Metamusic

The artist and researcher Reinhard Gupfinger investigated the situation of Grey Parrots that are held in captivity in the context of Animal-

Computer Interaction (ACI), and focused on the development of interactive sound installations and electronic musical instruments as an attempt for auditory enrichment [Gupfinger and Kaltenbrunner 2020]. With the underlying conviction that wild animals should not be kept in man-made environments, the project attempts to help improve the well-being of those parrots that were forced into captivity. By developing new technologies for animals from an animal-centered design perspective, Gupfinger aims to provide a better understanding of how grey parrots communicate through sound, how they perceive and respond to auditory stimulation and if they use those new musical technologies to generate sound and music.

Figure 1.3.3: Metamusic - *Reel instrument*.

Building on previous work of the artists group *Alien productions*, and in collaboration with zoologists and animal keepers, Gupfinger developed various musical interfaces for grey parrots, that took their specific needs and skills into consideration. During meetings in a zoological parrot shelter, and with the same group of grey parrots as intelligent, individualistic and communicative partners, Gupfinger conducted and documented multiple *jam sessions* to gain knowledge about auditory skills and musical preferences, and enabled playful interactions of parrots and humans, including the use of instrument prototypes. Based on this human-conducted co-design process, and with respect to the parrots intrinsic interest in acoustic and physical interactions, a number of dedicated musical interfaces were developed, including the *gong instrument*, the *DJ instrument*, the *reel instrument* and various other instruments (see Fig.1.3.3). The intention behind these instruments is to offer cognitive and auditory enrichment for the animals, while also to intrinsically motivate them to engage with the musical devices. Over the course of the research project, and as artistic research method, Gupfinger organized multiple interspecies music performances with both the grey parrots and invited artists and musicians, which further informed the design of the instruments. The artistic research project *Metamusic* provides an overview of recent animal-computer interaction and musical instruments that involve animals in the music-generation process, it contributes valuable insights in the methodology and design of musical instruments for animals, and especially documents individual preferences and musical interaction of grey parrots [Gupfinger 2020].

1.4 UNIVERSAL DESIGN AND DISABILITY

This research project focuses on accessible musical interaction and digital music-making for VIB musicians. It centers on the use of computers as musical and creative platforms and attempts to design accessible software and hardware tools to explore the benefits and implications of tangible musical interaction for accessible music-making. The need for new, accessible software and hardware interfaces stems from the fact that current technical developments in the field of computer music still lack awareness of and accessibility for users with diverse backgrounds and abilities. Music hardware and computer software are often designed with an idealized, 'normal' user profile in mind. This profile represents the majority of users who have no physical or cognitive limitations. Conversely, users with limitations regarding vision, hearing, motor skills, or cognitive abilities often have to use specialized solutions that are expensive, outdated, limited in functionality, or unavailable.

Yet the group of people with disabilities worldwide is huge - according to the *World Health Organization* (WHO) there are 1.3 billion people experiencing significant disability, which represents 16% of the worlds population, or 1 in 6 persons.[13] The WHO notes that disability is an integral part of being human and is integral to the human experience, which is also reflected in the fact that the group of people with disabilities is very diverse in regard to sex, age, gender, identity, sexual orientation, religion, race, ethnicity and economic situation. And the amount of people with disabilities is growing because of an increase of noncommunicable diseases and people living longer. Rupert Bourne et al. attempted to estimated the global number of people with vision impairments or blindness by conducting a systematic review and meta-analysis in 2020. The study estimates that globally 49.1 million

[13] https://www.who.int/news-room/fact-sheets/detail/disability-and-health

people were blind, 221.4 million had moderate VI and 33.6 million had severe VI [Bourne et al. 2020]. From this global number of 304.1 million people that are partially sighted or blind, the European Blind Union estimates 30 million people only in Europe.[14]

To address the needs of people with disabilities including visual impairments, various concepts of accessibility and disability inform the process of designing products, services, interactions and environments. As a vision for improvements through accessible web design Hans Persson et al. cites the region of Västra Götaland in Sweden: "What is essential for some specific users for them to be able to use a product, often makes it more efficient to use for most people" and links this claim to digital accessibility research, which shows that the design of websites according to WCAG 1.0 makes it not only easier to access for individuals with disabilities, but also reduces maintenance costs, page load time and increases search engine traffic [Persson et al. 2015; Rømen and Svanæs 2012].

Perspectives on Disabilities

The notion towards people with disabilities and their integration in the western culture changed hugely over the last centuries, especially in regard to the perception and understanding of disability. As Colin Barnes shows, disability was over a long period of time regarded as an individual medical problem and a 'personal tragedy' and was confronted with widespread oppression and prejudice, yet prior to the industrial revolution persons with disabilities were integrated into the community [Barnes 2019]. According to Barnes this changed with the industrialization, urbanization, changing work patterns and new ideologies like liberal utilitarianism, medicalization, eugenics and social Darwinism, that all together led towards increased discrimination and the removal of disabled people from mainstream social and economic life. As Barnes says, it was the cruelty of the German Nazi Government and its "euthanasia" program that later caused a "softening" of political attitudes towards disability in the United Kingdom (UK) and the United States of America. Also the huge number of war-wounded after the second World War and a growing share of a population with disabilities through medical advances led to the expansion of community-based services and the formation of disability organizations, that later split from uni-disability to multi-disability organizations.

[14] https://www.euroblind.org/about-blindness-and-partial-sight/facts-and-figures

Disability activists in the UK fought against poverty, social isolation and the dominance of non-disabled experts, organized in the *Union of the Physically Impaired Against Segregation* (UPIAS), which was founded in 1974. They argued, based on personal experience and sociological insights, that the common concept of disabilities was less based on biological impairments, but was a form of social oppression, similar to that encountered by other minorities: "Disability is something imposed on top of our impairments, by the way we are unnecessarily isolated and excluded from full participation in society. Disabled people are therefore an oppressed group in society." [UPIAS 1976] This 'social model' of disability, in contrast to the previously dominant 'medical model', now allows to identify disabling social structures and to understand disability as a form of oppression, which influenced the self-perception of disabled persons as well as politics, education and research ever since. Nonetheless authors like Shakespeare and Watson point out that this social model of disability as a radical political guideline has its limitations and that "people are disabled by society as well as by their bodies" and that not all disability is imposed and can therefor be resolved on a social level [Shakespeare and Watson 2002].

The historical shift in the perception of disability was included in the *Universal Declaration of Human Rights by the United Nations* in 1948: "Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family, including food, clothing, housing and medical care and necessary social services, and the right to security in the event of unemployment, sickness, disability, widowhood, old age or other lack of livelihood in circumstances beyond his control."[15] Later declarations like the 1971 *Declaration on the Rights of Mentally Retarded Persons*, the 1975 *Declaration of the Rights of Disabled Persons* or the 1981 *International Year of Disabled Persons* paved the way for the *United Nations Convention on the Rights of Persons with Disabilities*,[16] which was adopted by the European Union, informed the *European Disability Act* and serves as guideline for improvements on diverse challenges for persons with disabilities through agreements like the EU Strategy for the *Rights of Persons with Disabilities 2021-2030*: "The goal is to ensure that persons with disabilities in Europe, regardless of their sex, racial or ethnic origin, religion or belief, age or sexual orientation: enjoy their human rights, have equal opportunities, have equal access to participate in society and economy, are able to

[15] https://www.un.org/en/about-us/universal-declaration-of-human-rights
[16] https://www.un.org/disabilities/documents/convention/convoptprot-e.pdf

decide where, how and with whom they live, can move freely in the EU regardless of their support needs, no longer experience discrimination."[17]

Regarding the question what and who needs to be adapted, two converging movements are often referred to: inclusion and integration. The concept of inclusion describes the creation of an environment that enables all people to participate regardless of their differences by adapting the environment to the people. Integration on the other hand means to provide help and opportunities for excluded people to adapt and integrate themselves into the existing structures and mainstream group, which requires the adaptability of the individual. In this regard, the disability activists at the UPIAS and their 'social model' of disability, the *UN Convention on the Rights of Persons with Disabilities*, the resulting *European Disability Act* and the *EU Strategy for the Rights of Persons with Disabilities 2021-2030* demand, that the process of adaptation for disabled people cannot be accomplished through individual integration but needs to be based in societal and environmental inclusion.

Disability activist and inclusive art consultant Thomas Tajo goes even further and argues that there exists no difference between 'normal' and disabled people, but that the reality of human and non-human beings worldwide alike is universal diversity, including aspects such as diverse abilities, race, gender, sexual-orientation etc. For Tajo, the reality is a living diversity, which demands the acknowledgment of diversity as a norm and not as exceptions, which "imposes responsibility on us, to be respectful in our interaction with diversity of beings and to acknowledge their diverse abilities."[18] Following the concept of *Bioplasticity* as the potential to adapt to diversity, and that diverse abilities of humans are the norm, he argues that "access needs" are a universal reality, not the problem of a few individuals and communities, and should be anticipated and incorporated in the design of any product and service from the very beginning.

Design and Accessibility

When designing products and environments for a diverse group of people with and without disabilities different design concepts emerged over the last decades, starting with *barrier-free design* as response to the huge numbers of war-wounded people in the US in the 1950s. Making buildings accessible for handicapped people was a strategy to enable education and employment opportunities as alternative to institutionalised

[17] https://data.europa.eu/doi/10.2767/31633

[18] https://www.linkedin.com/pulse/notes-design-diversity-thomas-tajo/

health care. This concept of accessibility expanded towards the extensive development of assistive technologies in the areas of architecture and home equipment, such as the one hand blender, remote controls and wider doors in trains [Persson et al. 2015]. The *barrier-free design* approach then evolved towards concepts like *design for all* and *inclusive design*, which are all attempts to design for the widest possible range of people. The *European Institute for Design and Disability* (EIDD) is convinced that "good design enables, bad design disables" and defines *design for all* as "design for human diversity, social inclusion and equality"[EIDD 2004].

A design concept similar to the *design for all* approach is the concept of *universal design*. In fact, they are so similar that they are used interchangeably in recent research [Stephanidis 2001]. *Universal design* is a term coined by architect, product designer and educator Ronald L. Mace. It describes the concept of designing products and environments for the needs of people, regardless of their age, ability or status in life [Story et al. 1998]. Mace et al. present seven principles which inform and constitute *universal design*:

- *Equitable Use* The design is useful and marketable to people with diverse abilities.
- *Flexibility in Use* The design accommodates a wide range of individual preferences and abilities.
- *Simple and Intuitive Use* Use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level.
- *Perceptible Information* The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities.
- *Tolerance for Error* The design minimizes hazards and the adverse consequences of accidental or unintended actions.
- *Low Physical Effort* The design can be used efficiently and comfortably and with a minimum of fatigue.
- *Size and Space for Approach and Use* Appropriate size and space is provided for approach, reach, manipulation, and use regardless of user's body size, posture, or mobility.

Other approaches towards designing for people with diverse abilities are the methodological *user-centered design* (UCD), the user aware *user-sensitive inclusive design* (USID), the design for changed abilities and older people with the *design for dynamic diversity* (DDD), or the broader perspective of *universal access design* [Gregor et al. 2002]. Common to all those design approaches is the goal of implementing accessibility into new products, devices, services or environments so that the widest range people with all diverse abilities are able to participate and use them, both unassisted through "direct access", and also assisted through "indirect access" by utilizing assistive technologies. For instance, VIB individuals use a number of assistive technologies, such as screen readers, refreshable Braille displays or screen magnifiers to gain access to visual information.

The principles of *universal design* and *user-centered design* are taken into account and applied during the design of musical software and hardware in this research project. This software and hardware is developed in collaboration with VIB experts.

1.5 RESEARCH FIELDS

The following section will briefly present the related research fields of this research project. The project focuses on various fields, including tangible musical interaction, which provides VIB musicians with an accessible way to use computers as musical instruments for digital music-making, improvisation, and stage-based live performances. To enable this, we are developing tangible hardware interfaces for interacting with computers. These musical interfaces and their interactions are designed based on the concept of tangible interaction to support barrier-free artistic practice for VIB musicians. To investigate accessible digital music-making and computer music, this research process draws on insights from various fields, including *human-computer interaction*, *new interfaces for musical expression*, and assistive technology. These different fields of research are briefly summarized below.

1.5.1 Human-Computer Interaction

Human-computer interaction (HCI) is the study of how people interact with and through the computer. It aims for an analysis of tasks that people perform with computers, with the goal of designing more usable and reliable computer systems [Sharples 1996]. To this end, HCI focuses on three key aspects: the human user, the computer as a machine, and the interaction between the two. To better understand these key elements, the interdisciplinary research field of HCI draws from various disciplines, including ergonomics, psychology, engineering, design, computer science, and sociology. (see Fig.1.5.1). Overall, HCI aims to ensure safety, effectiveness, utility, efficiency, accessibility and usability of interactive computer systems. Thereby a focus is on the user interface as a means to interact with the system, application or telematic service, with which the user comes into contact cognitively as well as perceptually and physically [Stephanidis 2001].

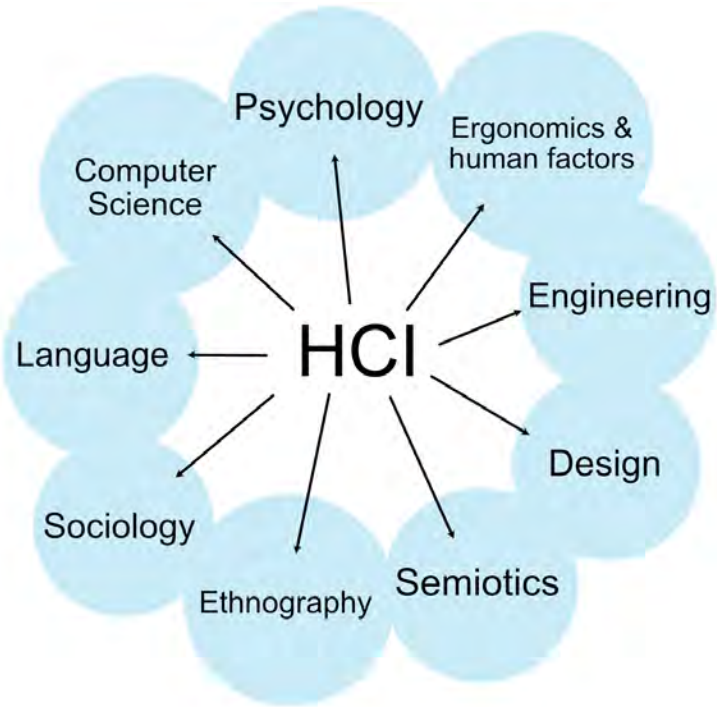

Figure 1.5.1: HCI disciplines

To design appropriate computer interaction, the needs and perception capabilities of the human user need to be taken into account, especially given their limitations in processing information. Common channels for sensation and the receiving of information are the visual channel, the auditory channel, the haptic channel and movement. Information is then stored in various forms of memory, such as sensory memory, short-term or working memory, and long-term memory. To process and apply the information, the human user relies on strategies like reasoning, problem solving, skill acquisition and error. Most importantly, users are diverse human beings that share common capabilities, but differ in their individual characteristics, perceptions and abilities [Dix et al. 2004]. Similarly, a computer is a system comprising various elements that receive, process, store, and deliver information.

Input devices, such as a mouse or touch pointer, a keyboard for text input, or a microphone for speech input, enable interaction, text entry, drawing, and selection from the screen. Various visual output devices enable the interactive display of information, including different types of screens, virtual reality systems, and other displays for shared or public use. Physical input and output channels include various physical controls, dedicated displays, sound input and output, as well as smell and haptic feedback. Furthermore, sensors can measure many physical phenomena, including temperature, movement, and bio signals [Dix et al. 2004].

HCI focuses on the interaction between the human user and the computer. Interaction models such as Norman's *execution–evaluation cycle* or its redesigned successor, the Abowd and Beale's *Interaction framework*, attempt to translate the needs and expectations of the user and the capabilities and responses of the computer (see Fig.1.5.2). Ergonomics improve the physical characteristics of the interaction and analyze how they influence its effectiveness. Even the style of the interface affects and influences the dialog of the user and the system. Moreover, each interaction of the human user and the computer takes place in an social and environmental context that is affecting both the user and the system [Norman 1986; Dix et al. 2004; Hinze-Hoare 2007].

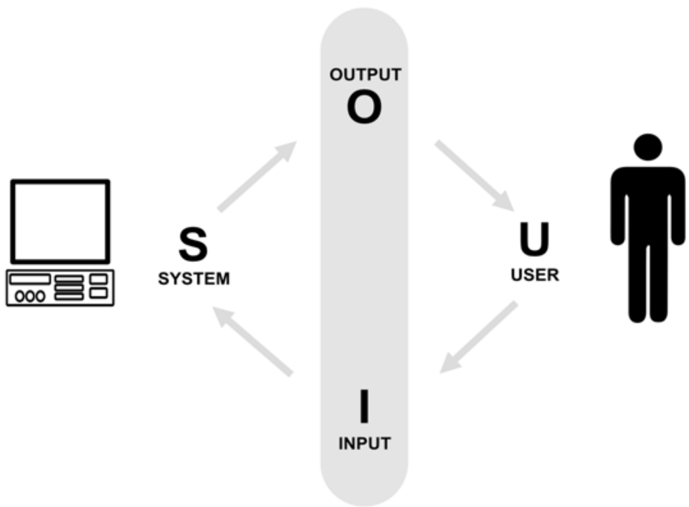

Figure 1.5.2: *Interaction framework* after Abowd and Beale, based on the four components *system*, *user*, *input* and *output*.

In order to ensure, demonstrate and measure the usability of an interactive computer system, various paradigms evolved over time, which serve towards the improvement of human-computer interaction and the use of computers in the various contexts. Among the various paradigms are *personal computing*, various *programming toolkits*, *WIMP* interfaces, the use of *metaphors* and *direct manipulation* as an interaction technique with its subsequent *WYSIWYG* paradigm (*"what you see is what you get"*).

A paradigm, which is especially relevant within this research project, is the *multi-modality* of human-computer interaction. *Multi-modal interaction* involves the use of multiple communication channels simultaneously. So for instance, when attempting to start a program, *multi-modal interaction* allows the use of other input channels to perform the same task in addition to point and click the mouse on the screen, such as speech input, e.g. a spoken command, or the use dedicated physical buttons, the detection of gestures by sensors or the interaction with other input devices. The same is true for the computer output, where *multi-modal interaction* provides additional output channels to the common visual display or sound output, such as haptic feedback, speech synthesis, etc. Other paradigms that shape the way computers are used are *ubiquitous computing* as a concept of seamless computing anytime and everywhere, *sensor-based and context-aware interaction* and more recently the implementation and use of *artificial intelligence* [Dix et al. 2004; Dhar 2023].

Overall, HCI is an interdisciplinary and evolving discipline, that attempts to improve the way humans use computers. It intersects with many other disciplines centered around technology, the human condition and the aims and claims of computer use. New technological developments, increased processing power, smaller footprints and the availability of affordable computing devices enable experimentation, the artistic exploration of computers as creative tools and the design of accessible and playful interaction.

1.5.2 NIME

This research project is also informed by the field of musical interaction and expression through computers and external interfaces. Since the early days of computer technology, computers are used for artistic practice and creative explorations, as tools for musical expressions and as platforms for new musical interaction. The availability of affordable computer hardware, micro computers and sensors, the development of new digital music technology and the artistic curiosity for new sounds and sonic interactions led to numerous proposals and designs of novel musical interfaces, hybrid instruments and new approaches towards digital music-making. This research interest into novel musical instruments, new musical expressions and artistic performances, with a focus on interdisciplinarity and new technologies manifested as an annual scientific conference under the name *New Interfaces for Musical Expression* (NIME),[19] which quickly became not only an umbrella term for new musical interfaces, but one of the most relevant platforms for artist researchers and scientific exploration of new musical interfaces not only in the fields of arts and music, but also for therapy, special needs education, installations, and cross-cultural collaboration (see Fig.1.5.3).

Figure 1.5.3: Halldorophone by Halldór Úlfarsson at NIME 2018: *"a new electroacoustic string instrument which makes use of positive feedback as a key element in generating its sound"* [Úlfarsson 2018]

The NIME conference began in 2001 as a workshop at the *ACM Conference on Human Factors in Computing Systems* (CHI) in Seattle, Washington. From there, approaches from HCI were adopted into the development of new interfaces for musical expression, or so-called NIMEs, such as "evaluating" instruments, approaching musician as "users", following the various HCI design practices, and more. Perspectives from computer science, sound synthesis, digital signal processing, electronic engineering, innovative sensor techniques, robotics, and machine learning became part of the design of NIMEs, as well as insights and inspirations from traditional instruments [Bin 2021].

Over the years, the NIME conference and its community produced an extensive collection of cataloged output, such as numerous peer-reviewed publications, musical performances and artistic installations, which serves as source for artistic research, inspiration and critical reflection.[20] Beside the cataloged output there exists a wider discourse in

[19]https://www.nime.org/
[20]https://www.nime.org/archives/

the NIME community, which includes artistic practices, conversations and personal relationships, and which also reflects on political and social implications of work in this field, including a increasing awareness for problems in the areas of diversity, representation and political engagement [Bin 2021]. McPherson et al. describe, how the design of musical interfaces has a long history of enabling music making for novices, non-musicians or children, that even predates digital technology. This goal of guiding novices towards the playful and accessible sound generation by providing musical interfaces and accessible controls is also pursued by many research projects presented at the NIME. Moreover, in comparison with other HCI conferences, crowdfunding campaigns or commercial products, music instrument builders in the NIME focus more on interactive compositions and higher-level control metaphors, than on simple note-based MIDI-controllers [Mcpherson et al. 2019].

The NIME as a platform and archive is also relevant for artists, musicians and users that are impaired, and who are active in the research and presentation of accessible digital musical interfaces including new musical expressions and music-making approaches. Technologies such as various control interfaces and sensor technologies that are common to non-inclusive projects, are explored towards their use for accessible musical instruments, e.g. tangible or gestural controllers, vibrotactile feedback, brain-computer interfaces, accelerometer, sensors for bending, bio signals, pressure or light, as Emma Frid summarizes in a survey on ADMIs [Frid 2018]. The rich scientific exploration and documentation for new musical interactions, interfaces and approaches for musical expression informs and empowers the research and development of accessible musical instruments and interactions especially for persons with impairments [Förster and Komesker 2021; W. Payne et al. 2023; Skuse and Knotts 2020; Davanzo and Avanzini 2020].

1.5.3 Assistive Technology and Visual Impairment

Being human means to experience disability at some point during the life, which can either be temporary or permanently.[21] As mentioned above, the WHO estimates that 16% of the global population - or 1.3 billion people - experience significant disability, a number that is continuously rising due to factors like population aging or an increase in the prevalence of noncommunicable diseases. Disability, or being disabled, can result from health conditions, such as cerebral palsy, Down syndrome or depression, through personal and environmental factors

[21] https://www.who.int/health-topics/disability

including negative attitudes, inaccessible transportation or limited social support. It can be caused by limitations of hearing or sight, or other functional or cognitive impairments. Thereby the environment has a huge effect on the experience and extent of disability. As the WHO points out, inaccessible environments create barriers that often hinder participation of persons with disabilities in society on an equal basis with others. Addressing these barriers and supporting persons with disabilities in their daily lives improves social participation and thus enables autonomous interaction.[22]

Assistive technology (AT) enables the participation and autonomy of persons with disabilities, and can be summarized as any item, piece of equipment, software program, or product system that is used to increase, maintain, or improve the functional capabilities. It helps people who have difficulty speaking, typing, writing, remembering, pointing, seeing, hearing, learning, walking, and many other things. Hereby different disabilities require different assistive technologies. AT can involve various different technologies and approaches, such as *low-tech* communication boards made of cardboard, *high-tech* special purpose computers, *hardware* such as prosthetics or positioning devices, *computer hardware* like special keyboards or pointing devices, *computer software* such as screen readers, *inclusive or specialized learning materials* and *electronic devices* such as wheelchairs, walkers, braces, educational software, power lifts, pencil holders, eye-gaze and head trackers, and much more.[23]

An international, legally binding instrument that sets minimum standards for rights of people with disabilities and promoted the development of assistive technology, is the *United Nations Convention on the Rights of Persons with Disabilities* (UNCRPD) from 2007, which states that persons with disabilities have the same rights as everyone else. It builds on principles such as respect for inherent dignity, non-discrimination, participation and inclusion in society, equality of opportunity, accessibility, equality between men and women, and respect for the evolving capacities of children with disabilities and the right to preserve their identities.[24] Various other national and international programs, laws and directives attempt to protect and support persons with disabilities, ensure the availability of accessible products and services, reduce personal barriers and improve the functioning of the internal

[22]https://www.who.int/health-topics/disability
[23]https://www.atia.org/home/at-resources/what-is-at/
[24]https://www.un.org/disabilities/documents/convention/convoptprot-e.pdf

market for assistive technologies, such as the *European Accessibility Act*, the *Assistive Technology Act 2004 in the US* or the *Barrierefreiheitsgesetz in Österreich*.[25][26][27]

Regarding vision impairment, the WHO estimates that 2.2 billion people globally have near or distance vision impairment. The leading causes of vision impairment and blindness are refractive errors and cataracts. The WHO states, that vision loss can affect people of all ages, but most people with vision impairment and blindness are at an age above 50 years.[28] Visual impairments decrease visual acuity, limit the visual field, they can impact color recognition or lower the depth perception. Distance vision impairment can classified as *mild, moderate, severe* or *blindness*, where *mild* is visual acuity worse than 6/12, *moderate* is visual acuity worse than 6/18, *severe* has a visual acuity worse than 6/60 and *blindness* starts at a visual acuity worse than 3/60. Near vision impairment is visual acuity worse than N6 or M.08 with existing correction.[29]

For persons with vision impairments or blindness the German portal REHADAT lists a number of devices, technical aids and recommendations to support communication, orientation and information for equal participation.[30] This includes tools for operating the computer, using the internet, reading content and finding the way as key prerequisites for being able to be informed, to communicate and being mobile. For tactile orientation in buildings and outside, the *white long cane* can be used, which helps with sensing surfaces and obstacles through the tip of the cane, e.g. guide lines on the street and edges. Textual information is presented as Braille symbols, a system that was invented by Louis Braille in France in 1824.[31] Braille is a tactile language encoding system based on combinations of six raised dots that can be read with the tip of the finger. Braille notation can be printed on paper with Braille embossers or displayed on refreshable Braille displays, which enables access to text, literature and computer programming for VIB individuals. International standards such as ISO and DIN for the

[25] https://ec.europa.eu/social/main.jsp?catId=1202
[26] https://www.congress.gov/bill/108th-congress/house-bill/4278
[27] https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2023_I_76/BGBLA_2023_I_76.pdfsig
[28] https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment
[29] https://www.paho.org/en/topics/visual-health
[30] https://www.rehadat-hilfsmittel.de/en/produkte/kommunikation-information/sehhilfen/hilfsmittel-fuer-menschen-mit-sehbehinderung-und-blindheit/
[31] https://www.afb.org/blindness-and-low-vision/braille/what-braille

Braille system ensure its usability and compatibility.[32][33] Similar to the pin-based Braille notation, various refreshable tactile graphic displays such as Orbit's *Graphiti* or the *Dot Pad* can be used to access visual information, convey shapes, maps and other tactile information.[34] A powerful but static means of displaying graphical information are the use of swell paper and swell printers such as the *Swell Form Machine* to print tactile pictures.[35]

Other typical features of assistive products and services for VIB people according to REHADAT are large numbers or letters, large, illuminated displays, voice input and voice output, guide lines and edges, two-sense principle of accessibility (acoustic and vibrating/tactile alarm signals), ultrasound or GPS (Global Positioning System) for orientation and RFID technology (Radio Frequency Identification) for labeling or product recognition. Audio players such as DAISY players can be used to play audio files such as DAISY audio books. For the work with the computer, refreshable Braille displays are used, as well as other AT tools such as screen readers, text recognition software, text-to-speech (TTS) and speech-to-text (STT) software, magnification software, optical-character-recognition (OCR) software and scanner, voice output and specialized apps, that help with smartphone use, barcode scanning etc. Software such as *Seeing AI*, an app that describes what the camera see's with the help of AI, provides access to text, people, currency, colors and objects.[36]

Since web technologies, digital communication and information has become an essential part of the daily live, AT also plays a role in the development and design of of web content in browsers, blogs, search engines, and other software to ensure consistent and accessible digital experiences. Guidelines such as the *Web Content Accessibility Guidelines* (WCAG) 2.0 provide a foundation for web accessibility, which makes web content accessible to a wider range of people with disabilities, not only including blindness and low vision, and will also often make web content more usable to all users in general.[37]

Moreover, assistive technologies are constantly being developed for the use of computers as artistic and creative tools. Researchers like

[32] https://www.din.de/de/mitwirken/normenausschuesse/nagesutech/veroeffentlichungen/wdc-beuth:din21:98366852

[33] https://www.iso.org/standard/58086.html

[34] https://www.livingbraille.eu/multi-lined-and-graphical-refreshable-braille-displays-pillars-of-the-braille-future/

[35] https://www.youtube.com/watch?v=1j4eumYpj_g

[36] https://www.microsoft.com/en-us/garage/wall-of-fame/seeing-ai/

[37] https://www.w3.org/TR/WCAG20/

Rao and O'Modhrain investigate the use of refreshable tactile graphic displays for game design and applications such as the tactile display of spatial data. Other research projects focus on accessible digital music-making by developing haptic and tactile displays to convey shapes, graphs, and audio information to VIB users, such as the *Slide-Tone and Tilt-Tone* interface by Fan et al. or the audio access device *Haptic Wave* by Parkinson and Tanaka [Rao and O'Modhrain 2019; Fan et al. 2022; Tanaka and Parkinson 2016].

1.6 RESEARCH QUESTIONS

The research project has two main research questions, which are situated within the context of computers as artistic tools, tangible musical interaction, and stage-based live performances of visually impaired or blind musicians. Focusing on the physical representation of sound and embodied haptic control feedback, the project addresses the following questions:

A What are the benefits of tangible musical interaction for visually impaired and blind musicians?

B How does tangible musical interaction contribute to the artistic expression and musical performance of visually impaired and blind musicians?

1.7 RESEARCH METHODS

Situated in the artistic context of the University of Arts Linz and the department of Tangible Interaction Design (Tangible Music Lab), the project is based on an interdisciplinary approach and applies the following combination of scientific and artistic research methods:

- collaboration with the Federal Institute of the Blind in Vienna (BBI)
- workshops with VIB pupils and experts
- user-centered iterative development of tangible musical interfaces
- unstructured interviews with VIB experts
- artistic practice and performances by VIB musicians
- observation of the artistic practice
- interpretative analysis and evaluation

1.8 CHRONOLOGY OF THE PROJECT

The following section provides an overview of the chronology of the research project, from its inception to the completion of the thesis.

The research project began in 2018 at the University of Arts in Linz and started with initial workshops at the BBI in Vienna. In 2019, the project was presented at the TEI conference. Further workshops were held at the BBI Vienna. The accessible, web-based music software *Welle* was developed. Workshops and artistic practices were carried out at the OCC event in Austria. The first prototypes of tangible devices were sketched. In 2020, the music software was published as a paper at the NIME conference. The iterative development of the tangible prototypes continued. In 2021, the prototypes were further developed, and the development process was published at the TEI conference. In 2022, workshops on digital music-making with *Welle* continued at the BBI Vienna. During multiple sessions, feedback was received from VIB experts regarding the tangible interface prototypes. During an artistic residency in Barcelona, the author explored the tangible musical interfaces and the *Welle* software for new, experimental musical applications. In 2023, Erich Schmid created a musical composition with the tangible musical interfaces and a custom music software, and performed it live on stage. During this period, interviews and explorations of the tangible interfaces were conducted with VIB experts. The thesis writing process began. In 2024, the final research results were published at the ICCHP conference in Linz, Austria. The thesis was finalized in 2025.

Chronological summary:

- 2018 - Initial meetings, research exposé, applications for fundings, beginning of the project, first workshops at the BBI Vienna

- 2019 - Workshops at BBI Vienna and OCC, development of accessible music software *Welle*, publication of the research project at TEI conference, start of the prototype development

- 2020 - Publication at NIME conference about the insights of the accessible music software *Welle*, continued development of prototypes

- 2021 - Publication about the interactive prototypes at TEI conference, continued development of prototypes

- 2022 - Workshops with pupils, expert feedback on the prototypes and finalization of the development of three tangible musical interfaces
- 2023 - Artistic practice with the tangible interfaces by blind expert Erich Schmid, including composition and stage performance at OCC 2023. Further VIB expert feedback through interviews and explorations. Beginning of thesis writing.
- 2024 - Publication of the research results at ICCHP conference Linz, Austria
- 2025 - Thesis completion

1.9 RESEARCH CONTEXT

The research project is conducted at the University of Arts Linz, the Institute of Media and the department of Tangible Interaction Design (Tangible Music Lab). It is carried out in cooperation with the Institute for the Blind in Vienna (BBI) and Erich Schmid, a teacher, musician, and blind expert who serves as the primary contact person. Brief introductions of the institutions and experts involved are provided below.

Tangible Music Lab

The Tangible Music Lab is an artistic research group at the Institute of Media, University of Arts Linz, Austria. It is focused on the development of novel musical interfaces through experimental exploration of the physical aspects of musical human-machine interaction. The research group, led by Martin Kaltenbrunner, is positioned between art and technology with an emphasis on the design of digital musical instruments in the context of artistic research experimentation. As the name reflects, the concept of tangible interaction design is a main focus and is brought together with the building and design of musical interfaces in an iterative artistic process, accompanied by co-working in an laboratory setting.

Previous research projects carried out include artistic research on the topic of interactive tangible music notation with Enrique Tomás project *Tangible Scores*. Reinhard Gupfinger's research project *Metamusic* focused on animal-computer interaction by designing multiple interactive musical instruments for grey parrots. The development of a new paradigm of interfaces for musical expression towards the embodiment of gestures within an instrument, short *Embodied Gestures*, was realized by an interdisciplinary research group around Enrique Tomás, Thomas Gorbach, Hilde Tellioglu and Martin Kaltenbrunner.

The Tangible Music Lab is currently working on projects such as the *OTTOsonics*, a collaborative research project focused on affordable and accessible audio technologies for immersive sound creation, implemented by a team of sound-artists, scholars and sound engineers around Martin Kaltenbrunner, Manu Mitterhuber and Enrique Tomás. This collaborative effort led towards the design of the mobile and portable 20 channel sound sculpture *DodekaOTTO* by Kaltenbrunner, Manu Mitterhuber, Enrique Tomás and Benjamin Wesch.

Institute for the Blind

The main collaboration partner of the research project is the *Institute for the Blind Vienna*. The German name for the Institute is *Bundes-Blindeninstitut Wien* (BBI). The BBI is a school for children with visual impairments and blindness. Founded in 1804 by Johann Wilhelm Klein, the school was the first for blind pupils in German-speaking countries. The school's mission is to empower students with diverse abilities to live self-determined lives and engage in lifelong learning. To accomplish this, the curriculum is constantly adapted to economic, social, and environmental challenges, and teachers receive ongoing training in methodology, pedagogy, and practical skills. The school's teachers have a variety of special qualifications, which allows it to offer various areas of support, such as orientation and mobility training, including echolocation (click sonar method); practical life skills; various sports; dance and movement; instrumental music; creative design; and motopedagogy. The institution offers inclusive learning environments and provides a dormitory on the premises, as well as a swimming hall. The goal is to stimulate the individual talents and inclinations of learners to lay the foundation for careers and further education up to the university level.

The BBI offers various types of education, including elementary, primary, secondary levels I and II, education for the severely and multiply handicapped, and special education. These educational offerings are supplemented by early intervention, medical and psychological care, and a boarding school. The school runs a Braille library, and the Braille Center produces magazines, books, and learning materials. The center also advises on accessibility issues and produces and sells aids for people who are blind or have visual impairments.

Erich Schmid

Erich Schmid is a multitalented blind expert who works in the fields of education, art, and technology. Since 1976, he has been a computer science teacher at the BBI in Vienna. He is also a musician and the director of a church choir, for which he composes and conducts choral pieces. Schmid is also active in various institutions like the *Council for the Disabled or the Association for the Blind and Visually Impaired* and the *Austrian Braille Commission*.[38] As a specialist he is actively involved in the development of Braille and assistive technologies in organizations for standardization like the *Austrian Standards Institute* (ASI), the *European Standardization Organization* (CEN) and the *International Standardization Organization* (ISO). He is engaged in projects like the *DEFINE - Open Source Braille Keyboard*[39] or the *BlindBits*, an accessible level editor and player for creating orientation training games for blind and visually impaired students at the *Austrian Institute for Technology*.[40] Other projects among others that Erich Schmid was involved are the Braille input keyboard *Oskar* and the smartphone app *Find my stuff*, which both received several prices such as the *Unikate* price 2018, the *Wintek* price 2019 and the *Unikate* price 2020.

He contributed to the project by sharing his expertise in music, his insights into assistive technologies, his knowledge of computer science, and his experience in education at BBI Vienna. He encouraged pupils to participate in the project through workshops and performances.

1.10 CONTRIBUTIONS

During the course of the research project, several contributions were made to increase knowledge in the field of computer music, tangible interaction design, accessibility and artistic practice. The research process, including insights on the respective hardware and software tools as well as a summary of the findings were published in four peer-reviewed publications, and presented at conferences such as TEI, NIME and ICCHP. The papers are listed in the section *Publications*.

As part of the research project, the *Welle* music environment was created as a simplified musical tool to explore accessible digital music-making. *Welle* is open-source and free.[41] Furthermore, three tangible

[38] https://www.blindenverband.at/de/ueber-uns/fachgruppen-und-gremien
[39] https://defineblind.at
[40] https://blindbits.tech-experience.at
[41] https://welle.live/

music interfaces were developed in an iterative and user-centered design process. The tangible interfaces were then used during multiple explorations and artistic performances by VIB experts to gain insights on tangible musical interaction and to answer the research questions.

In addition to the academic publications, the research project has been presented to a wider audience at several symposiums and conferences, such as the *XXX_abilities* conference in Linz Austria, the *Young Researcher Symposium* at the Bauhaus University in Weimar Germany, during Science City in Linz and at the *Doctoral Symposium* at the TEI conference in Phoenix Arizona.

Several concerts and performances were realized both by VIB experts and pupils, as well as the author to present the project. Performances were staged during two editions of the *Austrian Summer Computer Camp* (OCC), as well as at the *Akusmonium* at Echoraum in Vienna Austria, at the event *Echoes around me* in Vienna, at the *International Research Center for Cultural Studies* (IFK) Vienna, at the *Science City Linz*, during the streaming of *St.Interface* of the University of Arts Linz, and during an artist-residency at the *Phonos Foundation* in Barcelona in Spain.

1.11 THESIS STRUCTURE

The thesis is structured in the following parts:

Chapter 1 The first chapter introduces the key topics of the research project and presents research context, research questions and methods. It presents the contributions to knowledge and outlines the thesis.

Chapter 2 In the second chapter, the related research context is presented in detail, including insights into computers as artistic tools, human-computer interaction, tangible musical interaction, digital music-making and accessibility.

Chapter 3 The third chapter presents the practical work that was realized during the research process, including the development of the music environment *Welle*, the exploration of sonic features, as well as the development of three tangible musical interfaces. The conducted feedback sessions and artistic explorations with visually impaired and blind experts is described.

Chapter 4 The fourth chapter provides the evaluation of insights gained during the practical work, the development process of the tangible musical interfaces and the expert feedback. The evaluation is grouped in four key topics.

Chapter 5 The fifth chapter concludes the thesis by summarizing the research activities and key findings. It comments on research methods and provides future perspectives.

Chapter 2

Background

To contextualize the research and shed light on its artistic and technological background, this chapter explores the use of computers for musical expression, the pros and cons of common human-computer interaction methods, and the impact of assistive technology on digital music creation for visually impaired and blind musicians. Key topics relevant to the research project will be introduced to provide context and relevant insights for the practical research activities. These topics include computers as artistic tools, tangible musical interaction, and accessible digital music-making. A special focus is placed on assistive technology and accessibility in relation to digital music-making, as well as its implications for the artistic process of visually impaired and blind computer users and musicians.

2.1 COMPUTERS AS TOOLS FOR ARTISTIC EXPRESSION

In this research project, one of the main technological protagonists is the computer as a musical instrument and a tool for artistic expression. The following section explores and contextualizes the role of computers as artistic tools and creative platforms. It will involve projects in which artists with impairments seek to benefit from computers as assistive creative machines.

In general, computers can be described as tools capable of performing tasks that were previously done by humans. According to the *Online Etymology Dictionary*, the origin of the word can be traced back to the Latin *computare* as *"to count, sum up, reckon together"*. In the 14th century, the *computist* was a person *"skilled in calendrical or chronological reckoning"*. In the 1640s, the expression transformed to *computer* as the *"agent noun from compute"*. In 1897, the meaning shifted away from the human *computer* towards the term *"'calculating* *machine' (of any type)"*, and from 1945 onward, the word *computer* describes *"programmable digital electronic device for performing mathematical or logical operations"*.[1]

The technological advancements in the 20th century and evolution of digital computing machines opened up a new era of artistic expression, and resulted in a multitude of new creative possibilities, digital musical instruments and artistic environments. Just like the discovery and harnessing of electricity led to the development of new musical instruments like the Theremin or the Trautonium, computer technology enabled new forms of musical expression, composition and artistic performance. The transition from electrical instruments to digital computers and music software transformed both the avant-garde music as well as the popular music. Composers like Karlheinz Stockhausen, Pierre Henry, Pierre Schaeffer or Iannis Xenakis, who previously worked with magnetic tape and developed their own digital tools like the Phonogène or the Morphophone, which continue to inspire new software and functionality in today's digital audio production.[2]

2.1.1 Early Computer Art and Music

Computers as artistic tools are used since the early 1960s as tools to generate works of art and music. Pioneers like Frieder Nake explored the intersection of technology and creativity, and used computers like the Zuse Z64 to draw images and called it *computer art* (see Fig.2.1.1).[3] First exhibitions like the *Cybernetic Serendipity* at the *Institute of Contemporary Arts* in London in 1968 presented a wide variety of computer art, poetry, music, dance, sculpture and animation [Reichardt 1968].[4] The artistic use of computers continued under terms like *cybernetic art* or *new media art* and continued to expand into many areas of the current artistic practices, including *generative art*, *AI art* and more.[5][6][7]

Early computers were also used to generate musical pieces, like the Australian CSIRAC, which publicly played "Colonel Bogey" in 1951 as first ever computer music piece. The first recorded computer music

[1] https://www.etymonline.com/word/computer

[2] https://interlude.hk/composing-2-0-the-purpose-of-computers-in-the-world-of-creative-music/

[3] https://monoskop.org/Frieder_Nake

[4] https://monoskop.org/Cybernetic_Serendipity

[5] https://www.artplacer.com/what-is-digital-art-the-history-and-value-of-an-evolving-concept

[6] https://ethw.org/Electronic_and_Computer_Music

[7] https://musicandcomputerscience.wordpress.com/the-first-recordings-and-uses-of-computer-music/

Figure 2.1.1: Frieder Nake - Random Polygon (1963)

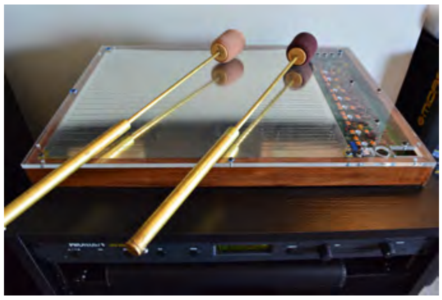

Figure 2.1.2: Radio Baton by Max Mathews (1987)

piece, a medley of "God Save the King," "Baa Baa Black Sheep" and "In the Mood", was played by the *Ferranti Mark 1* later in 1951. The first computer music software was *Music I*, written by Max Mathews at the Bell Labs for an IBM 704 computer in 1957.[8] Mathews later continued to developed the *Music N* series of programs as well as hardware interfaces for computer music like the *Radio Baton* (see Fig.2.1.2) [Mathews 1963; Mathews 1991].[9] He can be considered as one of the founding fathers of computer music and his work formed the bases for modern software such as *Pure Data* or *Max/MSP*.[10]

2.1.2 *Artistic Expression with Impairments*

With the increasing availability of digital computers, also artists with impairments began to use the new technology. In 1974, accessible audio games suitable for VIB players appeared as precursors to video games, such as Atari's *Touch-Me* console.[11] Likewise, artists turned to digital computer technology as a means to compensate for a loss of body control. Activist and artist Steve Cribb, who contracted Polio as a child, lost his ability to draw with his hands and turned to the Apple Mac computer with an *Headstart View Control Pack* interface to convert his heads movements into cursor moves in order to draw digital images ranging from portraits and graphics to cartoons. Cribb was an advocate of disability rights and member of the *London Disability Arts Forum*, exhibiting his artistic works such as the image "Going Out"

[8] https://120years.net/music-n-max-mathews-usa-1957/
[9] https://www.youtube.com/watch?v=3ZOzUVD4oLg
[10] https://cycling74.com/articles/max-mathews-an-appreciation
[11] https://www.arcade-museum.com/Arcade/touch-me

(1992) in various group exhibitions (see Fig.2.1.3). As the *National Disability Arts Collection & Archive* (NADCA) points out, Cribb's work "Going Out" marks the beginnings of the empowerment of disabled artists to be creative through the use of digital technologies.[12]

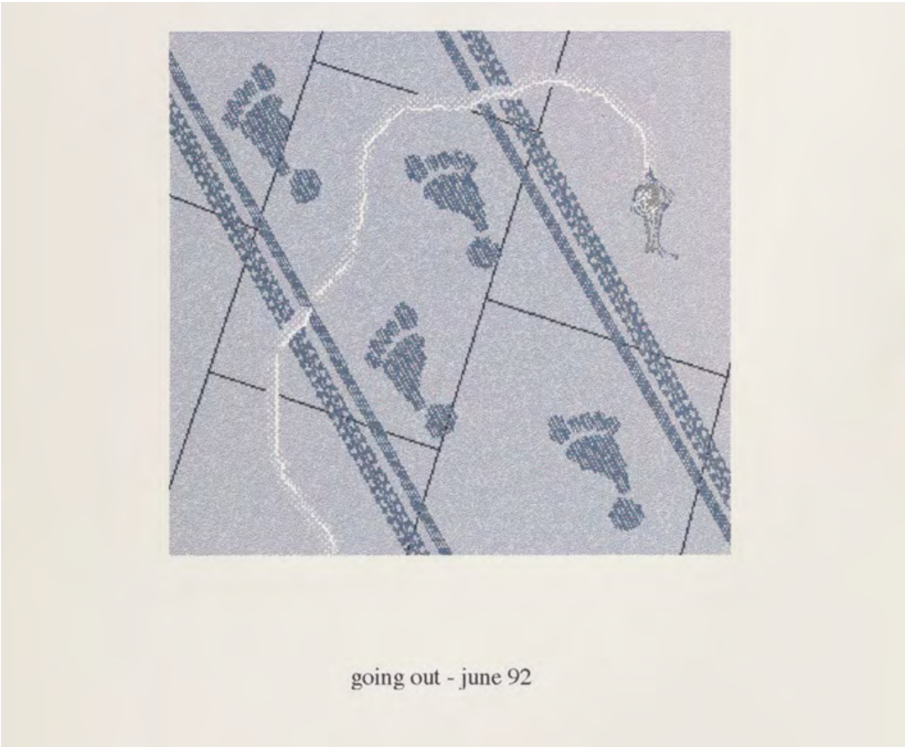

Figure 2.1.3: Steve Cribb "Going out" (1992)

To enable access to computers for individuals with disabilities, research projects explored approaches such as various eye-tracking techniques [Majaranta and Räihä 2002]. One of them is the *Eyewriter* project realized by a team around Zach Lieberman. The *Eyewriter* is a low-cost and open-source eye-tracking device, that enables persons with amyotrophic lateral sclerosis (ALS) to engage with computer software (see Fig.2.1.4). The project was initiated to support former graffiti artist, publisher and activist TEMPTONE, who was diagnosed with ALS in 2003. The disease caused him to be physically almost completely paralyzed, except for his eyes. The *Eyewriter* enabled him to use his eyes to control the computer and to draw again.[13]

Another computer interface developed for persons diagnosed with ALS is the *EyeHarp*, a gaze-controlled digital musical instrument by Zacharias Vamvakousis and Rafael Ramirez of the Music Technology

[12]https://the-ndaca.org/resources/audio-described-gallery/going-out-by-steve-cribb/
[13]https://www.eyewriter.org/

Group at the University Pompeu Fabra in Barcelona, Spain. The device enables its users to learn, perform, and compose music with their gaze as control mechanism. It facilitates a step-sequencer layer and a melody layer for chords and arpeggios for creating musical pieces in real-time, and allows expressive performances from both the performer and the audience perspective [Vamvakousis and Ramirez 2016].

Figure 2.1.4: Eyewriter by Zach Lieberman, James Powderly, Evan Roth, Chris Sugrue, Tony "TEMPT1" Quan, Theo Watson (2009)

2.2 HUMAN MEETS NON-INCLUSIVE COMPUTER

The following section will take a closer look at the underlying concepts regarding computers as multidisciplinary tools, the limits and benefits of software design, accessibility aspects, and the computer's role as a universal artistic and musical platform.

Computers generally offer many possibilities for creating art, composing music, and performing live. However, people with disabilities still face various access barriers and limitations when using computers. These limitations often stem from software design paradigms and the characteristics of human-computer interaction, which can be traced back to the early days of computer technology. In those early days, engineers, programmers, and researchers—mostly people without disabilities—designed computer systems, software, and human-computer interaction. Instead of following a design process that would enable all potential users to access the new technology, a concept that was later defined as *universal design* (see Chapter 1.4), computer software and hardware was developed by and for persons without impairments. But human bodies and minds are not uniform, which is even more relevant today since computers entered all aspects of personal and professional life, including the artist studios, music rooms and concert stages. This exclusion of computer users with impairments led to various attempts of adapting software and interaction design afterwards, in order to provide access to a previously inaccessible system. Unfortunately, this approach can only improve accessibility to a limited extent.

2.2.1 Input - Output - Interaction

Computers are interactive systems that can be operated based on user input, which is then processed towards an according output. Thereby the interaction with the computer is like a dialogue, where the user's intentions are observed, interpreted, performed and presented. The choice of the interfaces has a profound effect on the quality of this communication [Dix et al. 2004].

Various input and output devices are used to enter commands and content, and to receive the results, such as computer keyboard, mouse or touch pads, computer displays. Depending on the use scenario and requirements, there are many more devices to interact with the computer. Input devices can be trackballs, datagloves, eyetrackers, thumb wheels, scanner, webcams, microphones, sensors and various physical controls in ubiquitous computing. Among the output devices are loudspeaker, printers and other specialized devices.

One of the most common models to describe human-computer interaction is Norman's *execution-evaluation cycle* [Norman 1986], which divides the interaction between user and computer into two main phases, execution and evaluation, which in turn are subdivided into further phases of user activity. In a more intuitive way, Abowd and Beale have simplified this Norman model into their own more interaction model (see Fig. 2.2.1), with the interface providing input and output means sitting in the middle between the user and the system and a four-stage interactive cycle of articulation, performance, presentation and observation [Hinze-Hoare 2007] [Dix et al. 2004].

2.2.2 The Rise and Limits of the Graphical Interface

One of the main reasons VIB musicians are excluded from digital music technology is its strong focus on visual interaction. The shift toward visual interaction with digital machines began in the early days of computers and continues today. The following section attempts to rework the beginnings and impact of this shift on accessible music technology.

Since the very beginnings of computer technology, the communication between human and computer supported by graphical means was

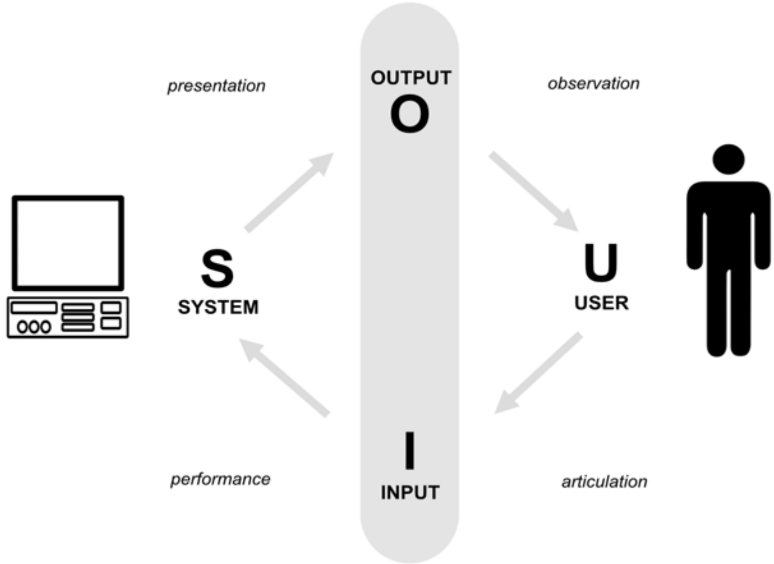

Figure 2.2.1: Interaction Model after Abowd and Beale.

a main topic of research. In 1963 Ivan Sutherland presented his *Sketchpad* with the intention to make computers *"more approachable"*. The *Sketchpad* enabled drawing through the use of a pointing device and a graphical representation and was among the first programs that used a graphical user interface, received various prices and until today influences the way users understand the interaction with the computer (see Fig.2.2.2) [Sutherland et al. 2003; Jacko 2012].

The focus and interest in computer graphics continued with Alan Kay's *Dynabook* in the 1972, which represented his concept of a portable

Figure 2.2.2: Ivan Sutherland's Sketchpad 1963 was the first graphical computer interface. On the display a drawing can be seen, as well as the light-pen in the hand that enables drawing lines on the screen.

"personal computer for children of all ages".[14] that is able to display and store texts and drawings [Kay and A. Goldberg 1977] The subsequent research at the *Xerox Palo Alto Research Center* (PARC) led to the development of the programming language *Smalltalk* and to the development of the *Xerox Alto*, the first computer using a GUI based on windows and icons. In the following years various other computers were presented, that all used a GUI, among them the *8010 Star Information System or Xerox Star*[15] in 1981, Apple's Lisa in 1983 (see Fig.2.2.3) and the Apple Macintosh 128K in 1984, the Atari ST, the Commodore Amiga and the Microsoft Windows 1.0 in 1985.

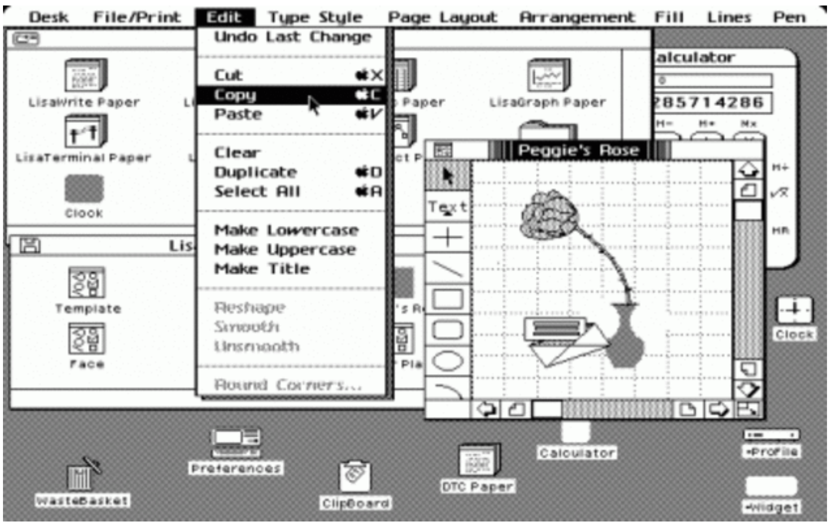

Figure 2.2.3: Apple's Lisa OS interface[16]

The success of the GUI is based on its ability to enable user interaction with the computers underlying complexity through the use of graphical icons and visual indicators. Compared to the previously dominating command-line interface (CLI), which requires a steeper learning curve, the GUI-based interaction is more intuitive for new computer users.[17][18] GUIs are also used for various other electronic devices like media players, gaming devices, smartphones and other household or industry hardware. A main part of the development of the GUI was the implementation of the *model–view–controller* (MVC), a software design pattern, that ensures stability of GUI implementations by dividing the interaction into three components: the model serves as the internal representation of data, the view is both the visual output of this data

[14] https://mprove.de/visionreality/media/kay72.html
[15] https://en.wikipedia.org/wiki/Xerox_Star
[17] https://www.computerhope.com/issues/ch000619.htm
[18] https://learn.microsoft.com/en-us/archive/blogs/mscom/the-gui-versus-the-command-line-which-is-better-part-1

as well as an interface for user input and both are connected by the controller as communication and update instance. This division into three different components enables the separation of of the graphical representation and the actual data and makes the system much more flexible.[19]

To improve the interaction with the different visual elements, the WIMP interaction paradigm was developed at Xerox PARC, a system that is based on the use of *windows*, *icons*, *menus* and *pointers*. The design of the icons and indications for interaction are modeled after the *desktop metaphor*, a graphical system based on representations of common office elements in the form of icons, e.g. files, trash bin, folders or notebooks. Pointer devices such as the computer mouse could now be used to interact and manipulate those graphical metaphors, i.e. dragging a file icon above the drawer icon to move the file into another directory, or to drag the file icon above the icon of a trash bin to delete it. This interaction with icons and graphical representation is called the *direct manipulation* and is exclusive to GUIs. Both the *desktop metaphor* and the WIMP interaction were attempts to hide the complexity of the underlying algorithms (see Fig.2.2.4) [Sharples 1996]. The GUI systems including WIMP interfaces had huge commercial success since Apple's Macintosh and continues to exist with minimal changes, next to the development of other interaction systems like 3D modeling, recognition-based user interfaces, ubiquitous computing and more [Myers et al. 2000].

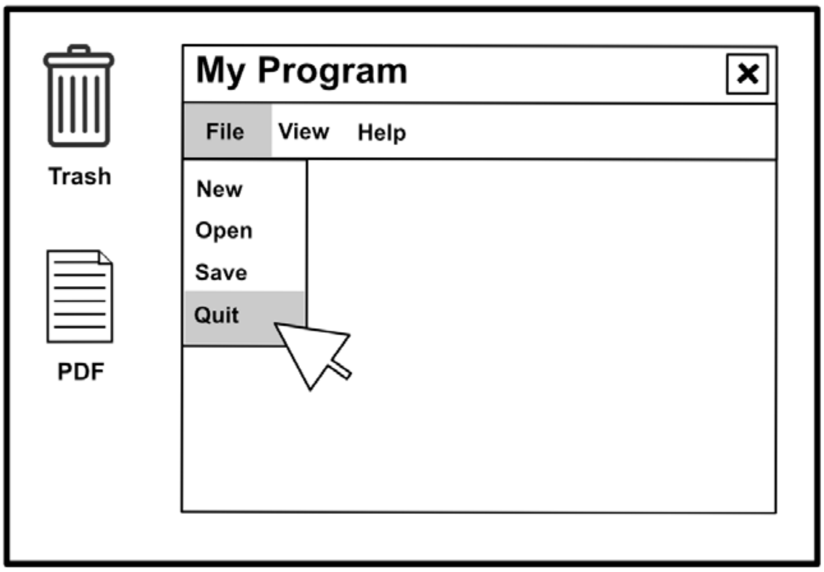

Figure 2.2.4: WIMP interface and desktop metaphor

[19] https://www.geeksforgeeks.org/software-engineering/benefit-of-using-mvc/

A limitation of the focus on GUIs as main user interaction system since the early days of personal computers is the inherent exclusion of people with impairments. In particular people with visual impairments or blindness have been sidelined by the introduction and spread of the graphical user interface, since they can hardly or not at all access interfaces based on graphical representations. The strategies, that are supposed to hide the complexities of the computer, instead make access for some people even impossible. The shift towards the interactive GUI has *"left the visually impaired community behind in the evolution of computation"* [Carneiro and Velho 2004].

2.2.3 *User Interfaces for All*

The accessibility barriers arising by the focus on graphical user interfaces and their implicit exclusion of VIB users is just one aspect of the challenging task to provide accessible interactive software and hardware systems for all users. Already in 2001, Constantine Stephanidis proposes the concept of *User Interfaces for All*, which demands a paradigm shift in HCI towards creating computational environments embracing the broadest range of human abilities, skills, requirements and preferences. Informed by concepts such as *Universal Access* and *Universal Design* (see Chapter 1.4), she is convinced that accessible user interfaces should not be factored as single solutions for the diverse user groups. Instead she proposes new perspectives on HCI by *"seeking to unfold and reveal challenges and insights, and to instrument appropriate solutions for alleviating the current obstacles to access and use of advanced information technologies by the widest possible end-user population."* [Stephanidis 2001] Stephanidis therefore proposed an extended focus on traditional design principles such as *user-centered design* [Norman and Draper 1986] through a better exploitation of existing practices and knowledge from disciplines like psychology and social sciences towards involving *social contexts* into the development process. Likewise she questions traditional architectural models for user interface software focused on GUIs, window managers, event mechanisms, notification-based architectures or toolkits of interaction objects. Instead a key ingredient of the new paradigm of *User Interfaces for All* should be the encapsulation of alternative interactive behaviors, which should be less depended on physical interaction but more focus on higher-level dialogue properties and other mechanisms for articulating interactive components.

Designing user interfaces and environments for a diverse user group accessible by *anyone*, *anytime* and *anywhere* [Stephanidis 2001] poses many challenges, and for non-disabled persons it can be difficult to gain an understanding of all the implicated needs and limitations on a cognitive, physical or sensory level. Another way of understanding and approaching the diversity in computer users, and to look beyond the *"typical user"* while developing user interfaces, is the focus on older people as a user group with a changing and dynamic diversity of abilities. Characteristics of older people as user group compared with younger people involve individual variability of physical, cognitive and sensory functionality, which among others can include vision loss, that can increase with age. To meet these changing abilities and to extend the rigid design principles of *user-centered design* towards adapting to the diverse requirements of older people, Gregor et al. propose the paradigm of *Design for Dynamic Diversity*, a design approach, that takes the changing abilities of older users into account by providing interactive and adaptive interfaces [Gregor et al. 2002]. As a framework they propose *User Sensitive Inclusive Design*, a methodology that reflects on the variety of user characteristics, personalizable and tailored interfaces, communication difficulties, ethical issues and underlines the importance of an open mind-set of the designer.

As a guideline for the development of new human-computer interfaces, both design paradigms offer a deeper understanding of the requirements of developing for a diverse user group, be it older people, or users with physical or cognitive impairments. Developing *User Interfaces for All* as proposed by Stephanidis based on the methodology of *User Sensitive Inclusive Design* presented by Gregor et al. represents a sensitive approximation towards the development of accessible and inclusive interfaces based on the principles of *Universal Design*.

2.2.4 Visually Impaired and Blind Computing

But which strategies and technologies are used by visually impaired and blind computer users who require assistive technology to access and navigate computers and graphical user interfaces? VIB users have to adapt their computer setup and workflows to their needs in order to operate the computer. Thereby all visual information, control interfaces, texts and images need to be converted into an accessible form, which for VIB users commonly means the conversion of the visual content into Braille notation and audible feedback. In this regard the most important assistive technology for VIB computer users is the screen reader, a software that converts images, text and navigation elements

Figure 2.2.5: Refreshable Braille display and keyboard.

Figure 2.2.6: Braille embossed in paper.

Figure 2.2.7: Braille display and input keyboard

into speech and Braille output. Algorithms like *text-to-speech* conversion (TTS) provide text as audio stream by using a synthetic voice that reads text aloud. Likewise, characters and text are transmitted to refreshable Braille displays (see Fig.2.2.5). Screen reader can also be used to announce or change the position of the cursor. Various screen readers are available for all major platforms, such as JAWS or NVDA for Windows, VoiceOver for OSX/iOS, TalkBack on Android or ORCA for Linux.[20][21][22][23][24] The resulting computer hardware setup of VIB users is based on the use of a computer keyboard, loudspeaker and a refreshable Braille display, whereby some Braille displays include an additional input keyboard and can be used as stand-alone devices or notetakers (see Fig.2.2.7).

Braille itself is a system based on raised dots to display symbols, letters and text. It is used by people who are blind or have low vision (see Fig.2.2.6). Developed by Louis Braille at the National Institute for

[20] https://www.freedomscientific.com/products/software/jaws/
[21] https://www.nvaccess.org/
[22] https://www.apple.com/voiceover/info/guide/_1121.html
[23] https://netz-barrierefrei.de/en/android-blind.html
[24] https://help.gnome.org/users/orca/stable/introduction.html.en

Blind Youth in Paris in 1824, the system consists of separate cells in a line, whereby each cell has six dots arranged in two rows. The resulting 64 different combinations within a single cell can be used to represent characters such as alphabet letters, numbers or punctuation marks.[25] For computer users, the traditional six dot Braille was extended to the so-called *Computer Braille* featuring eight dots, which increases the amount from 64 to a total of 256 different combinations. Worldwide, different Braille system are used, the mainly used system in Europe is called *Eurobraille*.

Assistive technology such as screen reader, text-to-speech synthesis and refreshable Braille displays enable the use of computers for tasks such as office work, digital content creation [Zhang et al. 2023], software development [Mountapmbeme et al. 2022] or as a music platform for recording, composing and songwriting [W. C. Payne et al. 2020]. Nonetheless, access barriers still exist and impact the use of computers for VIB people. On the software side, access barriers are mainly caused by vision-centric software design and the inherent inaccessibility of graphical information, which is often combined with insufficient implementation of accessibility features for the communication with screen reader software. This is especially true in fields like music software, where some software platforms requires additional scripts to increase accessibility, while other software is not accessible at all. Likewise barriers and hurdles exist on the hardware side. Refreshable Braille displays are expensive, with costs of several thousand euros per device, and their output is limited by the amount of cells, mostly ranging between 12 and 80 cells.[26]

Various research projects and Do-it-yourself (DIY) projects attempt to envision more efficient and powerful devices and contribute knowledge and new concepts. Sile O'Modhrain et al. presented the *Holy Braille*, a concept for an accessible Braille tablet device similar to an Apple iPad. The project was based on their work on a new technological solution to display Braille characters through pneumatics (see Fig.2.2.8) [B. Gillespie et al. 2016]. Other researcher and makers presented projects like refreshable DIY Braille modules[27], Open-Source and low-cost Braille embosser such as *OpenBraille*[28] or the *BrailleRAP-*

[25] https://www.afb.org/blindness-and-low-vision/braille/what-braille

[26] https://www.perkins.org/resource/overview-braille-devices/

[27] https://hackaday.io/project/191181-electromechanical-refreshable-braille-module

[28] https://www.instructables.com/OpenBraille-a-DIY-Braille-Embosser/

SP,[29] or the mobile Braille input keyboard *Oskar*, which was developed as part of the project D.E.F.I.N.E.[30][31]. Other projects tackle the automated reading of embossed Braille, like the *Braille Sensor*, a robot hand, that is placed on top of Braille pages and interprets the Braille.[32]

Figure 2.2.8: Holy Braille by O'Modhrain and Gillespie.

Figure 2.2.9: Oskar, a Open-Source and mobile Braille keyboard.

Nonetheless, according to Jenna Gorlewicz et al. the graphical access remains a main problem for VIB individuals: *"While there are promising pathways forward, the graphical access challenge for VIB individuals remains a vexing and largely unsolved problem. We argue that the solution requires advancements on several fronts, including ideological, technological, and perceptual."*. Gorlewicz et al. are convinced that a shift in thinking is necessary, away from perceiving assistive technologies as single-purpose specialized hardware solution, towards considering them as mainstream technologies. They promote a shift from the practice of retrofitting existing technologies for accessibility towards embedding *universal design* in technologies from the beginning. Furthermore they argue that all available modalities should be leveraged as the primary mode of interaction, not just traditional unimodal feedback. And lastly, they propose that future software and hardware design should be driven by end-user needs supporting efficient and effective usage and implementation instead of maximizing features, capabilities and developer interests [Gorlewicz et al. 2019].

[29] https://braillerapsp.github.io/BrailleRapSite/
[30] https://www.netidee.at/oskar
[31] https://defineblind.at/
[32] https://www.heise.de/news/Roboter-liest-Braille-Schrift-doppelt-so-schnell-wie-ein-Mensch-9613598.html

2.2.5 *Haptic Interaction*

As seen above with the refreshable Braille display, accessing digital data, information, and interaction can be accomplished not only through sight or hearing with the use of GUIs and auditory feedback, but also through touch. Touch is one of the five human senses, along with sight, hearing, smell, and taste. However, touch is the first sense to develop in a human embryo, and it is the primary nonverbal channel for conveying intimate emotions. The ability to process large amounts of data through touch can be observed when watching VIB individuals read Braille with their fingertips [Erp and Toet 2015].

As a primary human sense, touch is a relevant human-computer interaction modality. Already in 1965, Ivan Sutherland proposed an immersive, computer-controlled *"ultimate display"*, where he envisioned a mechanism for rendering computational data for tactual senses in a *"kinesthetic display"*, a display able to project physical forces back on the body and thereby simulating the body's physical interactions with matter. Later this terminology of touch, tactual senses or tactile scanning in HCI changed to *haptics* as a new discipline, which centers around the use of touch as a modality for computer interaction, and continues to be in the focus of scientific research in HCI over the last decades [Gibson 1962; Parisi 2018]. The sense of touch can be divided into two different areas: cutaneous or tactile perception, which refers to tactile sensations through the skin, and kinesthetics as the perception of movement and position. Today a multitude of haptic interfaces exist that use vibrations (cutaneous/ tactile), resistance, pressure or force feedback (kinesthetic), which can create perceptions of properties such as shape, texture, resistance and temperature as well as comparative spatial properties such as size, height and position [Dix et al. 2004]. The full range of tactile sensations further extends to balance, heat, coolness/wetness, electric shocks, pain and itch, which enable an even finer granularity of sensory stimulation possibilities for haptic interaction and interactive experience design [Obrist et al. 2016].

Most commonly haptic interaction is known through the use of vibrotactile feedback in devices such as smartphones or game controllers, lesser known are high-fidelity haptic devices for use in surgical training and remote manipulation, or the use of haptic technology embedded in prosthetic limbs as means of feeding complex tactile sensation back to the wearers [Parisi 2018]. As Culbertson et al. lay out, haptic experiences can also be created with the design of real-world surfaces that can be actively explored by a human, enabling simultaneous cutaneous and kinesthetic feedback. Ideally those devices would feel like natural surfaces, but could change their shape, texture and mechanical properties arbitrarily. Examples of digital controlled surfaces are devices that enable a vertical displacement of pins in a two-dimensional array, such as the refreshable Braille display with its 2.5-dimensional shape, or the large-scale pin array *inFORM*, that additionally includes visual overlays. Nonetheless they conclude that despite the huge potential of haptics in fields like remote surgery and prosthetic limbs, mobile communication and navigation or virtual reality, interaction is still mainly limited by the availability and expressiveness of hardware [Culbertson et al. 2018; Follmer et al. 2013].

A user group that particularly benefits from information and access through haptic interaction are VIB persons. Projects like the *SmartCane* or *Live Braille* enable the indication of obstacles through different types of vibrations (see Fig.2.2.10).[33][34] Haptic clothes and wearables assist VIB people to navigate,[35][36] and haptic feedback in combination with auditory feedback is used to enable access to VR environments, in which controllers mimic the experience of using a white cane to explore large virtual environments.[37] Projects like the *Haptic Glove TV device* by Diego Villamarín and José Manuel Menéndez enables VIB individuals to follow a TV soccer game and its ball movements by utilizing haptic feedback embedded into the gloves. Therefor the ball's location in the playing field is displayed through vibrations in the glove, synchronized with the video transmission [Villamarín and Menéndez 2021].

Another area of HCI that benefits from vibrotactile feedback and haptic interaction is the field of musical instruments. Institutions such as the *Association for Creation and Research on Expression Tools* (ACROE) and *Artistic Creation Engineering* (ICA) investigate since 1978 multi-sensory-motor interaction, force feedback and the development on the user interfaces for artistic creation [Cadoz et al. 1984; Cadoz et al. 2003]. Among the numerous interfaces that facilitate haptic interaction for musical tasks are projects like the *GENESIS-RT* platform for physical modeling of virtual musical instruments, the *FireFader* as extensible

[33] https://www.gadgets360.com/wearables/features/live-braille-aims-to-help-the-visually-challenged-move-about-independently-837107

[34] https://assistech.iitd.ac.in/smartcane.php

[35] https://www.livescience.com/46236-vibrating-clothes-help-blind-navigate.html

[36] https://www.chicagolighthouse.org/sandys-view/will-haptic-technology-help-vision-loss/

[37] https://www.microsoft.com/en-us/research/blog/bringing-virtual-reality-to-people-who-are-blind-with-an-immersive-sensory-based-system/

Figure 2.2.10: Smart Cane with haptic feedback.

open-source force feedback device, or the *Haptic Bracelets*, a system designed to help people learn multi-limbed rhythms including multiple simultaneous rhythmic patterns [Berdahl and Kontogeorgakopoulos 2012; Bouwer et al. 2013]. Giordano et al. focused on the concept of tactile languages and proposed the design of tactile icons as vibrotactile cues to be used by musicians. They developed a tactile-augmented belt, which together with a set of so-called *tactons* formed a *wearable score* system [Giordano et al. 2018].

Likewise the incorporation of haptic feedback into devices for digital audio editing and musical interaction is relevant of VIB users, who suffered from the transition from analog sound studios to digital environments. While previously VIB audio engineers were able to work for radio and TV, the introduction of GUI-based digital technology made it impossible to adapt. Sile O'Modhrain, a key figure in the research on haptic interaction for computer music and accessibility, worked as a blind audio engineer for the BBC before the 1990s. She had to quit her job because of the lack of accessibility of digital audio software that replaced the physical (and therefor accessible) work with magnetic tape. As a result she started to work in software design and sound engineering at the CCRMA at Stanford University to address this problem and continued to research the accessible interaction with digital audio streams and musical interactions for VIB audio engineers and musicians. There she came to believe that haptic interaction can bring back some of the former intuitiveness, flexibility and *"feel"* to the audio editing process and the musical arts [O'modhrain and B. Gillespie 1995]. Together with Georg Essl, O'Modhrain developed multiple interfaces facilitating haptic feedback for musical expression and granular synthesis such as the *PebbleBox* and *CrumbleBag* [O'Modhrain and Essl 2004]. For navigating the GUI of digital sound studios for VIB users Brent Gillespie and O'Modhrain developed the *Moose*, an extended computer mouse interface that displays haptic effects as substitutions for graphical objects (see Chapter 2.2.6) [R. B. Gillespie and O'Modhrain 1997].

The continuous scientific research on the use of haptic interaction for supporting VIB audio engineers in their digital sound studios led to a number of further interfaces such as the *HaptEQ* or the *Haptic Wave*, which will be discussed in detail below (see Chapter 2.4.9 and 2.4.10).

2.2.6 Discussion: The Moose

An example of a general computer user interface that has been developed towards the needs of VIB sound engineers in the context of digital sound studios is the haptic *Moose* interface (see Fig.2.2.11). Developed by Brent Gillespie and Sile O'Modhrain in 1995, the *Moose* and the supporting software attempts to provide access to the digital sound studio by communicating screen objects like windows, buttons, sliders or pull-down menus mechanically to the users haptic senses [R. B. Gillespie and O'Modhrain 1997]. The interface uses the functionality of a common computer mouse as a pointer for the GUI, while in the same time it provides a mechanically actuated haptic output according to the elements below the mouse pointer. For example, if the mouse cursor crosses the edge of a window, the user feels a detent under the mouse. Similarly, when crossing other items like check boxes, window icons, etc. with the cursor, the *Moose* assigns corresponding *hapticons*, which enable the orientation and navigation, using the interface both as input and output device.

The *Moose* was designed to enable VIB audio engineers to use the otherwise non-accessible GUI of digital audio software. Embedding haptic feedback into the interface provided an additional output modality, which makes space on other output channels like vision and auditory feedback. Likewise, the combination of user input through the mouse cursor and system output through haptic feedback embedded in the same interface proved to be feasible and useful. The research project shows one the one hand the limitations and exclusions, that VIB audio engineers have to deal with in a vision-centric computer environment.

On the other hand, the *Moose* highlights the possibilities of adding actuated feedback in addition to the interaction with GUI, and how this enables access for VIB users and stimulates creative engagement and new visions. The authors describe the use of the device to resemble the behavior of an analogue tape machine interface and to haptically cursor through an audio stream. They also mention the concept of *"haptic landmarks"* for the marking parts of the audio stream that are of special interest. These approaches paved the way for future research projects on accessible computer hardware for VIB audio engineers like the *Haptic Wave*, which successfully realized these visions (see Chapter 2.4.9).

Figure 2.2.11: The Moose by Sile O'Modhrain and Brent Gillespie.

2.3 BITS AND PHYSICAL PIECES

This next section introduces the concepts of physicality and tangible interaction with computers, as opposed to graphical interfaces and visual representations.

With the increasing importance of computers, digital environments and networked realities in everyday-life in the early 1990s, the interest in new forms of human-computer interaction evolved beyond traditional text-based command-line interfaces or graphical user interfaces with their WIMP paradigm based on the interaction with windows, icons, menus and pointers. Emerging concepts like *augmented reality* and *ubiquitous computing* challenged the nature of human-computer interaction with an inherent potential to estrange humans from their *"natural environment"*, which led to the belief, that instead of forcing users into a virtual world, on the contrary the real world around the user should be augmented and enriched. The user should be enabled to transition between *"the digital"* and *"the real"* by providing embedded computing in the existing physical environments and human practices [Wellner et al. 1993]. As Shaer and Hornecker point out, this attempt of retaining the richness and situatedness of physical interaction led to the emergence of *Tangible Interaction* [Shaer and Hornecker 2009]. An era of post-WIMP interfaces started, and this new focus on physicality and tangibility quickly detached from the initial concerns around *augmented reality* and *ubiquitous computing*, and began a life on its own in various areas of HCI, especially serving as inspiration for a vast variety of novel musical interfaces.

2.3.1 Tangible Interaction

The coupling of digital information with physical objects, that one can grasp and physically manipulate in order to alter the digital data, is the core concept of *tangible interaction*. The entanglement of the *"natural environment"* with digital control structures to increase the directness of data manipulation was first demonstrated 1995 by Fitzmaurice et al., who proposed a *graspable user interface* based on physical wooden blocks called *bricks*, that enabled the manipulation of virtual objects [Fitzmaurice et al. 1995]. In order to accomplish a graspable interaction, up to two *bricks* could be placed on a horizontal display surface, which recognized their position and linked it via the according software to the displayed virtual object. This configuration enabled the user to use the physical wooden *bricks* to interact with the virtual object, e.g. to rotate it, to move it or to zoom in and out by placing two *bricks* at each corner of the virtual object and drag them. The project by Fitzmaurice et al. thereby introduced the notion, that digital data could be altered through physical objects that are linked to it.

Shortly afterwards in 1997, Hiroshi Ishii and Ullmer Brygg attempted to bridge the gap between the digital space and the physical environment even more consequently by proposing the concept of *tangible bits*, or the *"coupling of bits and atoms"* [Ishii and Ullmer 1997]. Their vision is informed by the imbalance of the human physicality and skills in relation to GUI-based HCI designs and their limited input and output channels. Ishii and Brygg are seeking *"ways to turn each state of physical matter - not only solid matter, but also liquids and gases - within everyday architectural spaces into 'interfaces' between people and digital information"*, and by taking *"advantage of multiple senses and the multi-modality of human interactions with the real world"* they attempt to *"change 'painted bits' into 'tangible bits'."* With the aim of moving beyond the GUI and to make computing ubiquitous and invisible, they proposed the concept of the *Tangible User Interface* (TUI). TUIs augment the physical world through the coupling of digital information to physical objects and environments, while the ability to *"grasp & manipulate"* digital data through physical objects not only improves the quality of the interaction, but also increases the bandwidth.

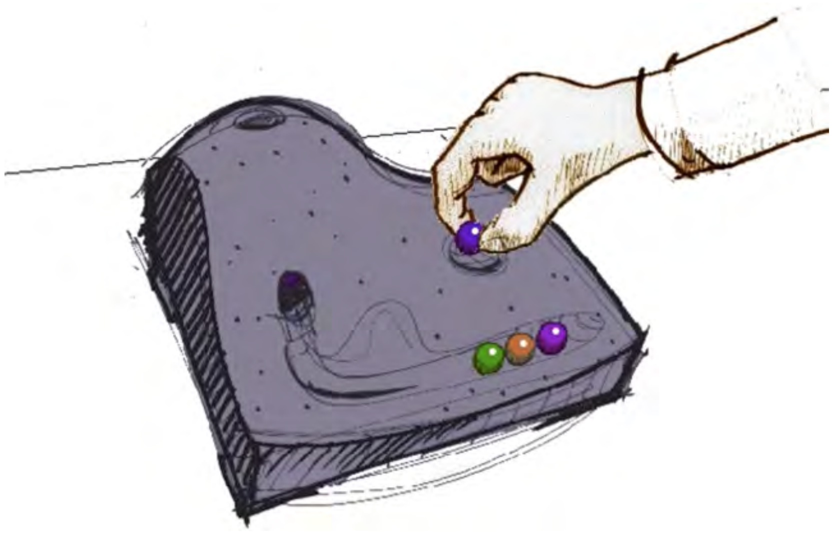

Figure 2.3.1: Marble Answering Machine by Durrell Bischop.

To illustrate their concept of a TUI, Ishii and Ullmer presented the *Marble Answering Machine* by Durrell Bishop as an example, a telephone answering machine, that stores incoming Voice messages on physically assigned marbles. The user interacts with the marble directly to listen to the message, or to automatically dialing the caller (see Fig.2.3.1). This digital information embodied into physical and tangible marbles shows the successful result of combining bits and atoms [Ishii and Ullmer 1997].

In the following years, a huge number of TUIs emerged in different related areas, such as *tangible augmented reality*, *tangible tabletop interfaces*, *ambient Displays* or *embodied user interfaces* [Shaer and Hornecker 2009]. These concepts can be summarized as *tangible computing*, an attribution which slowly shifts the focus away from the singular tangible user interface, towards the integration of computation into the everyday world environment, on which the user can act on *"in real time and real space"*. The relation of user actions with the space in which they are performed in, can be described as *embodied interaction*, which also reflects back on the effects, that the environment can have on the computing and user activity [Dourish 2001].

To further expand the concept of TUIs, Hornecker and Buur propose the term *tangible interaction*. They argue that the focus on physical *handles* to manipulate digital data is too narrow to encompass the emerging projects especially within arts and design, which create systems for bodily movement, rich expression and physical skill. Thus they argue, that the *data-centered view* of TUIs, which is focused on the *handle* and the according manipulation of digital data, should be opened towards an *expressive-moment-view*, that focuses more on the interactions, actions and user experience (UX) with the tangible interface. With the term *tangible interaction*, Hornecker and Buur emphasize on the tangibility and materiality, the physical embodiment of data, the bodily interaction, and the physical and social implications of embedding systems in real spaces and contexts [Hornecker and Buur 2006; Shaer and Hornecker 2009].

2.3.2 Space-Multiplexing and Direct Manipulation

The development of tangible user interfaces has given rise to many new ways in which humans can use computers. Using multiple physical *handles* to control virtual data embodies functional manipulation in the physical objects, which gives users concurrent access to multiple interactions at the same time. As part of Fitzmaurice's definition of *graspable user interfaces*, this concept of *space-multiplexing* through the use of multiple *handles* is one of its most powerful concepts, as Shaer and Hornecker point out [Shaer and Hornecker 2009]. Because of previous limitations of input and output channels, users had to perform tasks based on *time-multiplexing*, that is to accomplish tasks one after the other distributed over time, e.g. selecting a file, opening a software, interacting with messages. Tangible user interfaces that provide more than just one input *handle* allow the interaction through *space-multiplexing*, that is the distribution of tasks and interactions in space. This enables simultaneous interactions with the computer, e.g. by independent and potentially persistent selection of objects, or by two-handed interaction. By additionally providing spacial awareness and spacial reconfigurability, tangible user interfaces can accelerate their intuitive handling even further. Projects like the *KnobSlider* by Kim et al. attempt to unify principles of *time-multiplexing* and *space-multiplexing* into one shape-changing tangible device that enables the control of multiple parameters by providing both a knob and a slider in one combined interface [Kim et al. 2019].

Another important shift in HCI enabled by tangible interaction is the now possible physicalization of Ben Shneiderman's older concept of *direct manipulation* of virtual data on the screen, one of the fundamental paradigms of GUIs. In 1983, Shneiderman proposed four characteristics for direct manipulation: the continuous presence of the object of interest, the ability of performing physical actions on it, immediate visibility of incremental and reversible actions, and lastly the possible operation with minimal knowledge which expands through reinforcing feedback [Shneiderman 1983]. Tangible user interfaces provide the physical means to perform Shneiderman's proposition for GUIs. While WIMP interfaces use metaphors of the physical office environment, TUIs are able to connect the user to the actual physical environment.

Nonetheless, there are limitations of tangible interaction, as Shaer and Hornecker point out [Shaer and Hornecker 2009]. TUIs are not only limited in scalability, but users can also lose physical objects. Compared to GUIs, which are multifunctional and general-purpose interfaces, TUIs are less versatile and can cause user fatigue.

2.3.3 Tangible Musical Interfaces

A popular application domain of tangible interaction is the field of music and performance. The physicalization and embodiment of musical data and controls is particularly relevant to the design of musical interfaces and instruments. As Shaer and Hornecker describe, projects like the *Audiopad*, the *BlockJam* or the *Squeezables* were realized, incorporating various different approaches of tangible interaction and tangible controls of musical parameters [Shaer and Hornecker 2009; Patten et al. 2002; Dunn et al. 2003; Weinberg and Gan 2001]. Alberto Boehm presented the malleable *Sculpton*, an interface that embodied the vision of physically sculpting sound for live performances [Boem 2014]. While some of these interfaces provided physical blocks that can be stacked or moved to continuously generate sound (e.g. *Blockjam*), others encouraged squeezing, rubbing or other physical interaction with the interface (e.g. *Squeezables*).

A series of tangible musical pattern sequencers were developed based on grids of sequences and the use of physical marbles as means to control multiple instrument voices, such as the *Beatbearing* by Peter Bennett (see Fig.2.3.2) or the *Bubblegum Sequencer* by Hesse and McDiarmid [Bennett and O'Modhrain 2008; Hesse and McDiarmid 2008]. In 2022, Patricia Cadavid proposed the token-based tangible rhythm sequencer *Kanchay_Yupana//*, a musical instrument inspired by ancestral Andean technologies, that creates sound sequences based on a arithmetic calculations similar to an abacus [Hinojosa 2022]. An extensive overview and archive of various tangible musical interfaces, including music tables, audio building blocks, tangible toys and artifacts can be found in an online archive maintained by Martin Kaltenbrunner.[38]

Shaer and Hornecker distinguish four different approaches of higher-level musical TUI interfaces: there are *instruments* that are fully controllable sound generators such as the *Reactable* [Jordà et al. 2006]. Another category of TUIs are *sequencers* that enable the arrangement of patterns for playback, or the mixing of audio samples. Next, TUIs can be classified as *sound toys*, which offer only limited control to the user. Finally, there are are *controller* interfaces, that can be used to control arbitrary remote music software or hardware [Shaer and Hornecker 2009].

A prominent example for an expressive and complex musical instrument based on a tangible tabletop user interface is the *Reactable*, developed by Sergi Jordà, Martin Kaltenbrunner et al. [Jordà et al. 2006]. The *Reactable* is a standalone musical instrument that enables collaborative music composition, modular sound synthesis and live performance through the use of physical tokens on an interactive visual display (see Fig.2.3.3). Each token controls different parameters for sound synthesis, audio effects, modulation or musical composition. Its visual programming and the *"dynamic patching"* is intuitive and can be performed by multiple players at the same time.

[38]https://modin.yuri.at/tangibles/

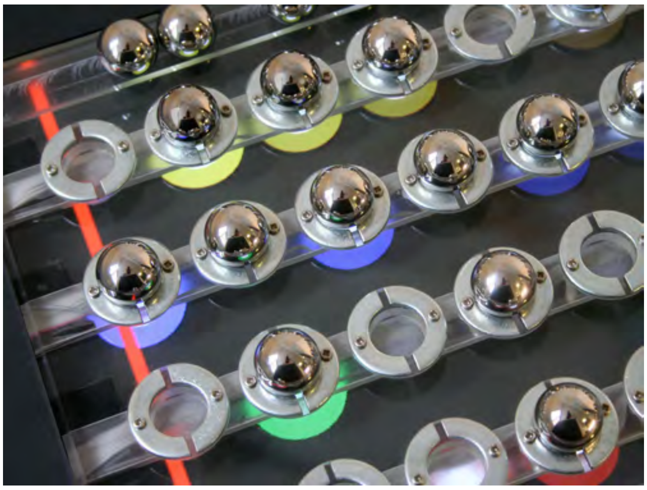

Figure 2.3.2: Beatbearing, a Tangible Rhythm Sequencer.

Figure 2.3.3: Reactable Live.

Another example of a complex and expressive tangible musical instrument is the *Tquencer* [Kaltenbrunner and Vetter 2018]. The instrument is a portable and low-cost tangible music sequencer. It is inspired by interfaces such as the *Reactable* with its explorative interaction through physical tokens, and the token-based tangible sequencer *Beatbearing* and its static interface design. The *Tquencer* enables the use of an eight-step sequencer grid and physical tokens to compose complex patterns. It provides dynamic pattern and sound assignment through tangible overlays that store musical patterns by keeping tokens physically attached (see Fig.2.3.4). This design allows for intuitive, collaborative, and expandable music composition and performance while providing enough depth for skilled professionals.

Figure 2.3.4: Tquencer interface with tokens and overlays.

2.3.4 Tangible Interaction for VIB Users

Despite continuous research interest in the development of TUIs across many fields of HCI, there is still little work on non-visual TUIs, even though VIB individuals have efficient manual exploration strategies, as Anke Brock et al. point out [Brock 2017]. They state, that most technologies that are accessible to VIB people are based on the replacement of vision through audition and touch. While Brock et al. consider touch to be a promising modality for the substitution of vision, especially since studies showed that VIB persons exhibit a superior tactile acuity over sighted people [Cattaneo and Vecchi 2013], they emphasize the advantages of tangible interaction, e.g. that TUIs foster collaboration or increase participation of students in educational environments. Furthermore Brock et al. highlight the flexibility and dynamic configuration of TUIs compared with raised-line representations traditionally used by VIB people. For example, TUIs enable to add, move and remove tangible objects, while a relief map is a static representation. Rearranging the tangible objects as part of constructing a map also improves the understanding of the map and enhances the memorization of the spatial information [Brock 2017]. As a result of their insights in accessible and non-visual TUIs for VIB people, Brock et al. suggest, that future research should investigate various interface design aspects in order to improve accessibility: they propose *actuation* in TUIs to provide active haptic feedback as tactile cues for VIB people, they propose *haptic aesthetics* as a version of *"feel aesthetics"* instead of visual aspects, and lastly they propose *additional sensory modalities* through the combination of tangible interaction with other senses like audio cues or other forms of *multisensory interaction* [Brock 2017].

Nevertheless, a number of general research projects on accessible TUIs for VIB users have been presented in recent years, such as the *FlexiBoard* with its focus on tangible and tactile graphics, the *TangibleGrid* that presents a tangible web layout design for VIB users, the *BrailleBuddy* as a TUI that supports VIB children in learning Braille, or tangible programming toolkits such as *CodeRhythm* and *Torino* [Raynal et al. 2024; Li et al. 2022; Lang et al. 2023; Rong et al. 2020; Morrison et al. 2018]. Sabuncuoglu presented a conceptual design and user study on *tangible music programming blocks* for VIB children, in which he uses musical composition techniques to teach the basics of computer programming [Sabuncuoglu 2020].

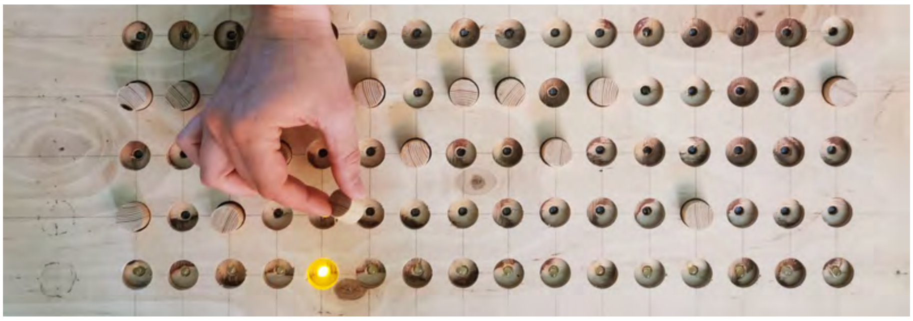

Figure 2.3.5: LoopBlocks by Andreas Förster and Mathias Komesker.

Unfortunately, only few research projects investigate the field of accessible musical TUIs for VIB users. among them is a tabletop music application for composition based on tangible objects for VIB individuals [Omori and Yairi 2013], or the *MuBiks*, although this is not a musical instrument, but an accessible music player for VIB individuals [Gupta et al. 2014].

Among the few tangible interfaces usable for VIB users is the *LoopBlocks* project, an accessible, token-based, tangible step sequencer. Although it was designed for Special Needs Education, it could also be used by VIB musicians due to its tactile and tangible design (see Fig.2.3.5) [Förster and Komesker 2021].

2.3.5 Actuation and Shape Changing

In the context of human-computer interaction (HCI), another strategy that can be used to convey information in addition to tangible or haptic interaction is mechanical actuation. Examples include pin-based displays, vibro-tactile feedback, and interaction with handles, tokens, and interactive surfaces. However, mechanical actuation is underrepresented as an interaction strategy in new HCI user interfaces, despite the fact that human interaction with the physical world primarily happens through active touch, enabling the perception of the shapes, physical functions, and properties of surrounding objects [Gibson 1962; Lederman and Klatzky 1987]. As Shultz et al. pointed out in 2023, this lack of tactility is well known and has been extensively commented on by researchers and the HCI community. Over the last decade only a small number of research projects approached tactile computer interaction through the work on haptic and shape-changing displays [Shultz and C. Harrison 2023; Coelho and Zigelbaum 2011; Sturdee and Alexander 2018; Rasmussen et al. 2012; C. Harrison and Hudson 2009].

Shultz et al. argue that the lack of interfaces with dynamic and complex haptic shape-changing abilities is due to the cross-disciplinary nature of the field, which involves not only material science, electronics, and mechanical engineering, but also human-machine interface design, psychological perception, and more. Thus, creating shape-changing interfaces remains challenging, despite the availability of many technologies that enable the construction of haptic or shape-changing interfaces, such as solid actuators, pneumatic systems, and hydraulic actuation devices. Examples of interfaces based on hydraulic and pneumatic technology include the Flat Panel Display by Shultz et al., which is a miniaturizable, shape-changing display based on electro-osmotic pumps; and the Pneu Shape Display by Russomanno et al., which uses pneumatics to augment touchscreens with haptic overlays and raised buttons [Shultz and C. Harrison 2023; Russomanno et al. 2017].

Many projects and interfaces use various actuators due to their low cost, availability, and versatility. Examples include DC motors, solenoids, and voice coil actuators, as well as piezoelectric actuators. VIB users, for instance, work every day with piezo-ceramic actuated pins embedded in Braille displays and refreshable tactile graphic displays. These displays can convey not only text, but also multimodal spatial data [Rao and O'Modhrain 2019]. To convey more complex shapes, graphs and spacial characteristics, Fan et al. developed the *Slide-Tone and Tilt-Tone* interface, which uses a motorized sliding and tilting interface to convey height and inclination. The data retrieval is thereby supported by sonification and speech output of the according x and y values [Fan et al. 2022].

A growing category of interfaces that has received much attention in HCI communities over the last decade is that of shape-changing pin displays. Projects like *inFORM* and *transFORM* explore the versatility and potential of pin-based, dynamic, shape-changing interfaces that can display 3D forms in contexts such as geospatial data display, tangible interaction, interactive shape-changing furniture, and physical telepresence [Follmer et al. 2013; Leithinger et al. 2014; Ishii et al. 2015; Vink et al. 2015].

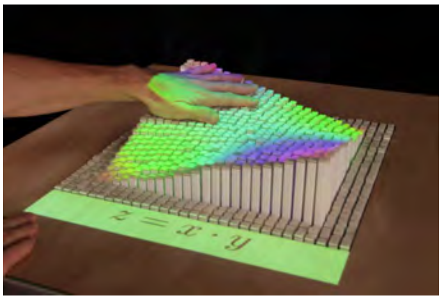

Figure 2.3.6: inForm shape display for math

Figure 2.3.7: inForm shape display, remote actuated sphere

Other approaches to pin-based displays are the *shapeShift*, the *Inforce* shape-display, or *Lumen* by Poupyrev as a more aesthetic approach to shape-changing displays [Siu et al. 2018; Nakagaki et al. 2019; Poupyrev et al. 2004].

In contrast to pin-based interfaces facilitating discrete pins with sharp edges, Steed et al. propose a *mechatronic shape display* based on the use of auxetic and bending materials [Steed et al. 2021]. Inspired by theater stages, Nakagaki et al. focus on the dynamic appearance and disappearance of TUIs in order to create a novel interaction design space for expressive displays. They propose the *(Dis)Appearables*, in which self-propelled TUIs re-shape the workspace by autonomously appearing and disappearing from the users attention [Nakagaki et al. 2022]. Other research projects explored shape-changing designs that are detached from rectangular designs and the physical replacement for a GUI. Based on Ishii et al. notion of *Radical Atoms*, they focus on objects that dynamically change their form and appearance and thus are just as reconfigurable like pixels on a screen, as physical materialization of digital information that enables direct interaction [Ishii et al. 2012]. Projects like the *MorpheesPlug* by Kim et al. provide a toolkit for prototyping various shape-changing interfaces. The aforementioned *KnobSlider* enables the control of musical parameters by providing both a knob and a slider in one combined shape-changing interface [Kim et al. 2021; Kim et al. 2019]. Likewise, the *LineFORM* interface focuses on interaction design that is embedded and displayed in a physical snake-like form, and uses inherent interactions, affordances and constraints for the user interaction [Nakagaki et al. 2015].

Figure 2.3.8: LineFORM - Shape Changing Interface.

In the field of sonic interaction and musical interfaces, numerous researchers and instrument builders are inspired by actuation and shapes-changing interfaces. Instruments such as the *Hummellaphone* use electro-mechanical actuation both as part of the musical interface, as well as sound generation mechanism [Schmidt and Gurevich 2023]. Wicaksono et al. presented *PerForm*, a deformable interface for the exploration of sound through shapes, where each shape portrays a different musical instrument with a unique sonic behavior [Wicaksono et al. 2018]. Tangible musical interaction based on dynamic shape-changing displays was also explored by projects like the *SoundFORMS*, which is able to project waveforms and audio samples in three dimensions, or the *Kinéphone*, which proposes 3D shapes as compositional elements of step sequencers and modular keyboards [Colter et al. 2016; Xiao et al. 2016].

2.3.6 Discussion: KinéPhone

The *KinéPhone* is a musical interface designed by Xiao et al., which is designed based on the use of the actuated pin-based shape display

TRANSFORM [Xiao et al. 2016; Ishii et al. 2015]. It realizes three different musical instrument approaches by facilitating the shape display as input device, as controller interface, and finally as output device for shapes and acoustic sound creation.

Figure 2.3.9: KinéPhone Step Sequencer

Figure 2.3.10: KinéPhone Keyboard

Apart from using the mechanical sounds of the pins for sound generation, Xiao et al. created a step sequencer that plays and sequences layered rhythms inspired by the Tenori-on [Nishibori and Iwai 2006]. The step sequencer used the main region of the display as interface to play, compose and control a musical sequence, while the respective pins of the top portion of the interface acted as actuators to generate percussive acoustic sounds through attached shakers (see Fig.2.3.9). This configuration enabled the physical real-time actuation, composition, and improvisation with musical sequences. In another configuration, the interface is transformed into a modular keyboard that uses the actuated pins of the shape display to strike resonant sound objects, such as a wooden xylophone or metallic chimes (see Fig.2.3.10). The modular layout of the shape display leaves room for individual configuration both as personalized keyboard as well as the exploration of different acoustic sound objects and materials.

The *KinéPhone* project shows, how actuated shape-changing interfaces can be used in a musical and performative context, both for the asynchronous composition of step sequences, as well as an interactive musical instrument that enables to play melodies and rhythms in real-time. Using actuated pins to strike and shake acoustic sounds underlines its versatility. Even though Xiao et al. do not mention accessibility aspects, the *KinéPhone* can easily be imagined as an accessible modular music sequencer and keyboard interface for VIB musicians, by providing hands-on interaction that is supported by its 3D shape displays and its tactile, explorative and pin-based design.

2.4 DIGITAL MUSIC MAKING

While the previous sections focused on computers as multidisciplinary machines that can be used for artistic purposes alongside the integration of assistive technologies, this section will explore how computers can be used for musical purposes, considering their affordability, expressiveness, artistic versatility, and customizability. Special focus will be given to the underlying meaning of music and sound. The section will explore the predecessors of modern digital music technology and present various sound synthesis methods. Furthermore, the section will explore computers and code as a means of accessible music-making and describe various new interfaces for musical expression.

2.4.1 Time-based Poetry and Music-Making

Any investigation of musical instruments and sonic interaction should begin with the question: What is music? One could argue that music is both joy and art—a time-based poetry of sound and meaning. Music connects humans through shared experiences, empowers musicians and listeners alike, and is practiced as a *"cultural universal"* by all human cultures worldwide. Archaeological evidence of musical activities predates even the earliest known cave art [Morley 2013]. As a sensation of organized physical vibrations, synchronization, and resonance that overlap with meaning and context, music stimulates the body and mind. It is a highly versatile medium for expressing human creativity and transcending everyday life [Toynbee 2012]. The interdisciplinary nature of music is reflected in the variety of *musicology* fields, including psychology, sociology, acoustics, neurology, natural sciences, and computer science [Beard and Gloag 2016].

To provide a practical definition of music, the *Encyclopædia Britannica* states that music is *"art concerned with combining vocal or instrumental sounds for beauty of form or emotional expression, usually according to cultural standards of rhythm, melody, and, in most Western music, harmony. Both the simple folk song and the complex electronic composition belong to the same activity, music."*[39] Artist, theorist, and musician G Douglas Barrett see's music rather as a *"historically mutable, contingent, and ultimately revisable art form that, when*

[39]https://www.britannica.com/art/music

radically conceived, exceeds any strict adherence to specific mediums or material forms including sound itself."[40] The diversity and richness of music as *"cultural universal"* is documented and archived worldwide in music libraries, catalogs and online music archives.[41][42][43][44] An impressive collection of musical heritage of vocal and instrumental music, musical notation systems, music performances and more can also be found in the UNESCO lists of intangible cultural heritage.[45]

One way of describing the artistic process of creating sound and music is the notion of *music-making*, both in professional settings, but also in a playful and explorative meaning. Thereby *music-making* as an artistic approach extends the common sequence of *musical thought, composition, performance* and *listening* by shifting the focus from the musical *result* to an *ongoing* artistic process [Moore 1990]. The exploration of the musical instrument and its sonic materialities becomes an equal part of the creative process, as well as the iteration over the stages of musical creation in a random order, scrambling *listening, musical thought, performance* and *composition*. Or as Insook Choi puts it: *"Music is a structured sonic event for listening. This description is inclusive of a listener who is an actor in musical interaction. Music without a listener is ontologically incomplete. Composers and performers model listening experiences by being listeners themselves in planned or on-the-fly production of musical events."* [Choi 2022]

Music-making can be practiced with many different tools and techniques. For example, it can involve the use of traditional musical instruments or the experimental creation of sound with sonic or resonant physical objects. It can also involve the production and artistic rearrangement of field recordings, the generative and algorithmic composition of musical pieces with a computer, or the process of writing notations for sonic compositions. In general, *music-making* could be described as activities that generate organized or unstructured sounds and noises [R. Goldberg 1988; Demers 2010; Jensenius 2024; Magnusson 2019]. This broad definition of *music-making* attempts to abandon the duality of *music* versus *sound art*. The former stands in the tradition of combining harmony, rhythm, and rational thought, while the latter is a medium of contemporary art that encompasses non-conceptual or

[40] https://www.akademie-solitude.de/de/studio-visits/critical-music-after-sound/
[41] https://www.iaml.info/
[42] https://archive.org/details/etree
[43] http://www.openmusicarchive.org/
[44] https://www.ubu.com/
[45] https://ich.unesco.org/en/lists

instrumental sound, often as part of a broader social, political, and artistic universe.[46] Instead, *music-making* focuses on the creative process. It attempts to encourage curiosity beyond musical education as an instrumentalist or composer. It also attempts to reduce barriers to participation by detaching the generation of sound and music from exclusive virtuosity on traditional instruments. Moreover, it attempts to integrate both tonal sounds and textured clicks and noises into a shared musical experience. Practically speaking, *music-making* enables beginners and professionals alike to use various tools, instruments, and materials for sonic experimentation. It supports adaptation to individual strengths and needs and enhances confidence for continuous education toward a rich musical and practical experience.

2.4.2 Origins and Impact of Digital Music Technology

A versatile means of achieving this inclusive concept of musical practice is digital music technology. This technology enables music-making by providing a wide range of tools for sonic artistic expression. It encompasses platforms and devices such as digital musical instruments, audio effects, computer music software, hardware controllers, and digital audio equipment. Less constrained by economic exclusion, expensive acoustic instruments, and costly analog music recording studios, digital music technology enables musicians from diverse financial, educational, geographic, and ethical backgrounds to practice audio and music production. Using free or open-source computer software and affordable digital hardware synthesizers, sequencers, and audio effects allows interested individuals, aspiring musicians, and professionals to explore sound creation, music composition, and live performances.

Digital music technology is used for various artistic practices, including sound engineering, computer music, audio-visual works, audio mastering and post-production, composing music for film and multimedia, producing sound effects for games, as well as sound and music research. In the following, *digital music-making* refers to artistic practices concerned with creating sound and music with digital music technology, including digital musical instruments, digital composition platforms, digital sound synthesis, or using digital technology as a recording and production environment.

Today's digital music technology has a long history that dates back to the early days of modern computational systems. It began with the

[46] https://www.akademie-solitude.de/de/studio-visits/critical-music-after-sound/

abacus, one of the first calculation systems (see Fig.2.4.1).[47] With the emergence of electricity, telegraphs began using audible electric pulses to communicate, operating like electronic oscillators. At the beginning of the 20th century, electricity enabled the development of electromechanical musical instruments, such as Thaddeus Cahill's *Telharmonium*, Leon Theremin's *Theremin*, and Friedrich Trautwein's *Trautonium*. These instruments used electric circuits to generate and control musical properties, such as pitch, volume, and timbre. This development informed later advancements in digital sound synthesis [Tanaka 2012]. Similarly, advances in technology, such as the development of magnetic tape machines, led to new musical practices. Examples include Pierre Schaeffer's *musique concrète*, which involved sampling and looping audio fragments, and Karlheinz Stockhausen's aleatory techniques, serial composition, and musical spatialization. In the 1960s, analog sound synthesis became popular with the introduction of the portable, voltage-controlled, modular *Moog* synthesizer by Robert Moog and the *Buchla 100 series* by Don Buchla [Pinch and Trocco 1998].

Figure 2.4.1: Chinese *Suan Pan* Abacus (around 190 CE). Calculations like addition, subtraction, multiplication and division can be realized by following a *bi-quinary coded decimal* encoding scheme.

Around the same time Max Mathews produced the first computer music piece with his *Music* software series, which made him the *"father of computer music"*, and initiated the digital era of sound synthesis and computer music [Tanaka 2012].

In the following years, digital musical instruments such as various synthesizers, samplers, sequencers or audio effects like auto-tune or

[47] https://kartsci.org/kocomu/computer-history/history-abacus-ancient-computing/

Figure 2.4.2: Roger Linn's MPC 60.

bitcrusher entered the music market, and created new fields of artistic expression and musical genres. Iconic digital stand-alone devices like Roger Linn's *MPC 60* and its successors were used as music production systems by hip-hop musicians and producers since the 1980s to produce their own music without the need of a big production studio (see Fig.2.4.2).[48] The repetition of audio samples in Pierre Schaeffers *musique concrète* evolved from analog tape reels to digital live samplers, that are able to capture, overdub and playback the audio loop on multiple audio channels simultaneously, today known as *"live looping"* [Shepardson and Magnusson 2023].

As computer technology became more affordable and powerful in the 1990s, computers began replacing hardware music setups. The development of MIDI as interface protocol and the first *Digital Audio Workstations* (DAWs) revolutionized the musical landscape on computers such as the Commodore 64, the Atari 520ST, the Commodore Amiga, and eventually the Apple Mac and Windows PC.[49] New music software enabled novel techniques of sound synthesis and sequencing, digital audio recording and post-production, and inspired new approaches to artistic practice and experimentation.

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[48] https://www.vox.com/culture/2018/4/16/16615352/akai-mpc-music-history-impact

[49] https://www.musicradar.com/news/early-daws-the-software-that-changed-music-production-forever

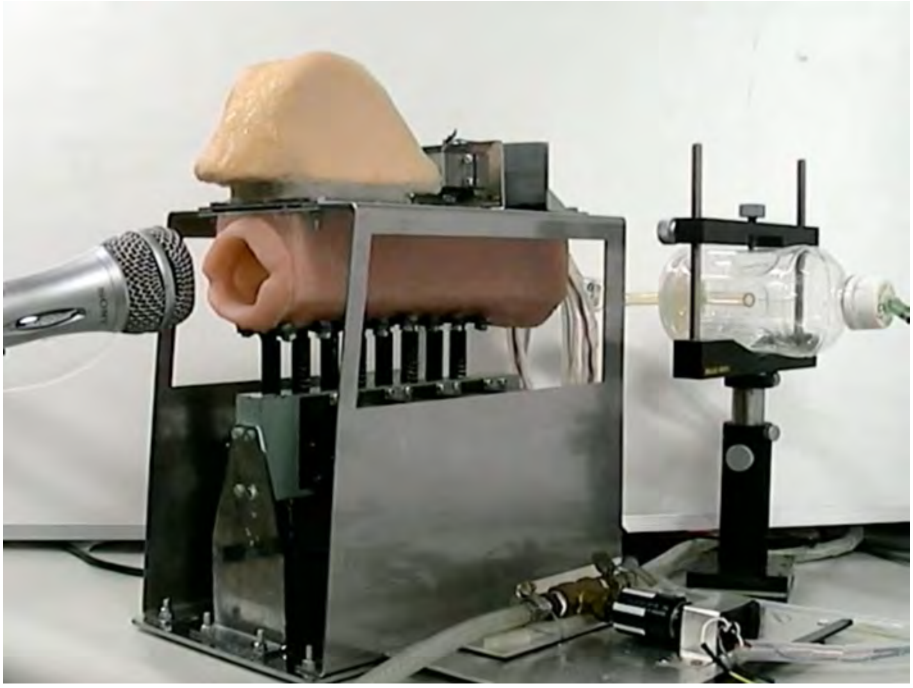

Figure 2.4.3: Robot Mouth by Hideyuki Sawada.

A notable example of the advancements in digital music technology is the evolution of speech synthesis as a sound generation technique. Coming from early experiments with analog devices such as Kempelen's *Speaking Machine* in 1791,[50] newer devices used electricity for the synthesis process, such as the *Voder* in 1939.[51] In 1961, the first computer-based speech synthesis was realized on an IBM 7094 that performed the song *Daisy Bell*, with the vocals programmed by John Kelly and Carol Lockbaum, as well as an accompaniment that was programmed by Max Mathews.[52] As a precursor to modern speech synthesis software and assistive technology, John Eulenberg and J.J. Jackson developed a system based on a Votrax synthesizer at Michigan State University's Artificial Language Laboratory. This system enabled people with speech impairments to communicate. One of the first experiments involved Donald Sherman, who had Moebius syndrome and had never ordered a pizza over the phone before, successfully using the computer system to do so in 1974.[53] In 2011 at the Kagawa University in Japan, Hideyuki Sawada developed a physical shape-shifting device looking like a robot mouth, that sings the Japanese children song *"Kagome Kagome"* (see

[50]https://www.youtube.com/watch?v=oIjkzZGe2I8
[51]interactive demo of the *Voder* - https://griffin.moe/voder/
[52]https://www.historyofinformation.com/detail.php?entryid=4445
[53]https://www.youtube.com/watch?v=94d_h_t2QAA

Fig.2.4.3).[54] With advancements in deep learning and artificial intelligence technologies (AI) in recent years, speech synthesis and voice generation is used to enhance accessibility, to personalize digital interactions and to produce artistic works and musical compositions.[55]

Today, the abundance of digital music instruments, free and open-source music software, affordable yet powerful computers, educational materials, and networked online services has liberated music-making practices. Technological developments such as ubiquitous computing, sensors, and actuators, as well as the rise of AI technologies, are constantly expanding the potential of digital music technologies and their applications for creating and exploring sound and music.

2.4.3 Sound as Artistic Medium

The material central to digital music-making is sound as fundamental artistic medium. Sound is both a physical vibration within the audible frequency spectrum that propagates as an acoustic wave through a transmission medium, as well as the physiological reception and psychological perception of these waves in the human brain. It can be generated by exciting physical resonant materials, by creating an electrical signal, or by algorithmically generating digital data, which is then played back through a speaker. The production, filtering, shaping, manipulation, or amplification of synthesized sound can be realized using electrical, or digital components. Examples of these components include waveform generators, oscillators, filters, envelope generators, modulators, and amplifiers.

There are many different synthesis techniques that can be used to generate complex sounds by patching combinations of sound-generating and control modules in analog and software synthesizers. Early examples of sound synthesis include Thaddeus Cahill, who used *additive synthesis* around 1902. Using his 200-ton *Telharmonium*, he created mixtures of sine tones to form more complex timbres.[56] In 1957, Max Mathews used *wavetable synthesis* within the first iterations of the *MUSIC* software series to generate computer music. [57] *Wavetable synthesis* is a technique that produces a sound signal by cycling through a table of values to generate periodic waveforms of varying frequencies (see Fig.2.4.4).

[54] https://www.youtube.com/watch?v=Bht96voReEo
[55] https://waywithwords.net/resource/ai-speech-synthesis-and-voice-generation/
[56] https://120years.net/the-telharmonium-thaddeus-cahill-usa-1897/
[57] https://120years.net/music-n-max-mathews-usa-1957/

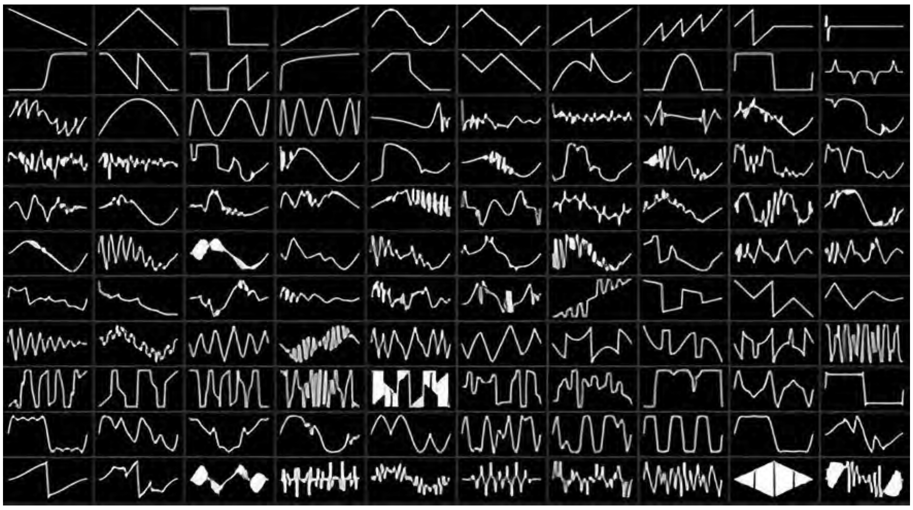

Figure 2.4.4: An example of a wavetable contained in a synthesizer.

Other synthesis techniques are *subtractive synthesis* which attenuates partials of an audio signal through filtering to alter the timbre of the sound, *amplitude modulation synthesis* (AM synthesis) that alters a carrier wave's amplitude by a modulator wave, or John Chowning's *frequency modulation synthesis* (FM synthesis) as a form of sound synthesis where in its simplest form the frequency of one signal called *carrier* is changed by modulating it by a second signal called *modulator* [Chowning 2008]. Another synthesis technique is Ianni Xenakis' *granular synthesis* that operates on the microsound time scale and is based on the same principle as sampling, however here the samples are split into small pieces of around 1 to 100 ms in duration and are called grains [Xenakis et al. 1992]. Other existing synthesis techniques are *physical modeling synthesis, sample-based synthesis, vector synthesis* or *optical sound synthesis*, with new techniques constantly emerging, such as the *crumpling sound synthesis* [Cirio et al. 2016].[58] These sound synthesis techniques is are then used in various different fields, such as multimedia, film or games, as part of the artistic practice of music-making or *sound art*, but also in scientific research, electronics and telecommunications, as well as practices such as *sonification* to convey information derived from digital data.[59]

In addition to using sound as source material for music and sound art, sound can also be represented visually, displaying and visualizing its properties. As part of his studies of vibration, Ernst Chladni sprinkled sand on resonant plates and excited the plates with a bow. The re-

[58] http://jiyounkang.com/wordpress/index.php/archives/1142
[59] Sonification of a Hubble Deep Space Image: https://www.youtube.com/watch?v=H-Ci_YwfH04

sulting characteristic patterns, later known as *Chladni figures*, revealed insights on nodes and modes of rigid surfaces (see Fig.2.4.5) [Chladni 1787]. Chladni's work inspired many artists since to experiment with mechanical visualizations of sound. For instance, Hans Jenny introduced *cymatics* as the study of visible sound vibrations, Alvin Lucier focuses on sound images in his work *The Queen of the South*, and Carsten Nicolai uses liquids to visualize lower frequencies in his *Wellenwanne* [Rühse and Horvath 2023].

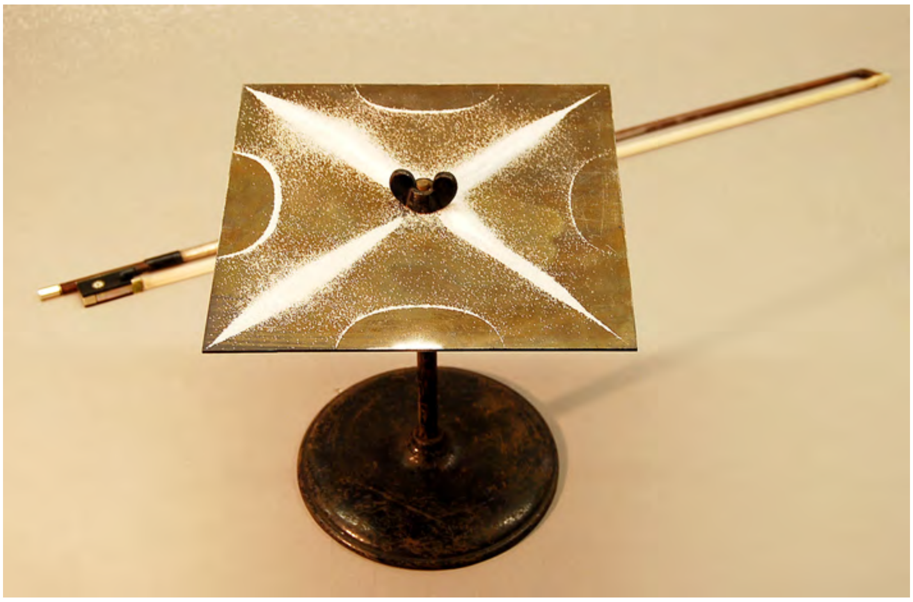

Figure 2.4.5: Chladni plate. A pattern forms as the plate vibrates, the sand on the moving areas bounces off and accumulates on the nodes.

The researcher and artist Reinhard Gupfinger transforms sound with his project *Sound Shifting* in order to visualize complex frequencies and rhythmic patterns [Gupfinger et al. 2019]. Similarly to the visualization of sound as physical vibration, it can also be analyzed and visualized in its digital form. Algorithms like FFT (Fast Fourier Transformation) can be used to convert a signal into individual spectral components and thereby provide frequency information about the signal, e.g. for spectrograms and their visual representation [Rader and Maling 1967].[60]

In order to visualize sound in both its analog and digital forms, oscilloscopes can be used to display frequency, amplitude, and distortions over time. Artistic attempts resulted in a genre of music called *"Oscilloscope Music"*, an artistic practice that deliberately generates sounds to produces shapes and transitions in the oscilloscope. Artists like Jerobeam Fenderson and Hansi3D use two channels of audio sig-

[60] Michael Klingbeil's Spear - FFT synthesis https://www.klingbeil.com/spear/

nals produced by software or synthesizers, which are then fed into an oscilloscope set in X-Y mode in order to create both sound and visual art (see Fig.2.4.6) [MacIsaac 2018].[61][62]

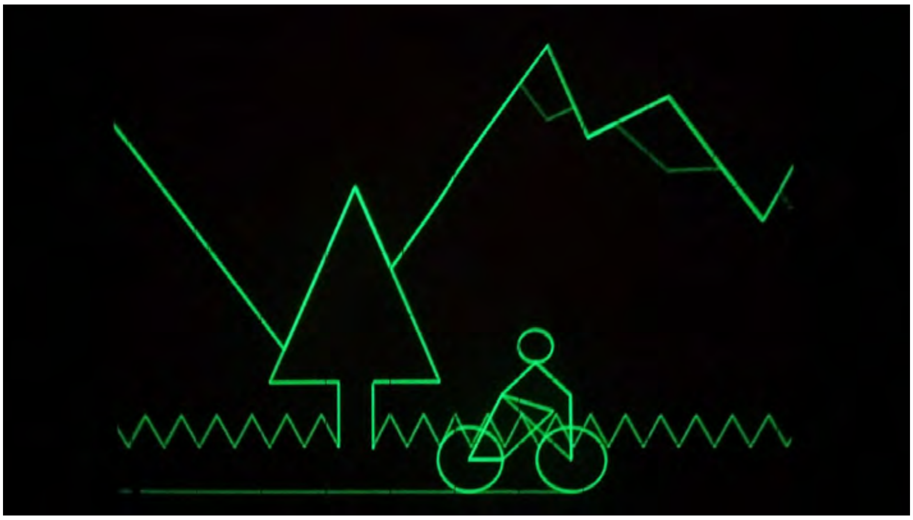

Figure 2.4.6: Oscilloscope Music Kickstarter by Jerobeam Fenderson.

In summary, sound is a versatile artistic medium that inspires new artistic approaches, sonic tools, forms of expression, and ways to connect people. Technologies for generating and visualizing sound allow for a wide spectrum of artistic experimentation, pushing the boundaries of existing toolkits and exploring new sonic territories.

2.4.4 Computers as Musical Platforms

Today, computers such as PCs, laptops, smartphones, and tablets are among the most popular platforms for music production. They are versatile, affordable, and easy to learn, and they can be used for various applications and scenarios.[63] As tools for music production and artistic creation, they can be used for many musical purposes, such as audio recording and editing, creation of multimedia and audiovisual artistic works, composition of computer music, as tools for digital sound synthesis, as musical instruments on stages and in music studios. Last but not least they are also the most popular playback devices for listening to sounds and music, e.g. via music streaming services.

With their rapid evolution and refinement since the 1980s, computers quickly replaced traditional music recording, editing, performing

[61] https://www.xythobuz.de/osci_music_player.html
[62] https://oscilloscopemusic.com/software/oscistudio/
[63] https://www.musicradar.com/tuition/tech/10-good-reasons-to-start-making-music-on-a-computer-178100

and listening practices. They replaced tape recording machines, analog sequencing and composition practices, analog sound synthesis, or physical storage mediums for music such as tapes and vinyl records.[64] Computers such as the Atari ST, the Commodore 64 or the Fairlight CMI provided enough computational power to enable professional music composition through *"tracker"* style sequencer and early music software.[65][66][67][68][69] Computers from that era are still used for artistic and audiovisual works, such as Robert Henke's project *CBM 8032 AV*, in which he re-purposes Commodore CBM 8032 computers from the 1980s for the creation of abstract graphics and sound, and produces audiovisual compositions and live performances.[70] Today, the development of new music software, software instruments, MIDI, sound synthesis algorithms, advancements in computer audio technology and the rise of real-time sound synthesis cemented the role of computers as central musical tool and platform.

A major application for computers in music production is the recording and editing of sound and music, for which a wide range of audio software is available today, that mainly differs in functionality, complexity, user interface and pricing. Free audio editors like *Ocenaudio* or *Audacity* allow recording and editing of single audio files. For more complex projects, a specialized audio software can be used called *Digital Audio Workstations* (DAWs), which allows multi-track audio recording and editing, composition and production of music, the production of sound for video and podcasts, sound design, and more. DAWs are among the most versatile, ubiquitous and widely distributed music software platforms today [Bell and Cali 2015]. A wide range of specialized DAWs covers the needs of professional audio engineers, music producers or live performers alike, e.g. *Pro Tools*, *Logic Pro X*, *Bitwig*, *Studio One*, *Ableton Live*, *Reaper*, etc. (see Fig.2.4.7).[71] Over the last years, a

[64] even tough cassettes and vinyls seem to have a comeback in recent years: https://www.ricable.com/en/ritorno-alle-origini-vinili-e-musicassette-al-top/

[65] https://daily.redbullmusicacademy.com/2017/10/atari-st-instrumental-instruments

[66] https://www.youtube.com/watch?v=OlspnqVcJho

[67] How the Fairlight CMI changed the course of music. https://www.youtube.com/watch?v=jkiYy0i8FtA&t=82s

[68] https://www.soundandrecording.de/stories/daw-history-vom-midi-navigator-zum-audio-allrounder/

[69] https://www.kvraudio.com/focus/the_early_days_of_software_sequencers_15670

[70] Robert Henke - CBM 8032 AV project https://roberthenke.com/concerts/cbm8032av.html

[71] https://www.soundonsound.com/daw-software

number of online web-based DAWs emerged, such as *Soundtrap* or *Audio Tool*, that provide the same functionality and can use the computer audio and controller hardware without being installed locally. Instead they use the web browser as software platform. That enables the users to change computers and to work remotely from different places and still use the same software.[72]

Even though the different DAWs have slightly different designs, workflows and functionality, they all have in common that they enable musicians and audio engineers to record audio and MIDI, to compose tracks and musical pieces, and to edit, mix and produce their own music. Many DAWs come with various different audio effects already built-in that can be used to enhance the audio. Thereby the historical evolution of audio effects as *"controlled transformation of a sound typically based on some control parameters"* is a perfect example of how music technology has borrowed ideas and technological advancements from other fields, and contributed back as *transsectorial innovation* [Wilmering et al. 2020]. For instance, in order to visualize composition and arrangement, DAWs borrow the time-based structure from traditional sheet music. Some DAWs provide additionally grid-based views, e.g. Ableton's *session view*. Direct access to clips, tracks and scenes is especially suitable for musical interaction and the performance of improvised live music in stage-based situations.

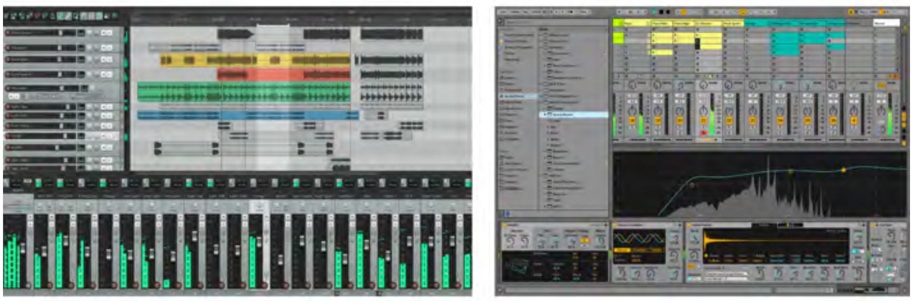

Figure 2.4.7: DAWs: Reaper (left) and Ableton Live (right).

Other music software platforms are more focused on sound synthesis, the generation of computer music and generally for the composition and creation of sound and music. With traditions dating back to the 1960s, programs such as the visual programming language *Max/MSP* or free and open-source *Pure Data* enable the creation of complex multimedia works, both for compositions in the studio as well as for

[72] https://blog.landr.com/best-online-daw/

stage-based live performances including real-time audio synthesis.[73][74] Many of the DAWs mentioned above also provide the means to generate, synthesize and sequence sounds, much like electronic synthesizers and step-sequencers. Most sound synthesis techniques and algorithms including *wavetable synthesis, sample-based synthesis, granular synthesis, physical modeling* and more, are provided either via built-in or via external audio plugins. In addition to the music platforms and DAWs mentioned already, a growing number of experimental and playful music tools are available today, that enable the playful creation of sound and sequences, and inspire artistic exploration, such as the *Hydra Synth* or the *Typatone*.[75][76][77][78][79][80][81][82]

2.4.5 Code as Instrument

Creating music with a computer is possible not only through standard audio editing software, such as GUI-based DAWs, but also through programming. Sound synthesis, musical patterns, sequences, and compositions can be created directly through programming source code. Even though the combination of programming and artistic musical expressions might seem like a contradiction, writing code can also be seen as thoughtful poetry, as *"embodied, sensorial and live technological-human relationship that is recursively iterated through sonic and visual outputs"* based on *"kinship relations between and through bodies and technology."* [Joanne Armitage and Thornham 2021].

Already the earliest computer programs for sound synthesis and composition, namely the *Music N* series programs by Max Mathews starting from 1957, were programmed based on written instructions.[83] Their artistic and technological impact manifested the role of computers as musical instruments and the use of programming languages to describe and perform musical scores, sound synthesis and music composition. As *"father of electronic music"*, Mathews inspired many more musical developments, such as *Csound*, a music computing system based

[73] https://120years.net/music-n-max-mathews-usa-1957/
[74] https://www.musicradar.com/news/early-daws-the-software-that-changed-music-production-forever
[75] https://ojack.xyz/PIXELSYNTH/
[76] http://typedrummer.com/
[77] https://addtexture.com/
[78] https://martinwecke.de/108/
[79] https://www.maxlaumeister.com/tonematrix/
[80] https://typatone.com/
[81] https://www.beepbox.co/
[82] https://webaudiodemos.appspot.com/
[83] https://120years.net/music-n-max-mathews-usa-1957/

on textual programming that was created in 1986 and is still used today [Mathews 1963; Hong Park and Hall 2009; Vercoe and Ellis 1990]. Other music programming platforms descended from Mathews *Music N* series are most notably audio programming languages like *Max/MSP* or *Pure Data* which continued the idea of using a modular system of software unit generators resembling the operating principle of an analog modular synthesizer [Puckette 2002]. Both platforms are used for real-time audio processing, sound synthesis, computer music and interactive multimedia works based on the visual *"patching"* of *"objects"*.[84]

Instead of visual patching of modular units, environments such as *SuperCollider* provide a text-based programming language for real-time audio synthesis and algorithmic composition [McCartney 1996]. Originally released in 1996, James McCartney released it as free software in 2002, which led to an active and enthusiastic international community of artists and researchers, that continues to develop and maintain the software. Based on its dynamic programming language, *SuperCollider* provides a framework for acoustic research, algorithmic music and interactive programming.

Using programming code as a musical instrument started to gain attention in the beginnings of the 2000s with the first attempts of live programming of generative music on stage. This process and artistic practice is also called *live coding*, often referred to as the process of editing and interpreting the source code of sound synthesis software in order to modify the running process in real-time [McLean 2014]. With the efforts of early pioneers such as Adrian Ward and Alex McLean and their music project *slub*, with artists like Julian Rohrhuber who provided the first attempts of *just-in-time* (JITLib) sound programming with *SuperCollider*, with the formation of the TOPLAP community platform and numerous meetings, live performances, the success of *Algorave* events, etc. the practice of live coding and the *on-the-fly* generation of music became an established art form on its own.[85] Practitioners like Sam Aaron, Nick Collins, Shelly Knotts, Alberto de Campo, Fredrik Olofsson, Thor Magnusson, Eli Fieldsteel, and many more continuously work on new artistic pieces and performances, they further develop various live coding platforms, teach live coding through workshops and online tutorials, and contribute with numerous scientific publications in journals and conferences such as the *Computer Music Journal*, the *International*

[84] Interview with Miller Puckett on Max/MSP & Pure Data. https://futureofcoding.org/episodes/047.html

[85] https://toplap.org

Conference on Live Coding (ICLC) or the *New Interfaces for Musical Expression* (NIME) [Alan F Blackwell et al. 2022; A. Blackwell and N. Collins 2005; Magnusson 2011; Aaron and Alan F. Blackwell 2013; Nick Collins and McLean 2014; Magnusson 2014; Jack Armitage et al. 2023; Aaron 2016].

Among the many live coding platforms that are used today for composition and performance are environments such as *ChucK*, *Tidal Cycles*, online web platforms such as *Gibber* and *Punctual*, esoteric programming languages like the procedural sequencer *ORCA*, to only name a few. An extensive collection of live coding environments, libraries, tools and talks by the developers and artists can be found in a curated list by TOPLAP.[86] Many of those live coding languages focus on professional computer music composition and live performance, other environments are developed as artistic tools for music education and beginners, such as the live coding environment *Sonic Pi* (see Fig.2.4.8) [Aaron and Alan F. Blackwell 2013]. The *Sonic Pi* software can serve as a platform to learn coding by composing or performing music, it can be used for music sessions in schools, as accessible music tool for VIB musicians, but also as tool for professional musicians and DJs.

Figure 2.4.8: Sonic Pi - live coding environment by Sam Aaron.

With the rising success of live coding and the interest in collaborative performances, developers turned towards web technologies as a platform for live coding system. Web technologies offer new possibilities for software design and music making, such as sufficient performance, portability for mobile and desktop devices and longevity due to

[86]https://github.com/toplap/awesome-livecoding

standardization. Mulshine et al. brought the *ChucK* music programming language to the web as *WebChucK*, which was possible due to advancements in browser technology including WebAssembly and the Web Audio API's *AudioWorklet* interface [Mulshine et al. 2023]. The main advantage of browser-based music environments such as *Estuary*, *Livecodelab* or *Gibberish* is the *"zero-installation"* approach, which circumvents cumbersome software installation experiences and restrictions, especially in educational environments like schools and universities. In addition, web browser provide strict security measures to protect computers and personal information and thus give an extra measure of confidence [Roberts et al. 2013; Ogborn et al. 2017].

Today, after two decades of research and artistic creation, *live coding* is an established art form, that is used not only for musical and audiovisual live performances, but also for experiments on new instruments, digital art, computer languages, HCI and pedagogy. It also inspired and stimulated the interest of electronic musicians to rethink the role of computers in music-making setups, in particular because of its flexible approach towards music production and its open-source background and FOSS (Free/Open Source Software) communities [Forment and McLean 2022].

2.4.6 Interfaces for Musical Expression

The use of computers as platforms for musical expression is not only limited to the use of music software such as DAWs or audio programming platforms. In parallel to early advancements in the fields of computer music software and sound synthesis algorithms, the pioneer Max Mathews developed the *Radio Baton* (1987) as an external musical interface that extended the existing computer hardware and allowed the control of musical parameters for computer-aided live performances [Mathews 1963; Mathews 1991]. In combination with the according music software *Conductor* and its improvisational options such as precomposed sequences, random functions and live performance gestures, the *Radio Baton* provided the means to interpret and perform traditional scores as a soloist.[87] This interactive extension to the traditional computer hardware together with its computational flexibility marked the starting point for an ongoing exploration of new digital musical interfaces, that combine musical computing with interactive physical control, and enable musicians to not only create new music, but to envision new musical interactions and to adapt them to their artistic and bodily needs.

[87] https://ccrma.stanford.edu/radiobaton/

With the rise of new technologies, ubiquitous and mobile computing platforms, new innovative sensors techniques, and powerful music computing platforms, the ideation and development of new interfaces for music and sound creation by artists and instrument makers accelerated even more. Various single-board micro controllers such as Arduino, Teensy, ESP32, Bela or Raspberry Pi are affordable, available and offer enough computational power to be used for musical instruments and enable the exploration of musical interaction. A wide variety of sensors, ranging from simple motion sensors to biometric sensors, enables the detection of bodily movement, the sensing of the environment, or measuring the behavior of the audience in a performance, which inspired numerous new musical expressions and interactive experiences.[88] The spectrum of artistic projects ranges from musical interfaces to sonic sculptures or tangible sequencers. Marco Donnarumma developed the *Xth Sense*, a wearable hardware sensor device for capturing biological body sounds and the use of muscle sounds for musical performances. Other works are Alberto Boem's innovative *Sculpton*, a malleable tangible interfaces that allows sound sculpting, Beat Rossmy's *StringTouch*, an interfaces that explores strings as metaphors for tactile musical touch interaction, or Patricia Cadavid's *Kanchay_Yupana*, a tangible musical sequencer based on the Abacus-like computation of the traditional Andean *yupana* (see Fig.2.4.9). [Donnarumma 2011; Boem 2014; Rossmy et al. 2021; Hinojosa 2022].

Figure 2.4.9: *Kanchay_Yupana* by Patricia Cadavid (2022).

[88] https://jerwoodvisualarts.org/digital-art-and-technology-glossary/sensor-based-art

2.4.7 *Accessible Computer Music for VIB producers*

Despite all the technological advancements and artistic possibilities, VIB musicians still face accessibility barriers when working with digital music technology. The barriers are mainly due to the vision-centric interface design of digital hardware synthesizers, sequencers or other audio gear, that is designed based on graphical representations, displays or visual feedback through LEDs. While traditional music studios a few decades ago provided big consoles with buttons, knobs and dials, today's music production has become digital and therefore much more visually orientated.[89] Computers as digital music environments offer many benefits since they are versatile, affordable and powerful musical platforms, but in order to work with audio and music software, VIB musicians depend on assistive technology such as screen readers or screen magnifiers for accessing and interpreting visual content and navigating the software (see Chapter 2.2.4). The various software and hardware elements incorporated by VIB musicians in their creative workflow can be summarized as accessible music technology (AMT). They are parts of a whole artifact ecology. These setups include mainstream music software and hardware, additional open-source software extensions and scripts, and other systems or devices that support the accessible digital music making [J. Harrison et al. 2023; Bødker and Klokmose 2011].

The main software platforms for accessible music making are DAWs (see Chapter 2.4.4). They enable audio production including recording, editing or mixing, as well as reading and composing of written music through notation, and obtaining accessible scores. In addition, DAWs can be used for instrumental or vocal live performances. Unfortunately, the workflow of most DAWs is dominated by visual representations and graphical user interfaces, e.g. audio waveforms that show the frequency and amplitude, automation graphs for parameter changes, regions of audio and MIDI in the timeline, visual interfaces for audio plugins, etc. There are no standardized low vision or non-vision equivalents for music making with DAW [W. C. Payne et al. 2020].

Among the many available DAWs, only a small number provide sufficient accessibility features and screen reader support to be usable for VIB musicians. After a series of interviews with VIB music producers, Jakub Pešek summarizes that DAWs like Pro Tools, Logic, and Reaper are mostly accessible for VIB users, even though the workflow is slower and less efficient then for sighted users. Less common is the use of

[89] https://www.fastcompany.com/91025338/the-quest-to-build-more-accessible-music-tech-for-blind-and-visually-impaired-artists

DAWs such as Cakewalk Sonar[90], FL Studio or Samplitude [J. Harrison et al. 2023]. Not accessible at all are DAWs like Ableton Live, Nuendo or Cubase, even though the developers of Ableton recently announced accessibility features and screen reader support for the latest iteration Ableton Live 12 [Pešek and De Man 2021].[91] Overall, accessibility barriers of DAWs still hinder VIB musicians to achieve their musical goals.

To support the workflow with DAWs, various workarounds and third party scripts are available that increase their accessibility, e.g. Flotools for Pro Tools or OSARA for Reaper.[92][93] These scripts allow to control non-accessible audio plugins by directly triggering their parameters, among other functionality such as additional shortcuts or menu access. An accessible tool for sound synthesis is the free and open-source *Surge XT* hybrid synthesizer plugin, which took accessibility into account from the very beginning of its development.[94][95] A valuable resource for VIB musicians is the *"Audio Plugin and Instrument Accessibility Catalog"*, a database of audio plugins, both instruments and effects, as well as sample libraries and their accessibility status, which is maintained by Toni Barth.[96] Other means to support accessible *music-making* are external hardware tools such as motorized fader controllers that allow remote and interactive control of DAWs. Likewise, few MIDI keyboards such as Native Instrument's *Komplete KONTROL* provide accessibility features.[97] In addition to audio production and music making with the DAW, various programs allow accessible music notation and composition in Braille, such as *MuseScore*, *Sibelius* on Windows, *Symphony Pro* for iPhone and iPad, or *Goodfeel* by Dancing Dots.[98][99][100][101]

A big challenge for VIB musicians remain non-accessible graphical information such as audio waveforms, automation graphs or equalizer curves. To address these accessibility barriers various research projects attempt to substitute graphical information with audio, tactile or haptic

[90] https://www.afb.org/aw/2/2/15042
[91] https://gb.readly.com/magazines/computer-music/2024-02-21/65cf35ee6a9169737156f170
[92] https://flotools.org/
[93] https://osara.reaperaccessibility.com/
[94] https://www.kvraudio.com/forum/viewtopic.php?t=579136
[95] https://surge-synthesizer.github.io/
[96] https://timtam.github.io/musicalsight/
[97] https://emastered.com/blog/best-daw-controllers
[98] https://musescore.org/
[99] https://www.avid.com/sibelius
[100] https://symphonypro.net/
[101] https://dancingdots.com/main/goodfeel.htm

representation, e.g. *TouchEQ*, *HaptEQ* or the *Haptic Wave* [Pešek and De Man 2021; Karp and Pardo 2017; Tanaka and Parkinson 2016]. Other attempts to use the computer as accessible music platform are projects like the *Sound Cells*, a software that renders visual and Braille music in the browser, or the accessible redesign of the popular browser-based sequencer *Groove Pizza* [Ahmed et al. 2021; W. Payne et al. 2019].[102]

But access is not just limited by technology, as Harrison et al. point out. VIB musicians often use broader creative ecosystems beyond physical artifacts, MIDI controllers or software tools. Many rely on the help of online communities, mailing lists or online tutorials to improve in using their instruments, to solve problems or to keep updated on new developments, e.g. for *Reaper without Peeper*, *Logic Accessibility google group* or the *MIDI Mag mailing list*.[103][104][105] These online communities often compensate the absence of support by the mainstream music technology industry [J. Harrison et al. 2023].

Support and educational material for the exploration of technology and digital audio production is also provided by a number of institutions and platforms, such as *Recording Artists and Music Professionals with Disabilities* (RAMPD), *Drake Music*, the research project *Performance without Barriers*, the *Sound Without Sight* initiative, the *OHMI Trust*, the conference *Music & Physical Disability* and resources such as podcasts or video channels.[106][107][108][109][110][111][112][113] A recent attempt to improve this situation is the proposal of a *Music Accessibility Standard* (MAS) to raise awareness for accessibility in collaboration with music technology manufacturers and the MIDI Association.[114][115]

[102] https://apps.musedlab.org/groovepizza/
[103] https://groups.io/g/rwp
[104] https://groups.google.com/g/logic-accessibility
[105] https://www.freelists.org/list/midimag
[106] https://rampd.org/
[107] https://www.drakemusic.org/
[108] https://performancewithoutbarriers7.wordpress.com/
[109] https://soundwithoutsight.org/mission/
[110] https://www.ohmi.org.uk/
[111] https://www.ohmirp.org.uk/ohmiconference.html
[112] https://takeitaway.org.uk/bridging-the-gap/
[113] german DAW tutorials: https://www.youtube.com/@patrickenzo618/
[114] https://www.kvraudio.com/forum/viewtopic.php?t=579136
[115] https://midi.org/music-accessibility-standard-special-interest-group-youtube-event

2.4.8 Accessible DMIs

An attempt to develop accessible tools for music-making is the exploration and design of *accessible digital musical instruments* (ADMIs) in order to support persons with impairments both in their artistic practice, as well as to provide tools for rehabilitation, social inclusion, personal expression, physical and psychological wellbeing [Davanzo and Avanzini 2020; Farrimond et al. 2011; Samuels 2019].

Thereby the design of ADMIs is often based on the concept of *digital musical instruments* (DMIs), a genre of musical instruments that embraces technological advancements, computational power and expressive interaction, and therefore offers the potential to increase accessibility compared with traditional instruments. The engineer and electronic music pioneer Robert Moog saw DMIs as modular systems that consists of three parts: *"the sound generator, the interface between the musician and the sound generator and the tactile and visual reality of the instrument that makes a musician feel good when using it."* [Moog 1988]

Various different terms are used to describe ADMIs, that differ depending on their contexts, use cases and target groups. While the expression *Accessible DMI* focuses on professional digital music making and the performer experience, researchers like Emma Frid use a more open definition of ADMIs as *"accessible musical control interfaces used in electronic music, inclusive music practice and music therapy settings."* [Zayas-Garin and McPherson 2022; Frid 2019] Other definitions and expressions that are used to describe ADMIs are terms like *assistive music technology* or *adaptive music technology*. As Davanzo et al. point out, these definitions carry different meanings, as the term *assistive* implies an external technology that supports a disabled person, such as TTS for reading text, while the term *adaptive* emphasizes the adjustment of the instrument to the musician and the context, e.g. providing multi-modal output of information. In this regard, and with a focus on inclusion and *universal design*, the notion of adaptability remains a focus of *Accessible DMIs* [Davanzo and Avanzini 2020].

Harrison and McPherson further specify *accessible instruments* into two categories: those that are used for virtuosic or masterful performances by physically disabled musicians, which they call *performance-focused instruments*. Secondly, they describe instruments designed for *non-musicians*, that focus on therapeutic or wellbeing aspects for disabled people with physical and cognitive impairments and learning difficulties, which they call *therapeutic instruments* [Mcpherson et al. 2019].

Nonetheless, it is not only the technological adaptation, that makes musical instruments and platforms accessible, as Koichi Samuels describes after a series of workshops at the *Drake Music Project*: *"Throughout my study I found that it was not in the design of music technology devices that made them accessible. Rather, meaningful music-making emerged through the interrelations between the access music tutors, workshop participants and the music technology interfaces in the workshop environment."* [Samuels 2019]

The field of existing ADMIs is heterogeneous and facilitates many different technologies and instrument designs. Projects like John Kelly's *Kellycaster* adapts existing instruments to meet access needs and musical ambitions.[116] Various ADMIs have already been mentioned above, such as the *Eyeharp*, a gaze-controlled digital step-sequencer with melody overlays, the *PebbleBox and CrumbleBag* by Essl and O'Modhrain, or step-sequencers such as the *Beatbearing* by Peter Bennett and the similar *LoopBlocks* project, which both are based on physical tokens [Vamvakousis and Ramirez 2016; O'Modhrain and Essl 2004; Bennett and O'Modhrain 2008; Förster and Komesker 2021]. A number of ADMIs are commercially available, among them the *Skoog*, a low cost tangible pressure- and deformation sensitive cube for persons with cerebral palsy (see Fig.2.4.10), touch free interfaces such as the *SoundBeam* or *The Beamz*, as well as breath-controlled interfaces such as the *Magic Flute* and *Groovtube*, or the touch sensitive and breath controlled *Touch Chord* (see Fig.2.4.11) [Frid 2018].[117][118][119][120][121][122]

A characteristic of ADMIs is their attempt to provide access to the creation of sound and music to the various target user groups by facilitating a wide range of different control interfaces, sensor technologies, sound synthesis strategies and various output modalities, as Emma Frid describes in a survey on inclusive instruments and in a subsequent systematic review [Frid 2018; Frid 2019]. According to the analysis of 83 ADMIs in Frid's systematic review, a variety of different control interface categories could be identified, such as tangible controllers, touchless controllers, adapted instruments, Brain–Computer Music Interfaces (BCMIs), gaze controllers, touchscreen controllers, audio con-

[116] https://www.drakemusic.org/technology/instruments-projects/the-kellycaster/
[117] https://www.perkins.org/resource/skoogmusic-accessible-music-technology/
[118] https://www.soundbeam.co.uk/
[119] https://www.afb.org/aw/15/11/15620
[120] https://housemate.ie/magic-flute
[121] https://housemate.ie/groovtube/
[122] https://www.humaninstruments.co.uk/instruments

Figure 2.4.10: *Skoog*

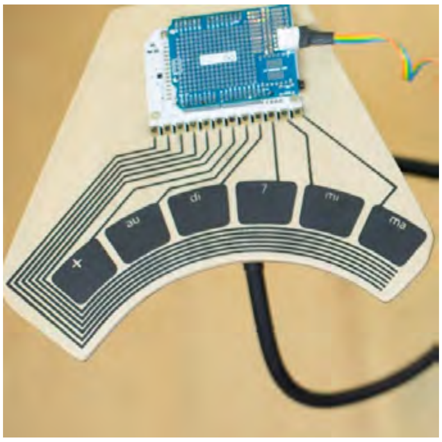

Figure 2.4.11: *Touch Chord*

trollers, mouth-operated interfaces, wearable controllers and prosthetic devices, and mouse-controlled interfaces. Among the most frequently used sensors were touch sensors, followed by accelerometers, various cameras, and microphones. The most used actuators were solenoid motors, motorized faders, vibration actuators, and vibration loudspeakers. Regarding the output modalities, a total of 39 (47.0%) ADMIs presented unimodal feedback, which was mainly sound, except one instrument that provided only vibratory feedback. Another 40 ADMIs (48.2%) presented bimodal feedback, of which 33 were auditory-visual, and 7 were auditory-vibrotactile. Only 4 (4.8%) instruments presented trimodal feedback with auditory, visual, and vibrotactile feedback channels. Frid summarizes, that the majority of the analyzed 83 ADMIs were instruments based on tangible or physical controllers. Relatively few ADMIs incorporated vibrotactile feedback, although haptic interaction could be an important modality for music making for many target user groups. But more importantly, although the ADMIs were developed for various user groups with physical impairments, for young users and children, only 3.6% ADMIs focused on persons with visual impairments [Frid 2019].

This means that despite numerous existing ADMIs available for various user groups, the number of *Accessible DMI* for VIB musicians is relatively small, which narrows the focus towards two possible routes for accessible music-making, which is firstly the use of acoustic instruments such as piano or guitar, and secondly the use of computers and accessible music software and hardware as platforms for digital music-making.

2.4.9 *Discussion: Haptic Wave*

An exemplary device for VIB audio producers, that enables cross-modal mapping of digital audio to the haptic domain, is the *Haptic Wave* developed by Tanaka and Parkinson (see Fig.2.4.12). The project addresses the editing process of digital audio, including basic time domain editing, cutting and splicing, sound detection or the precise definition of loops in rhythmic musical timing. It centers around computer-based digital audio editing that has become the standard in today's music production, and which is largely based on the interaction with a visual representation of the audio as waveform in the GUI. Physical interactions with audio on magnetic tape are now obsolete, even though many of the metaphors like *"scrubbing"* or *"cutting"* are still being used. However, the visual waveform display and graphical audio editing is not accessible to VIB producers, which led to the attempt of cross-modal mapping, in which the visual modality is substituted by the haptic domain in order to enable VIB producers to *"feel the sound"* [Tanaka and Parkinson 2016].

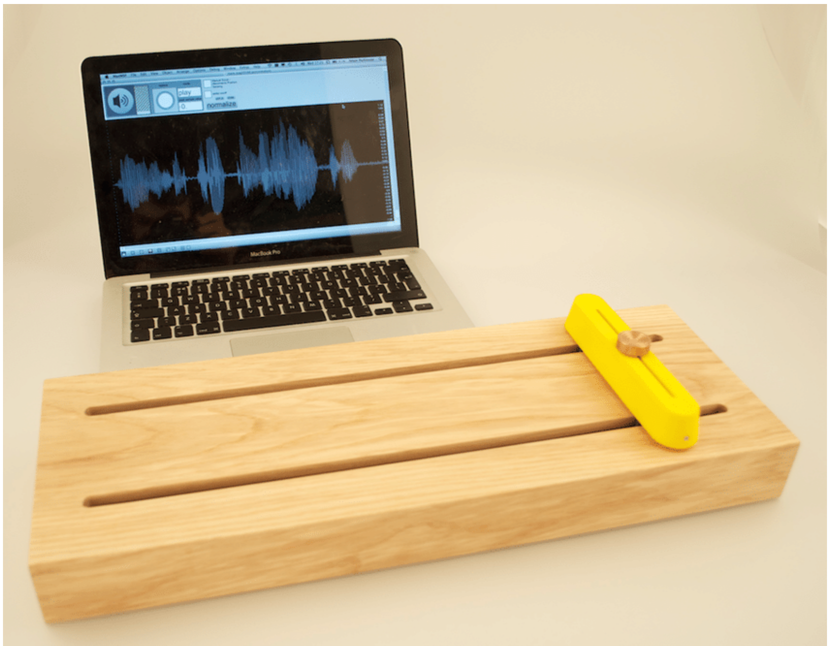

Figure 2.4.12: Haptic Wave interface by Atau Tanaka and Adam Parkinson.

Tanaka and Parkinson developed the *Haptic Wave* during multiple workshops and studio session with VIB audio producers, and through an iterative and user-centered design process. The interface provides a carriage handle with an vertically embedded motorized slider that enables force feedback. By moving the carriage handle horizontally, the cursor position of audio files in the time domain can be changed, while the vertical slider provides information on the amplitude, with additional force feedback indication when the amplitude rises up. The device was used to perform typical audio editing tasks like inspecting audio waveforms, finding silences or identifying start and ends of desired portions of a sound recording.

Through the various tests and studio sessions, the *Haptic Wave* project successfully demonstrated that the mapping of visual information of standard graphical audio editing tools to a sensory haptic domain is possible, and moreover is appreciated by practicing VIB audio producers as an intuitive extension of the audio editing work flow. With its kinesthetic display and direct sensory mapping of audio to the haptic domain, it enables direct manipulation and tactile interaction with the audio content, and even though it takes time to learn, users confirm its intuitive usage.

2.4.10 Discussion: HaptEQ

Another research project centered around the digital audio production of VIB producers is Aaron Karp and Byran Pardo's *HaptEQ*, a tactile interface that focuses on audio equalizers (see Fig.2.4.10). Professional audio production for high quality music recordings, radio broadcasts, podcasts or video includes the processing of audio tracks with signal processing tools like compressors for amplitude control, effects for reverberation or equalization. Accessibility barriers due to the focus on graphical displays and visual representations of effect settings in DAWs exclude VIB producers from an intuitive access and audio effects workflow.

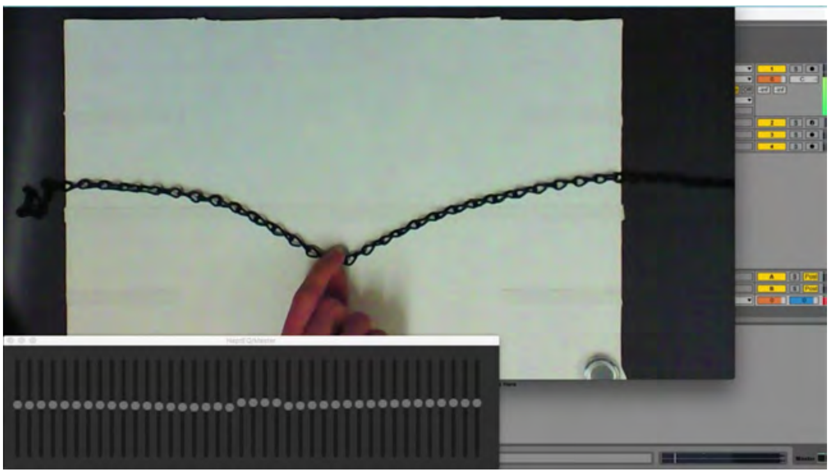

Figure 2.4.13: HaptEQ by Arron Karp and Bryan Pardo (2017)

In this research projects, the authors focus on parametric audio equalizers as tools for mixing and mastering, that affect the timbre of a sound or can be used for boosting or cutting the level of specified frequencies in the spectrum. The visual representation of a parametric equalizer in DAW software has the shape of a curve, ranging from the low frequencies on the left towards the high frequencies on the right. Karp and Pardo transferred this visual representation of an equalizer curve into the physical domain by using a flexible chain on a plain underground, that can be used to form different shapes of the equalizer curves. By using a camera mounted above the setup together with computer vision software, the shape of the chain can be translated into an equalization curve and send to a custom DAW equalizer plugin. VIB audio producers could *"feel"* the equalizer setting through tracing the chain with their fingers and were able to change the settings by rearranging the chain in order to draw a new equalizer curve [Karp and Pardo 2017].

The projects demonstrates, how VIB producers in the context of digital audio production and music composition can benefit from haptic interaction through the transfer of visual representations to the physical domain, and how the use of flexible physical materials and shapes can support haptic perception as complementary modality to sight and vision.

2.5 SUMMARY

The chapter introduced the computer as an artistic tool and musical instrument for expressing artistic vision and realizing various forms of digital music-making. It discussed human-computer interaction modalities and the historical focus on graphical representation. It also addressed how vision-centric software and hardware design excludes groups of computer users with disabilities, particularly those with visual impairments or blindness. The chapter presented related assistive technology, such as refreshable Braille displays and screen reader software. Together with the respective music software's accessibility features, this technology enables VIB musicians to benefit from digital music technology. Additionally, it presented a number of haptic interfaces that enable accessible digital music production using computers.

As a key topic, this chapter introduced tangible musical interaction, which links the digital and physical domains to enhance the bandwidth, tactility, and intuitiveness of computer interaction. It demonstrated how this could potentially be an interesting means of accessible digital music-making, despite the fact that there is only very limited research and knowledge on this topic. Finally, it introduced various aspects of sound as an artistic medium, as well as the practice of digital music-making, including an exploration of digital music technology, its music software, and its control hardware. The implications for visually impaired or blind musicians were then outlined. Furthermore, the use of programming code for music composition and performance was discussed. New interfaces for musical expression and various haptic interfaces and DMIs for accessible digital music-making were presented and described.

Chapter 3

Practical Work

This chapter presents the practical work and activities realized as part of the research project, which aimed to investigate and answer the posed research questions. First, it describes the initial research proposal, which focused on developing a multifunctional tangible prototype to enable investigating tangible interaction as an accessible means of digital music-making. The chapter then describes the initial lectures and workshops at the Institute for the Blind in Vienna and explains how the research proposal was adapted to the needs and circumstances of the pupils. Next, it presents the iterative development of accessible text-based music software, documenting the software components and practical experiences in detail. Then, it describes the iterative and user-centered development of three tangible musical interfaces in detail, including sonic features, technical implementations, schematics, and components. Meetings with VIB experts and musicians during development to inquire about the tangible interfaces are also documented. Lastly, the chapter presents the artistic staging of the tangible interfaces in collaboration with blind expert and musician Erich Schmid. Schmid used the devices to compose a musical piece, which he presented during a live stage performance.

3.1 PROPOSED ACTUATED INTERFACES

The research project initiated with the attempt to investigate HCI modalities such as *tangible interaction*, *haptic interaction* and *multimodal interaction* as means for musical interaction for VIB users. The main target group of the research project are VIB musicians, both professional composers and musicians, as well as non-trained beginners in digital music-making. Thereby the main focus was on *tangible interaction* and the attempt to access digital data through its physical representations. Since no suitable tangible interface were commercially available, the research proposal intended the iterative development of a custom tangible user interface, that is both able to physically represent digital musical data, and also provides physical control and haptic feedback (see Fig.3.1.1).

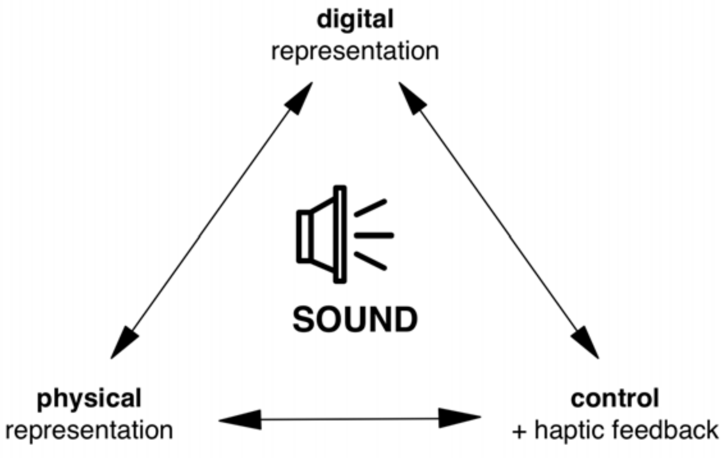

Figure 3.1.1: Digital and physical representations and their respective control for the creation of sound and music.

A key aspect of the proposed concept for the tangible prototype was the use of actuation and motorization. Inspired and encouraged from existing motorized control surfaces and actuated pin-based interfaces such as refreshable Braille displays, a physical configuration based on actuated components seemed suitable as a means for tangible interaction and accessibility. The design of the prototype centered around the adaptation of existing of-the-shelves motorized control surfaces, that would be modified in order to perform different tasks, e.g. connecting the fader heads with an elastic string to increase tactile access. Two application scenarios were proposed that utilize the motorized device both as an *tangible equalizer* and as a *tangible wavetable synthesizer*, which are both advanced sonic concepts in the field of audio production and digital music-making. This proposal presupposed an existing artistic practice of the participating VIB musicians, including basic knowledge of digital music technology, as well as audio theory on synthesis and audio effects.

3.1.1 Tangible Equalizer

The first proposition for the exploration tangible musical interaction was the *tangible equalizer*, an interactive prototype to explore equalizers and sound filtering in the DAW. The concept was inspired by research projects such as the *Haptic Wave* or the *HaptEQ*, that both explore the cross-modal mapping of digital audio data in the physical domain [Tanaka and Parkinson 2016; Karp and Pardo 2017]. In order to physically represent the settings and curve of a graphic equalizer, the prototype design proposed the use of 40 motorized faders and suggested an elastic band that connects the moving heads of the individual faders in order to convert virtual graphs to physical curves, as well as to provide tactile orientation (see Fig.3.1.2).

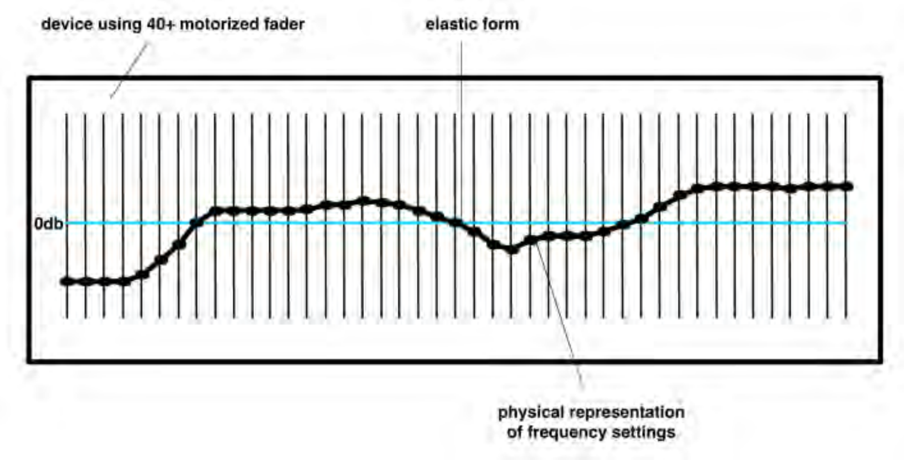

Figure 3.1.2: Prototype design of the *tangible equalizer*.

3.1.2 Tangible Wavetable Synthesizer

As a second application scenario, the design of a tangible *wavetable synthesizer* was proposed. This design would use the same prototype, including the 40 motorized faders and the elastic band. In this scenario, the device could be used to draw different shapes of waveforms in order to generate *wavetable synthesis*. Therefore the prototype could be used to represent the current waveform, as well as to physically manipulate and change the waveform, which affects both the resulting sound, as well as the digital model (see Fig.3.1.3). The concept of using a device with multiple motorized faders as a wavetable synthesizer is inspired by Seth Kranzler's *Wavetable Synthesizer*. Kranzler focused on externalizing and controlling digital *wavetable synthesis*. His interface provided additional abilities such as to zoom in and out of a waveform, to control the envelopes and to interact with other parameters of the synthesis process.[1]

[1] https://sethkranzler.com/wavetable-synthesizer/

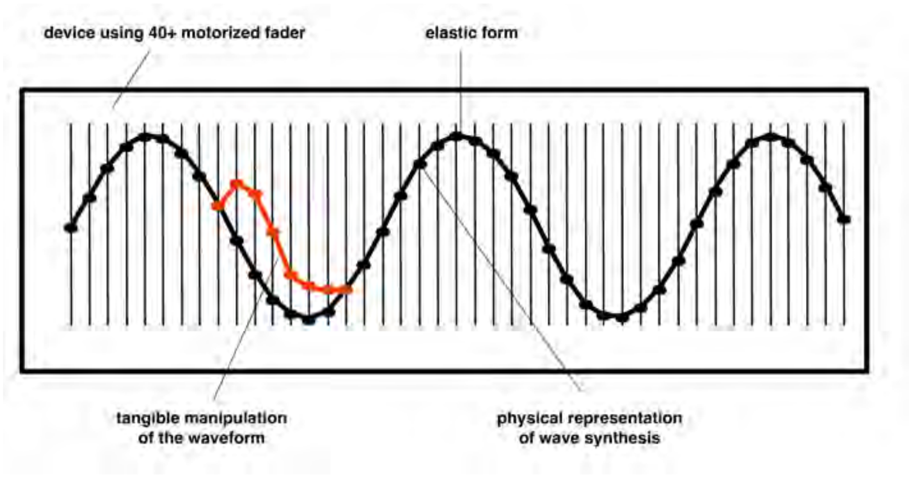

Figure 3.1.3: Prototype design of the *tangible wavetable synthesizer*.

3.2 WORKSHOPS AND WAVEFORMS

The practical work of the research project started with a series of workshops at the BBI Vienna on the topic of audio theory, sound synthesis and music. In collaboration with Erich Schmid, the workshops were embedded in the existing classes *Kreatives Gestalten* at the *Polytechnische Schule*. The classrooms were equipped with computers and Braille displays. The participants of these initial workshops were six pupils aged 10 to 14 and their teacher Erich Schmid.

3.2.1 Introduction of Digital Music Concepts

The initial workshops aimed to explore the pupils' individual musical backgrounds, experiences with digital music-making, and musical interests. The workshops were also intended to introduce core concepts of digital music-making, sound synthesis and audio editing. Teaching materials were manufactured to illustrate these theoretical aspects, such as a wooden plate showing an overview of tactile waveforms, e.g. sine wave, sawtooth wave, triangle wave (see Fig.3.2.1). The tactile waveforms were intended to prepare the pupils for the interaction with the proposed prototype, which was centered around the interaction with graphs and waveforms.

During the initial meetings with the pupils and Erich Schmid, it became clear that, despite having received previous musical education and having learned to play acoustic instruments such as flutes, pianos, and guitars, none of the pupils had experience using computers for music-related activities, such as recording audio through a microphone. Computers were not part of the pupils' musical practice in general,

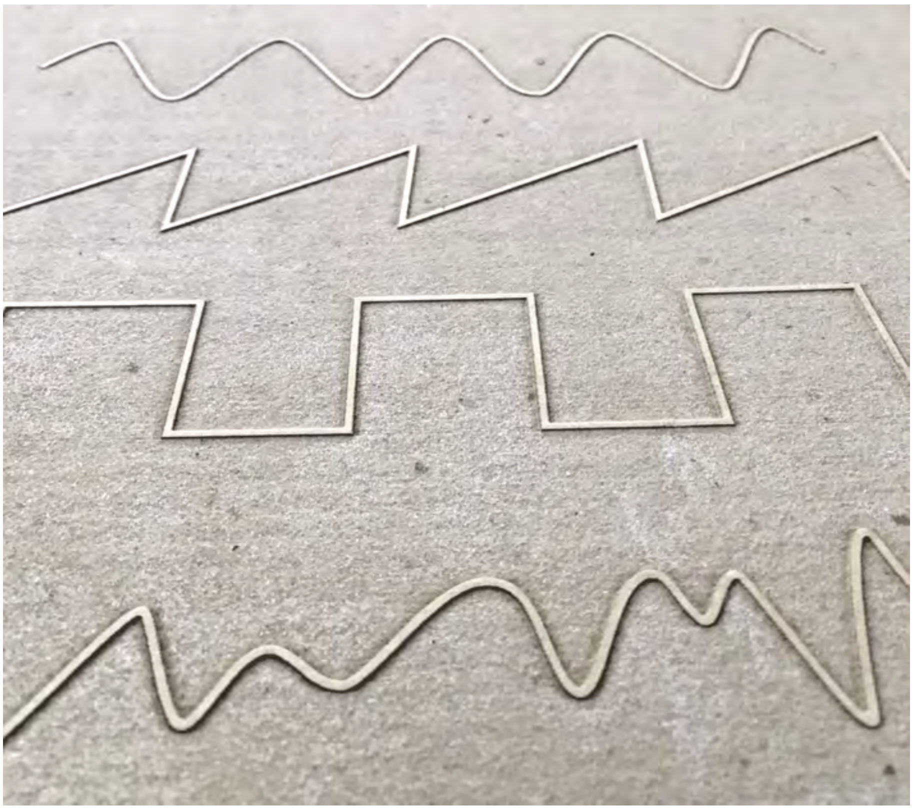

Figure 3.2.1: Tactile waveforms - workshop material for introduction to electronic music.

whether for composing music digitally or performing on stage with music software.

3.2.2 Accessible Music Software

Due to the pupils' lack of experience with music software, the practical work of the research project involving the introduction of music concepts as preparation for further exploration had to pause. Realizing that none of the VIB participants were experienced with using computers for music-making, composition, or performance led to a critical reconsideration of the initial research proposal. Developing a multifunctional tangible prototype to investigate tangible interaction in the context of accessible digital music-making did not seem like an appropriate initial step in the research process. The author believes that participants should have experience with digital music-making before participating in an investigation of physical musical interaction with computers because their experience will likely influence their perception and feedback regarding the effects of tangible interaction. Therefore the next step within the research project was to find and introduce a suitable accessible music software, and to enable digital music-making for the VIB participants, ideally by using a music platform that allows an interactive and performative use of the computer as a musical instrument.

The search for a suitable music software presented hurdles. None of the participants was aware of an accessible music platform that could be used for the workshop sessions. Additionally, installing new software on the school computers required significant technical and organizational effort. Existing DAWs such as *Reaper* or *Pro Tools* seemed to be to complex for beginners, and are also more geared towards audio recording, composing and mixing, than on interactive and performative musical expression. Other audio software such as *Audacity* or *Ocenaudio* do not provide the musical depth to be used as interactive and performative means of digital music-making, since they are primarily digital audio recorders and basic editors.

Online music platforms were taken into consideration as a feasible workaround, since they can be used directly in a web browser, without installing any software on the school computers. Various different online platforms were taken into closer consideration, among them web-based DAWs and various playful music apps.[2] Also online live coding environments were considered, since many live coding platforms are interactive and performative, despite a potential steep learning curve.[3][4][5] Numerous different web-based music platforms were tested during the following classes on the school computers, but unfortunately none of them was accessible [Vetter 2020].

3.2.3 Sonic Experimentation

The lack of a suitable accessible music software resulted in the decision to develop a custom music environment. The development began with a series of experiments in which pupils explored the interactive and performative control of sound and music based on text commands. A simplified, static website allowed the pupils to play back samples by entering commands into a text input field. The website provided multiple sub pages to access different musical instruments on each sub page, such as *bass*, *drums* or *vocals* (see Fig.3.2.2). The respective input fields allowed to enter predefined selection of text commands, e.g. *start*, *stop* or *play*, which subsequently started or stopped the according sample loop. To explore music-making through participatory

[2]https://blog.landr.com/best-online-daw/
[3]https://livecodelab.net/play/
[4]https://dktr0.github.io/Punctual/
[5]http://slang.kylestetz.com/

group experiences, each student was asked to choose a sound and play it by activating and deactivating sample loops. This resulted in playful, musical group improvisations.

Figure 3.2.2: Sonic experimentation. Display of various pages of an experimental website, that allows to select and control the playback of various sample loops with text commands, e.g. pads, bass or vocal samples.

The feedback received during the discussions and observation of the experiment confirmed that the pupils could use the computer as a musical platform and that the availability of tools, such as the musical test website, would encourage and motivate them to create more digital music. This observation encouraged the decision to develop a web-based music environment that is both accessible and can be used within the research project as a musical education platform and an environment suitable for exploring tangible interaction.

3.3 WEB-BASED MUSIC ENVIRONMENT

The following section describes the iterative development of the accessible music environment. This software development became necessary since there was no suitable, accessible software platform for digital music-making available to adequately conduct the research project, as described above. The section presents underlying musical concepts, technical frameworks, programming language, and interface design. It also summarizes the practical use of the music environment and the results of workshops and expert inquiries. The source code for the music environment can be found on Github,[6] while the application itself is available online under https://welle.live.

[6]https://github.com/JnsVttr/Welle

3.3.1 Requirements

During the previous experiments on web-based music-making with VIB pupils at the BBI Vienna, a number of basic requirements were identified that should inform the development of a suitable accessible musical environment. To ensure their adequate implementation, the development process should be accompanied by regular inquiries and feedback from VIB musicians. The following requirements served as a guideline for the development of the web-based music environment:

- **Zero-install.** The platform should follow a zero-install paradigm by using web technologies, in order to be used on computers in the school or at home without the need of any software installation.
- **Accessibility.** The software should be accessible by design, following the principles of *universal design*. Graphical representations for relevant information, menus or other control elements should be avoided.
- **Textual.** Based on previous experiments, using textual interaction based on a predefined set of commands seemed adequate. Therefore, the focus on textual interaction should be retained, and a set of easy-to-understand, meaningful commands and parameter controls should be provided.
- **Real-time.** The music platform should enable interactive and improvised music-making with just-in-time programming capabilities. It should enable low-latency performance and real-time interaction.
- **Playful.** The music environment should balance musical depth and direct musical expressions in order to provide both playfulness and expressivity for beginners and professionals. It should serve as an educational tool to explore and teach aspects of electronic and digital music.
- **Interface.** The platform should allow interactive communication and control of external music hardware such as tangible musical interfaces. It should therefore integrate communication protocols such as MIDI to send and receive control signals.
- **Network.** For the participatory music-making of groups of users to create shared compositions and live performances, and to potentially form some kind of a *Braille Orchestra*, the music en-

vironment should provide a networked communication between users.

- **Recording.** The environment should provide the ability to record and document compositions and live performances by providing an in-built audio recorder. The audio recording should then be made available for download.

3.3.2 Concept and Development

The technical concept for the music environment was to develop an online website that follows the zero-installation paradigm and is therefore accessible through the internet. The website should enable accessible, intuitive handling and ease of use, as well as performative musical expression. It should also serve as a platform for investigating and exploring tangible musical interaction. To separate sound creation and user controls, the website should be created using a server-client architecture that allows multiple users to connect and enables networked music-making. Inspired by command-line interfaces (CLI), a text input field should serve as the main interaction element on the website. The website should store a history of text commands, enable retrieval of the last commands, and provide feedback, such as error messages, for invalid input.

3.3.3 Sample-based Step-Sequencer

For the sonic design of the music environment a number of different sound creation and composition techniques were considered, for instance real-time sound synthesis concepts such as complex sequencing and patching of oscillators, envelopes, VCAs or LFOs. Likewise, arrangements similar to DAWs were considered based the use of abstract symbols or blocks of sounds in a time-line. In order to reduce complexity and to provide musical principles that are easy to understand and to utilize, the author decided to use a step-sequencer design as the musical paradigm, a composition technique that is commonly associated with electronic and digital music-making,

Initially, oscillators and noise generators were considered sources for sound generation, along with sound-shaping components like filters, LFOs, and VCAs. However, this complex setup contradicted the goal of simplicity and ease of use for beginners since these synthesis techniques require extensive instruction. Instead, using samples seemed more appropriate and intuitive since they can provide a wide range of sounds without the complexity of generating them in real time. Additionally, using samples enables users to curate and upload their own sample packs, allowing for customization and the realization of individual musical visions through personal artistic decisions.

For the final design of the web-based music environment, following musical and performative aspects were taken into account:

- Multiple step-sequences should play simultaneously
- Real-time changes to the running step-sequencer should be possible
- Parameter controls such as volume or panorama should be possible independently for each instrument
- The pattern length of each step-sequence should be customizable
- Randomization should be possible, e.g. randomized positions of events in a sequence
- Features that support musical composition should be available, such as snapshots that allow quick recall and switching of patterns and instruments
- Assignment of pitch values to single steps in a sequence should be possible

3.3.4 Architecture and Frameworks

The development and programming of the website was realized using the JavaScript environment *Node.js*, a cross-platform and open-source runtime environment that executes JavaScript code outside a web browser.[7] The code was optimized and converted using the packaging manager *Parcel*.[8] The sound generation and implementation of music sequencing was realized using the JavaScript library *Tone.js*, which is a Web Audio framework for creating interactive music in the browser.[9] *Tone.js* allows to use of familiar music software concepts such as global transport for synchronizing and scheduling events as well as pre-built synths and effects.

The website is realized based on a client-server architecture, where the sound generation and sequencer scheduling is realized on the client,

[7] https://nodejs.org/
[8] https://parceljs.org/
[9] https://tonejs.github.io/

while audio samples and control structures are located on the server (see Fig.3.3.1). For the communication between clients and server the library *Socket.io* was used, an event-driven library for web applications that enables real-time, bi-directional communication between web clients and servers.[10]

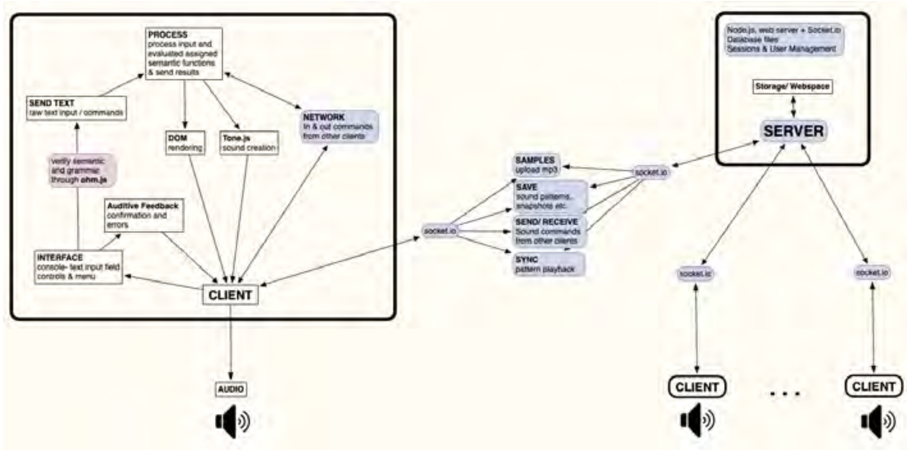

Figure 3.3.1: Flow chart of the system architecture including server and multiple clients.

The design of the programming language was realized using the JavaScript library *Ohm.js*, which is a parsing toolkit consisting of a library and a domain-specific language. *Ohm.js* can be used to parse custom file formats or to create parsers, interpreters, and compilers for programming languages.[11] *Ohm.js* differentiates between a *grammar* for the interpretation of inputted commands, as well as *semantics* for the assignment of resulting tasks and actions (see Fig.3.3.2).

3.3.5 Language Design and Notation Syntax

The design of the musical programming language aimed toward tasks such as pattern composition, controlling musical parameters, and randomization. In addition to musical interaction, the programming language should allow control of other elements of the music environment. For example, it should allow users to store or load sequences and sample packs or control the embedded audio recorder. The goal was to create an easy-to-use and easy-to-understand notation system for both experienced programmers and non-programmers. For this reason, the number of commands was minimized, and input was restricted to one line of code at a time.

---

[10] https://socket.io/

[11] https://ohmjs.org/

```
Exp =   Commands | Assignments

Commands =
    | ">>" PhraseList          --soloEvent
    | ">>"                     --startAllEvent
    | "?" PhraseList?          --questionEvent
    | ">" PhraseList           --playMultiEvent
    | "." PhraseList           --stopMultiEvent
    | "=" phrase               --savePartEvent
    | "/" PhraseList           --deleteEvent
    | "save" phrase            --saveEvent
    | "delete" phrase          --deleteWordEvent
    | "join" phrase            --joinEvent
    | "restart" phrase         --restartEvent
    | "store" phrase           --storeEvent
    | "load" phrase            --loadEvent
    | "upload" phrase          --uploadEvent
    | "record" phrase          --recordEvent
    | "mute"                   --muteEvent
    | "unmute"                 --unmuteEvent
    | ">"                      --playAllEvent
    | "."                      --stopAllEvent
    | "/"                      --deleteAllEvent


Assignments =
    | phrase ">" PhraseList                      --copyPattern
    | PhraseList floatPos? random? Pattern       --assignPattern
    | "bpm" intPos? floatPos?                     --setBPM
    | PhraseList Envelope                         --setEnvelope
    | PhraseList floatPos? random                 --setVolumeRandom
    | PhraseList floatPos                        --setVolume
    | PhraseList                                 --instrumentPreview
    | ""                                         --emptyEvent
    | "s" PhraseList                             --soloEvent
```

Figure 3.3.2: Custom grammar for the music environment *Welle*. Example for programming language design with *Ohm.js*.

Inspirations for this interactive textual programming system are drawn from interfaces like the *Livecodelab 2.5*, *ixi lang* or *Steno*, which all allow the intuitive creation of pattern-based music sequences with a focus on simplification and abstraction.[12][13][14]

System

To control the overall functionality of the music environment, simple commands were embedded for starting and stopping the sequencer, setting the BPM, controlling the audio recording, or to reset the sequencer:

```
>
.
BPM 145
record start
```

[12] https://livecodelab.net/play/
[13] https://github.com/thormagnusson/ixilang
[14] https://github.com/musikinformatik/Steno

```
record stop
/
```

Patterns

For the description of a musical sequence pattern, a notation based on the use of number signs # and dashes - was used to describe either a musical note event or a pause. The sequence pattern is defined through the number of symbols in a row, in which the number signs refer to an actual note, while dashes describe a pause or silence. An example for a simple sequence looks like that:

```
# # - # - - # # - - -
```

In order to assign pitch values to the single note events, an number can be attached directly behind the number sign, that describes the increase or decrease of the default pitch value in half-tone steps, similar to the 12 divisions of an octave on the piano. The attached number can be a positive number as well as a negative number with a preceding minus sign, e.g. 3, 12, -5 or -20. Thereby the use of the minus sign can be confusing since it is used both as musical pause symbol and as symbol for a negative number, which depends on its position in the sequence. An example for a sequence pattern that uses notes with default pitch, as well as notes whose pitch is increased or decreased:

```
#2 #5 - #-2 - - #-5 # - # -
```

Instruments

For the creation of a musical sequence, the user has to choose a sound from a list of multiple samples provided on the website. With the creation of a sequence, a new virtual instrument is created internally, that uses the selected sample as a source sound. The virtual instrument can then be accessed by using the name of the underlying sample. Instruments consist of the underlying sample, an assigned pattern, parameter settings for volume and Randomization.

In order to compose and control the musical behavior of entire instruments, the programming language provides various ways of accessing instruments and their parameters. It allows to address and change single parameters and the musical pattern separately, as well as to address all elements in one single command.

To address an instrument, the command has to begin with the name of the instrument. From there on either single parameters can be changed by adding the new value directly behind the instrument name. Likewise, all elements can be addressed in one command by adding them in a predefined order after the instrument name separated by blank spaces, e.g. *name volume randomization pattern*. An example for the description of an entire instrument, followed by an example of changing only one volume parameter of an instrument:

```
bass 0.9 0 #2 - # #5 - - - - # -
bass 0.7
```

Interactions

Various interactive controls were embedded in the language in order to re-use existing patterns, to control multiple instruments at once, or to control the playing state of instrument through muting or soloing. Following examples for an instrument called *bass* describe muting, unmuting, soloing, as well as deactivate soloing for all instruments:

```
. bass
> bass
>> bass
>>
```

Other options are the multiplying and copying of patterns and parameters. Parameters can be assigned to multiple instruments by using lists. Likewise parameters and patterns of one instrument can be copied to one or more other instruments. Similarly a number of new instruments can be initialized with the same parameters and pattern. Following examples describe the initialization of multiple instruments with the same pattern, as well as the copying of an instrument *bass* pattern to a number of other instruments:

```
bass drums string  # # #12 - #
bass > hihat noise piano
```

Snapshots

In order to increase performativity and real-time composition and musical improvisation, the functionality of snapshots was embedded. A snapshot stores the current settings of the sequencer and also store all existing instruments including their samples, patterns, parameters and play states. Unlimited snapshots can be stored and reloaded later in order to restore the saved sequencer settings. This technique only works in the same session and with the same sample library, e.g. when the browser tab is closed or when a different sample pack is loaded, the snapshots are lost. To store a snapshot in the current session, the user has to create a name in lower-case as a single word without special characters. This name has to be entered with a preceding equal sign. To reload the snapshot, its name has to be entered with additional signs. Following examples show storing and activating a snapshot called *refrain*:

```
= refrain
refrain
```

Network

In order for the participants to play together and collectively create musical sequences and explore sounds and music, the music environment allowed to log into a shared session via the internet and based on the server-client architecture. In this shared session, the sequencer could be used collectively, all participants could send and receive changes to the sequencer and associated instruments. The participants could also see the names of others that joined the session. The music environment initially only provided one shared session, that could be accessed with the command *"join"* followed by a name, which would then be displayed to all other participants.

3.3.6 Versions, Updates and Differences

This web-based music environment, called *Welle*, was developed in multiple iterations and versions. The first version of *Welle* was presented in 2019, followed by an updated second version, that was presented in 2021 (see Fig.3.3.3).[15] While the first version still enabled networked group sessions, the 2021 second version was updated based on insights from workshops with VIB pupils and experts, and no longer enabled group sessions. It embodied simplicity, abandoned networked sessions, and focused on integrating three tangible musical interfaces. Both versions of *Welle* used the musical programming language described above, its pattern creation and musical parameters, and also featured *snapshots*, which were then still called *parts*. But three aspects changed between the first and second version of the software, which were the interface, the ability to create poly-rhythm and the networked musical collaborations.

[15]live online version of *Welle* at https://welle.live

Figure 3.3.3: Welle 1st version (2019). Active group session.

Web interface

The web interface of the first version of *Welle* was rudimentary compared to the second version. While the first version already allowed the download and upload of instruments and compositions, the web interface did not provide any controls, the interaction had to be done via commands in the input field. Likewise, the 1st version did not display an overview of the *instruments* and the according patterns and parameters, but instead just displayed the name and mute state of the single instruments.

Based on insights from the practical use and developments of the proposed tangible interfaces, the interface was changed and updated in the second version of *Welle*. Controls, menus and a list of available instruments in the selected sample pack was added in order to increase usability, as well as an overview on active instruments and according patterns.

Poly-rhythms

The 1st version of Welle allowed to create poly-rhythms by entering sequences of different lengths. While the overall playback of the sequences was synchronized, the different lengths led to varying rhythms and musical variation. This ability to generate poly-rhythms was removed in the second updated version of *Welle* towards a more simplified 8-step sequencer design, mainly to match the musical interaction with the tangible musical interfaces, as well as to increase simplicity for non-trained beginners.

Network sessions

The musical networked sessions were one of the core features of the first iteration of the music environment. It enabled collaborative musical explorations over the internet. The aim was to enable and potentially form a *Braille orchestra* and according live performances. The removal of the networking feature was decided after observing the musical practice of pupils and teachers with *Welle*. It seemed that there was no request or artistic use of this feature, while its programming consumed time and energy. Therefore the ability of networked sessions was deactivated, but the underlying server-client architecture still remains functional.

3.3.7 Interface Design

The interface of the current version of *Welle* is organized in separate sections on a single website. The interface starts with the title and a button for language selection, available languages are German and English. The main interface components from top to bottom are:

- *Menu.* The menu section provides controls for files, settings, transport and instruments
- *Console.* The console is the main interaction element based on an input field for text commands and the display of the commands history and error messages
- *Snapshots.* The snapshot section shows available snapshots as clickable buttons with the respective names
- *Active instruments.* A table display shows an overview of all active instruments, including their mute state, name, parameters and pattern

- *Tutorial.* At the bottom of the interfaces is the help section, that gives an overview over the music environment, an introduction to pattern creation, a list of all commands and respective credits

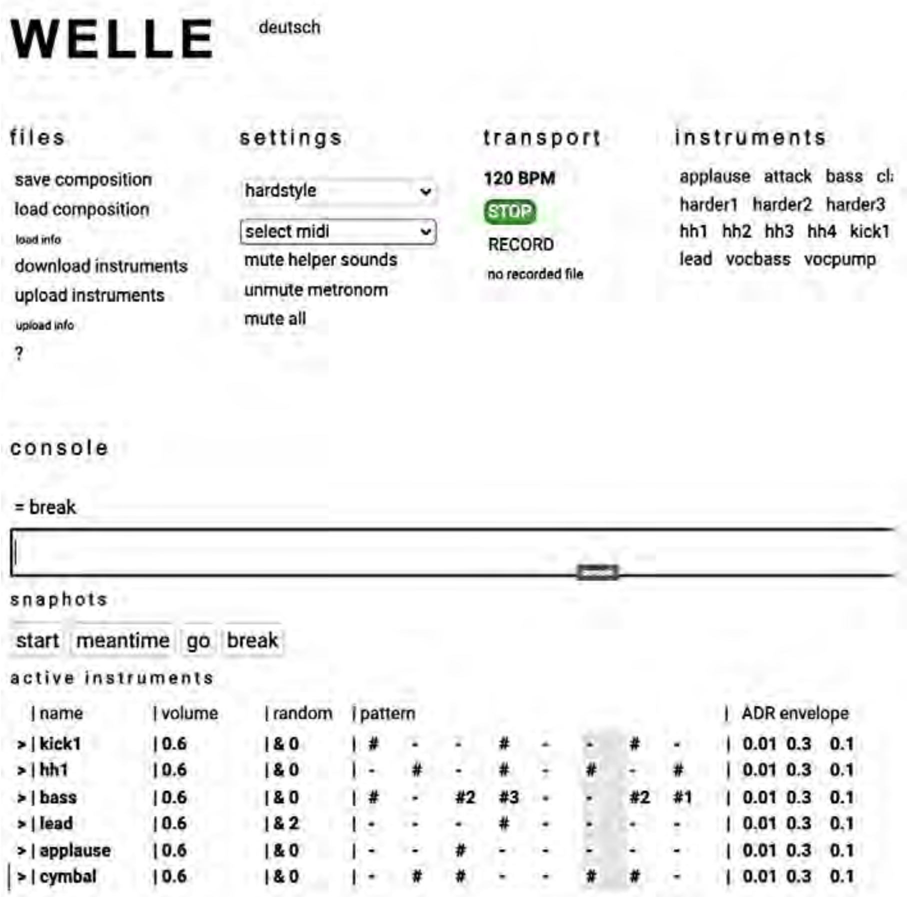

Figure 3.3.4: Welle - 2nd version (2021). The image shows an active session, including multiple instruments, their parameters, as well as various snapshots.

Files

The first section the menu part of the website is used for the *files* management. The first two buttons enable to save and load musical compositions that were created with the music environment, and includes the different instruments, parameters and pattern. The composition can be downloaded as a JSON file. Likewise, previously stored compositions can be uploaded into the music environment. An info box below the *load composition* button displays a text feedback when uploading a file, e.g. an error message if the file type is not JSON, or a success message The JSON file includes information on the respective composition, such as BPM, the name of the sample pack, it includes all instruments that have been activated and used for musical sequences, and it includes possible snapshots and their contents. Various instrument data is stored, such as the name, the mute state, parameters for volume and Randomization, the pattern including note events and pitch values.

Furthermore, the *files* section allows to download and upload samples and sample packs. Samples are MP3 files that are organized as collections of multiple samples, whereby the name of the MP3 file is shown as name of the sample. The samples are called *instruments*. The file size for samples is limited to a maximum file size of 130KB, which is approximately 3 seconds for a mono audio file at a bit rate of 320Kb/s. The music environment provides various sample collections, which can also be downloaded as a ZIP file, named after the *instruments* name, e.g. *default* or *hardstyle*. New sample collections can be uploaded. They can contain a maximum of 30 MP3 files. When clicking the *upload instruments* button, a file window opens that allows to select multiple files, which are then uploaded to the server, and subsequently are provided in the website. After a session ends, e.g. when closing the browser or reloading the website, the files are deleted from the server and have to be uploaded again. An information text field displays feedback and status of the upload process, e.g. confirmation if the upload succeeded, or error messages if there are too many files or if the size of files is too big.

On mobile devices some of the menu sections are not displayed, which includes the *files* section and its buttons for upload or download of compositions and instruments.

Settings

The next section of the menu is the *settings*, which provides various controls for the current session. The first element in the *settings* part is a selection box labeled with *"select instruments"*, and can be used to display and choose from the available sample collections, e.g. *default*, *buchla* or *electronique*. These sample collections are either provided by the author or are part of free collections by other artists, which are credited on the website. When loading the website, the system loads the *default* sample pack.

The next element of the *settings* is a selection box for MIDI devices to be connected. MIDI interaction can be use in multiple ways, either to use the music environment as a sequencer for external sound generation, as well as to receive MIDI in order to control parameters and patterns of single instruments. The MIDI interface is also used to interact with the tangible musical interfaces.

Below the MIDI selection controls for auditory feedback are located, that enable *helper sounds* to announce success or error for text input. Likewise, a metronome can be enabled, and all audio can be muted, for instance when using the music environment as MIDI sequencer to control external sound generators.

On mobile devices some of the menu sections are not displayed, which includes the *settings* section and its buttons for selecting the MIDI devices.

Transport

A next section of the menu is the *transport*, which displays musical settings and allows to manually control aspects of the sequencer. Firstly it displays the sequencers tempo as *beats per minute* (BPM). Secondly it provides a button that shows the running state of the sequencer and allows to *stop* or *play* it. Lastly the *transport* section provides a button to control the internal audio recorder, that allows to record the current session. After the recording is finished, a text box below the record button displays a link to to download the audio recording. The audio recording is provided as stereo WebM file.

On mobile devices some of the menu sections are not displayed, which includes the *transport* section and its button for audio recording.

Instruments

Lastly, the menu section provides a clickable list of the single *instruments* or sample sounds, that can be used for the creation of a composition. The samples are provided as clickable links displaying their names. They can be quickly reviewed by using the ENTER key to play the sample and the TAB key to change the focus to the next sample.

Console

The main part of the website is called *console*, which consists of various displays and input elements. The *console* provides an input field as the main musical interaction component, in which all commands for the creation of musical patterns have to be entered, as well as the commands for the creation of snapshots, compositions, live improvisations and other controls for the sequencer. The commands entered in the input field are stored internally together with other status messages, of which the respective last message or command is displayed on the website in a text field above the input field. The messages are status feedback or error messages, e.g. for misspelling of commands or the attempt to use instruments that are not available. The stored commands of the history can be recalled with the up and down arrow keys, similar to common CLI behavior.

Snapshots

Below the *console* is the interactive display of available *snapshots*, that allow to restored previously saved settings in the current sequencer. *Snapshots* are displayed as a row of clickable buttons, that are labeled with the respective name. Clicking the button, or entering the name in the input field, immediately restores the settings in the sequencer.

Active Instruments

The next part of the interface is called *active instruments* and displays an overview off names, parameters, patterns and mute states of all instruments. The display is updated after every command input, MIDI input or after activation of *snapshots*. The display is not interactive.

Tutorial and Help

Placed below the interactive parts of the interface is a introduction and a tutorial that describes and demonstrates the use of the music environment. This section also provides information on how to use the MIDI interaction, how to load and save compositions and how to download and upload instruments. It provides credits for the artists of the sample sounds and an information on the research project and development of the software.

3.3.8 Workshops and Expert Inquiries

The development of the software was accompanied by regular expert inquiries and feedback. It was also informed by observations during workshop sessions, which will be described below. The main collaboration partners were VIB expert Erich Schmid, as well as the VIB pupils in the BBI (see Fig.3.3.5).

The music environment was used for the first time during the *Austrian Computer Camp 2019 (OCC)* in a 3-hour workshop. A group of six visually impaired and blind pupils aged 10-14 years as well as three VIB

Figure 3.3.5: Exploration of *Welle* by Erich Schmid during a workshop at the BBI 2021.

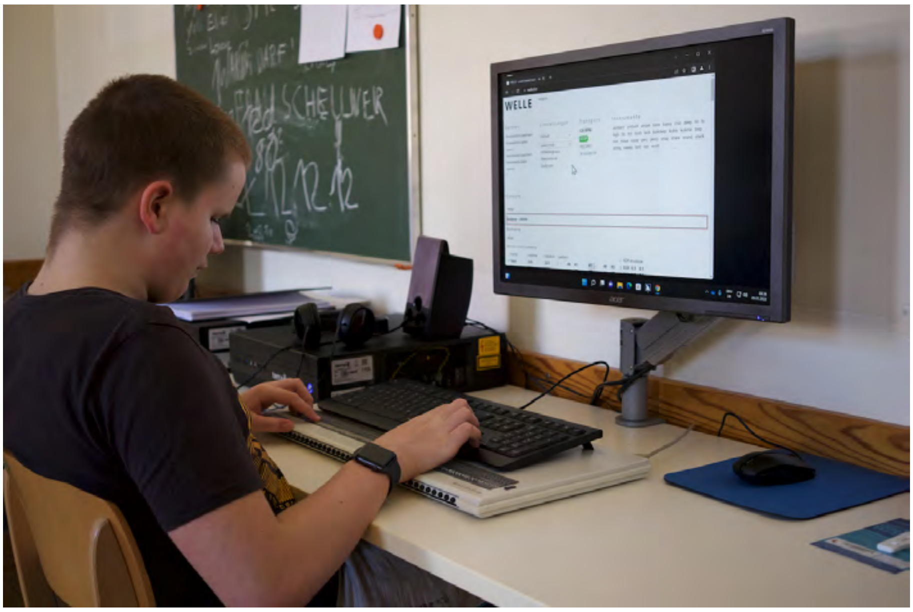

Figure 3.3.6: Exploration of *Welle* by Elias during a workshop at the BBI 2021.

teachers participated the workshop. The pupils had no prior experience with digital music-making or using the computer as a musical instrument. During the workshop, the use of different computers including different web browsers posed challenges, since *Welle* was developed for the *Google Chrome* browser, whereas most pupils were used to the *Internet Explorer* and the according shortcuts. Besides the initial issues, the pupils and also the teachers quickly accustomed to the music environment and its use of text commands to create sounds. They became familiar with creating multiple sequences and the respective instrument patterns. The participants were encouraged to explore the various instruments and the creation of music through entering patterns and notes, as well as to record their process. After some exploration of the software all pupils managed to generate their own sounds and musical patterns. At the end of the 3-hour workshop, all participants performed an improvised musical piece together. The piece was performed for an audience of other OCC participants, pupils and teachers.

The second version of *Welle* was explored in 2021 in a series of workshops at the BBI Vienna. Again, *Welle* was used to convey the core principles of digital music-making to the participating pupils and to prepare the exploration of tangible musical interaction. Besides one pupil who was not interested in music, all other pupils of the group were participating the process of learning how to use Welle. One participant was especially enthusiastic and even rehearsed the use of *Welle* at home (see Fig.3.3.6).

3.4 FROM SONIC FEATURES TO TANGIBLE SIGNALS

The following section will present and further explore the shift from the initial research proposal to develop a tangible prototype towards exploring sonic features as a basis for the iterative development of multiple new tangible musical interfaces. The shift is based on the experiences during the first workshops at the BBI Vienna that revealed a limited knowledge of the VIB participants regarding digital music-making and the use of the computer as a musical platform and instrument. While the initial research proposal was centered around the development of a multi-functional prototype that could be used as *tangible wavetable synthesizer* or *tangible equalizer* in order to investigate tangible musical interaction, this approach now seemed too specialized, since the VIB participants were beginners in digital music-making. So instead of pursuing the initially proposed tangible prototype for *wavetable synthesis* and *equalization*, new musical approaches and concepts for the development of tangible interfaces were considered.

3.4.1 Features of Synthesizers

At the core of the research project are common artistic concepts and musical approaches of computer music, such as sound synthesis, music composition, sound editing and manipulation. Approaches such as the initially mentioned *wavetable synthesis* or *equalizing* are used to generate and shape sounds in a sonically interesting way by altering the characteristics of the sound, such as timbre, dynamics, texture, fidelity, ambiance, and tone. The generation of sound by using digital or analog synthesizers is based on the use and combination of synthesizer features, such as oscillators, amplifiers, envelopes, modulators, as well as triggers and sequencers for switching sonic elements or signals flows. These synthesizer features can also be referred to as *sonic features*, since they are used to create, define and shape the characteristics of the resulting synthesized sounds. Most electronic and digital synthesizers provide a set of those common features. In this regard, *sonic features* describe the building blocks to generate melodies, compose musical sequences or shape the sonic expression by randomizing musical parameters. They not only describe sonic characteristics, but are the foundation for the creation of sound and music.

3.4.2 Abstracting Sonic Features

In order to realign the research project, and stimulate the ideation process for new approaches towards the development of suitable tangible musical interfaces, a review of the initial research activities provided new artistic inspiration. In particular the tactile waveforms, that were produced as educational material for the first workshops, resonated with the search for an adequate direction (see Fig.3.2.1). Combined with the insights from *Welle* as a platform for simplified digital music-making and with the awareness of *sonic features*, the waveforms inspired an artistic reconsideration of the design of suitable tangible interfaces, and became starting points for the ideation of new musical interfaces based on the concepts of *oscillation*, *alternation* and *modulation* (see Fig.3.4.1).

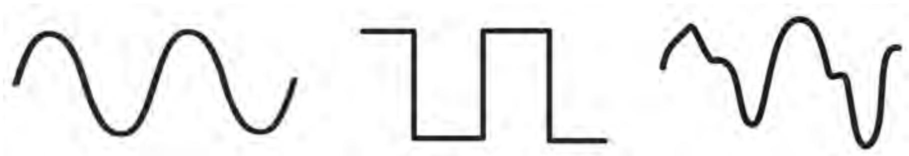

Figure 3.4.1: Waveforms as inspirations for sonic features: sine wave as *oscillation*, square wave as *alternation* and noise as *modulation* (from left to right).

Oscillation

The first inspiration for a new approach towards the development of tangible musical interface was the representation of a *sine wave*. A *sine wave* is an s-shaped waveform that oscillates periodically above and below zero, and can be described through its frequency and amplitude. Its oscillation is a repetitive variation of values over time around a central equilibrium position, often explained by referring to a pendulum in a clock or the movements of a spring.[16] *Sine waves* are also used as a *sonic feature* in synthesizers, both as a sound source in dedicated *oscillators*, as well as for control signals and modulations in form of *low-frequency oscillators* or LFOs. But instead of focusing on a time-based display of sound waves, as initially proposed with the *tangible wavetable synthesizer*, the concept of *oscillation* inspired the design of a continuous control over more abstract parameters.

Alternation

Likewise inspiring was the representation of a *square wave*, a periodic waveform that oscillates with a steady frequency between a fixed minimum and maximum value. Besides its sonic character, this waveform evokes concepts of binary data, that is commonly described as a series of *ones* and *zeros*, but can also be described as *on and off*, as *in and out*, or as the *low and high* in a square wave. For synthesizers and sound generation this duality is a relevant *sonic feature*. It can be found in *note on* and *note off* commands of MIDI keyboards, in the data stream of trigger sequencers, or in other modulating control signals. This underlying concept of *alternation* is also embedded in the music environment *Welle* through its use of a step-sequencer as central compositional element, as well as through binary controls like the *mute*, that allows to mute or unmute an instrument in the software. As an accessible and beginner-friendly concept of music-making, *alternation* will be used to inspire the development of new approaches for tangible interaction.

Modulation

A third waveform that stimulated artistic inspiration was the representation of irregular noise as a waveform. Noise is sound just like every other audible sound, except it is often defined as unwanted or unintentional sound. It can be continuous, variable, intermittent or impulsive depending on how it changes over time.[17] Noise is used by many synthesizers as a sound source, e.g. as *white noise*, *pink noise*, *brown noise* or other sources of variable noise. Beside its use for sound generation,

[16] https://byjus.com/jee/oscillation/

[17] https://www.ccohs.ca/oshanswers/phys_agents/noise/noise_basic.html

noise can also be used as a *sonic feature* and source for *modulation* of sound parameters through *low-frequency oscillations*. Noise as control signal for *modulation* provides a variable and randomized stream of values that can lead to more organic and rich sounds. Thereby *modulation* is a technique used for sound synthesis to create interest, variation and complexity by changing sound parameters over time, such as pitch, filter frequencies or amplitude.[18] For instance, common ADSR envelopes enable the interaction with four parameters in order to create rich modulations, e.g. *attack*, *decay*, *sustain* and *release*. The concept of *modulation* will serve as artistic inspiration to develop an interface for tangible interaction focused on the modulation of parameters of sound and sound effects.

3.4.3 Towards Tangible Signals

To recapitulate, the objective of this research project is to investigate tangible interaction as a means for accessible digital music-making in regard to the artistic use of the computer as a musical platform for composition and stage-based live performance. To that end the design of a multi-functional prototype was initially proposed, a device that can be used for sound creation and sound manipulation by providing an actuated and interactive display of waveforms for *wavetable synthesis*, as well as a tangible representation of an equalizer and its frequency settings (see Chapter 3.1).

The plans to develop this proposed multi-functional prototype was abandoned after the first workshops revealed a lack of experiences with digital music-making among the VIB participants. Simultaneously valuable insights were gained during these workshops, and *sonic experimentations* led to the development of the web-based music environment *Welle*, which enabled accessible digital music-making. The results of this practical work led to a reconsideration of the initially proposed tangible interface. Artistic inspiration and practical observation shifted the focus towards the musical concepts of *oscillation*, *alternation* and *modulation*. These abstract musical concepts are no longer based on time-based sound signals, but rather transpose the control of audio synthesis into the meta-control of *sonic features*.

Therefore, the next stage of the research project will be to develop tangible interfaces that enable the interactive physical representation of *sonic features*. Transposing these *sonic features* into interactive phys-

[18]https://www.patchwerks.com/blogs/patchnotes/what-is-ring-modulation-frequency-modulation-and-amplitude-modulation

ical displays will convert them into *tangible signals*. These interfaces will transcode digital sound generation into physical manifestations of *tangible signals*. They will be used to investigate tangible musical interaction in the context of accessible digital music-making.

3.5 INTERFACE - TANGIBLE WHEEL

This section will present the process and results of developing the *Tangible Wheel* interface in detail.

The development of the interface was inspired by the concept of *oscillation* and its repeated and continuous rotation of an element around a fixed center point (see Fig.3.5.1). In the following, the various iterations of the prototype development will be described, as well as the final interface, its main features, technical implementations and possible use cases.

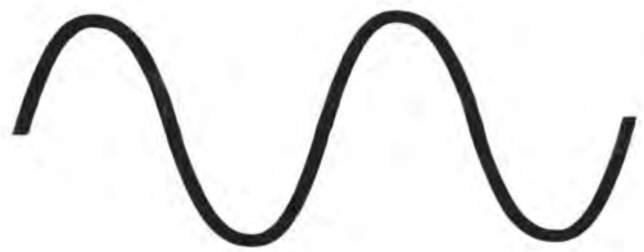

Figure 3.5.1: A sine wave inspired experimentation with tangible sonic interactions based on *oscillation*.

3.5.1 Prototyping Rotating Frequency

The development process started with the exploration of *oscillation* in a literal and time-based way by prototyping a device that enabled the display and interaction with *oscillation* itself. The idea was to represent a sound and its frequency through mechanical movement. The physical representation was supposed to enable the tactile exploration and manipulation of frequency values. The interface provided a rotating wooden handle of approximately 25 centimeter length and 4 centimeters diameter, which was moved with varying speeds by a DC motor. The speed of the handle was measured by using a piezo sensor, that was triggered at each full rotation. A Teensy 3.1 micro controller was used for the sensor readings, motor control and the communication with the computer (see Fig.3.5.2). A custom music software was designed to generated a single sine wave with a specified frequency. The interface and its wooden rotating handle served as a means physically represent the according frequency value of the generated sound by mapping the sine wave's frequency to the rotation speed of the handle.

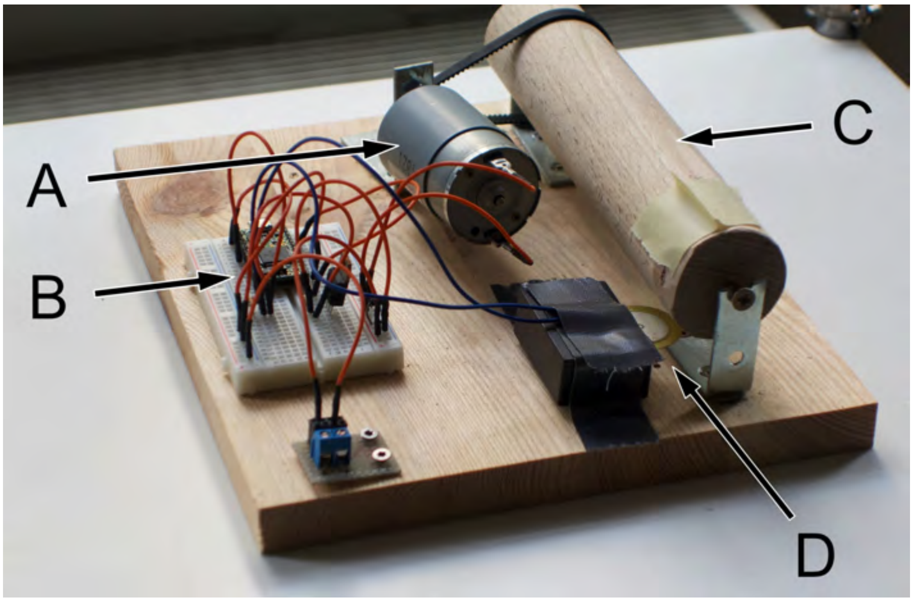

Figure 3.5.2: Tangible oscillation prototype. A rotating shaft that serves as a handle to represent and interact with frequency values during sound generation. (A) DC motor (B) micro controller (C) rotating shaft (D) piezo sensor.

The interface was designed to enable tangible interaction by physically representing the sound frequency through the rotating handle in the physical interface. The frequency of the sound could be perceived both by hearing the sound and by touching the handle and experiencing its rotation speed. The interface also included the possibility of manipulating the frequency by interacting with the rotating handle, e.g. increasing and decreasing the frequency values for the sound synthesis. For decreasing the frequency values a series of simple tests showed, that it was possible to decrease the frequency by manually decelerating the rotation speed of the wooden handle by blocking it. In order to increase the frequency values for sound generation, the user had to accelerate of the speed of the handle. Attempts to accelerate the rotation speed manually were not reliable or precise. Although it was somehow possible to achieve an acceleration effect, the design of the interface in combination with the motor and high rotations speeds of the handle made it impossible to control the acceleration and the according pitch in a useful way.

To improve the conditions of the experiment, the interface was updated (see Fig.3.5.3). The shaft and the bearings were updated to reduce friction resistance, using high quality stainless steel rods and ball bearings. The previous piezo sensor was replaced with a rotary encoder, which delivered precise readings of any movement of the handle, e.g. turning forwards or backwards. Also the wooden handle was replaced by a rubber handle of 14 centimeter length and an increased 7 centimeter diameter to improve the tactile experience and the grip for accelerating the handle.

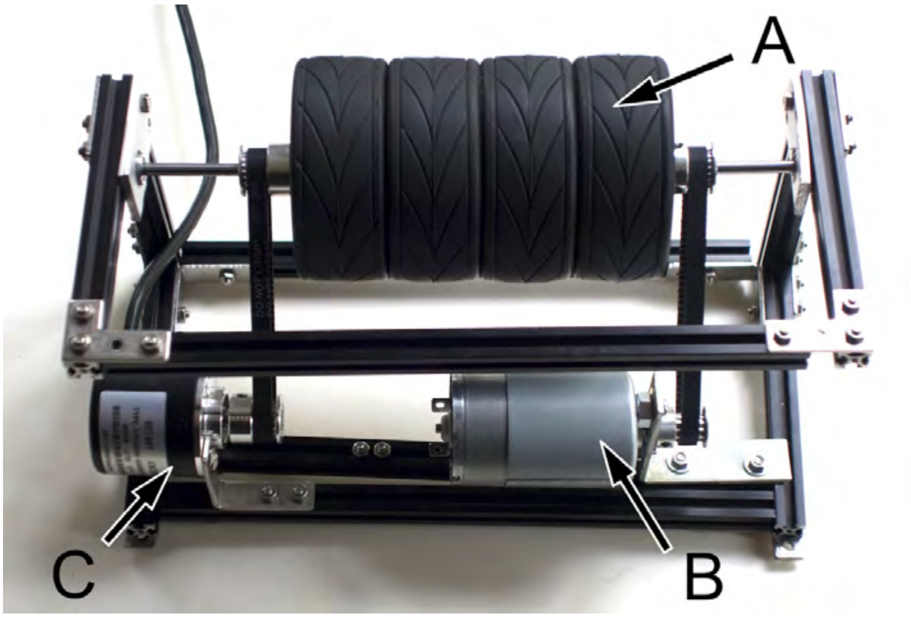

Figure 3.5.3: Tangible rotation prototype with rubber handle. (A) rotating rubber handle (B) DC motor (C) rotary encoder.

Unfortunately, the results of this second iteration of the test setup had similar shortcomings like the first prototype setup. It was lacking precision and reliability when attempting to accelerate rotation speed. For that reason this first attempt of exploring the concept of *oscillation* to represent time-base values like frequency for sound synthesis was abandoned.

3.5.2 Prototyping Vertical Control

The first attempts of using a rotating handle showed that the interaction with time-based signals poses difficulties, especially for creating acceleration. Nonetheless, the rotating handle including its precise position readings through the rotary encoder, and its motorization with a DC motor seemed to be a promising configuration. In a next step, the existing interface was reduced to its core functionality to provide a rotating handle, a precise measurement of its position and the motorization for updating its position. The rotating rubber element was converted from a longer handle towards a single vertical wheel element. Also the single components were covered in a closed housing to protect both the mechanical components and provide a minimum of interaction safety (see Fig.3.5.4). The use of the interface was detached from its display of time-based signals towards the representation of *sonic features*, namely continuous meta controls, e.g. for scrolling through a sound file. It provided haptic feedback through embedded vibration motors, and was designed to enable the interaction with markers, cue points or notes in a sequence.

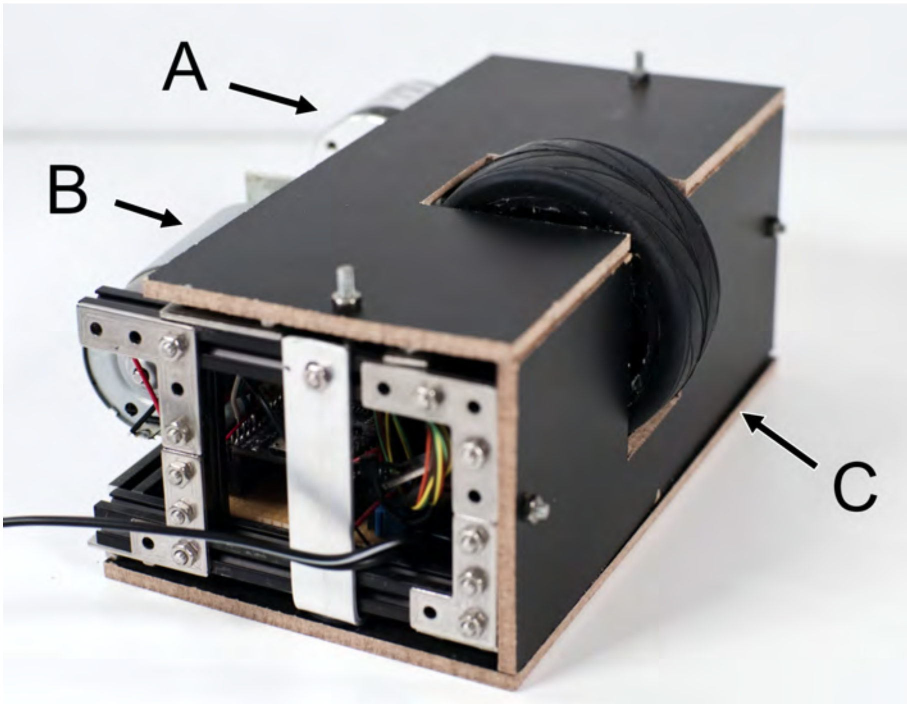

Figure 3.5.4: Tangible wheel prototype with vertical rubber handle. (A) rotary encoder (B) DC motor (C) vertical rubber handle.

3.5.3 Prototyping Horizontal Wheel

In parallel to the previous development of the tangible wheel interface, the music environment *Welle* was created. The interfaces seemed suitable to serve as an interactive physical control for continuous parameters within *Welle*, such as volume or panorama. For that purpose, the DC motor was replaced by a stepper motor, which has higher torque and more precise operation. The stepper motor also enabled to create the tactile sensation of detents embedded in the wheels rotation, e.g. force feedback points that could be placed on-the-fly. Based on the feedback from VIB experts, the position of the rotating wheel was changed towards the final horizontal position (see Fig.3.5.5). Additionally, this iteration of the wheel interface received a number of physical and touch buttons as additional controls.

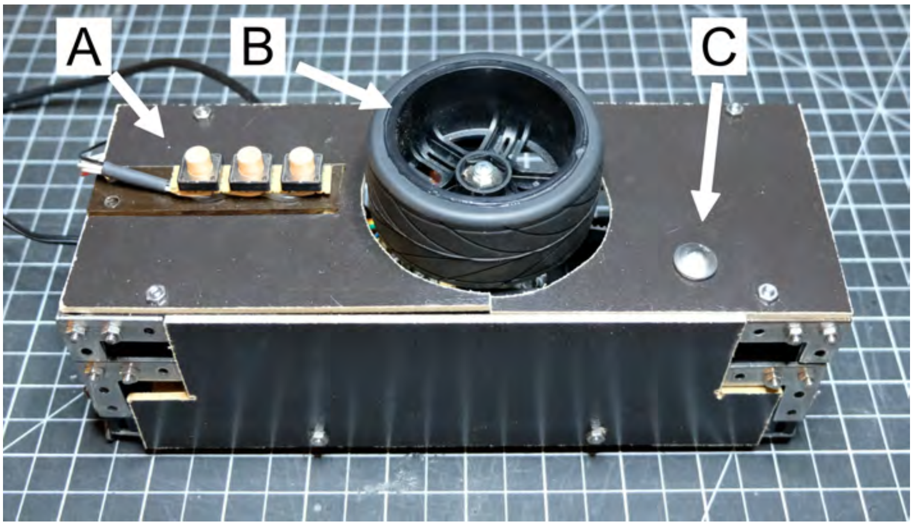

Figure 3.5.5: Tangible wheel prototype with horizontal rubber wheel. (A) buttons (B) horizontal rubber wheel (C) touch button

3.5.4 Main Features

Based on the various iterations during the prototype development, a final version of the *tangible wheel* interface was created (see Fig.3.5.6). The interface provides following key features:

- **Wheel.** Actuated rotating wheel as physical representation of continuous parameters, including a tactile pin for orientation.
- **Detents.** Force feedback embedded in the tactile operating the wheel through detents.
- **Buttons.** Three push buttons and one touch button as additional controls.
- **Serial Port.** Embedded micro controller for data processing, sending and receiving of serial messages and updating of the wheels position.

3.5.5 Technical Implementations and Hardware Design

The *tangible wheel* interface was realized using various software and hardware prototyping platforms, sensors and actuators (see Fig.3.5.7). For the programming and control of the electronic components, the

Figure 3.5.6: Tangible wheel interface, including three physical buttons and one touch button in its final enclosure.

open-source prototyping platform Arduino was used, in combination with the development board ESP 32.[19][20][21] The micro-controller serves as the main control for the interface including all its sensor and encoder readings, motor controls and internal calculations. It also serves as a transmitter and receiver of the relevant data towards the computer.

The design of the interface is centered around the rubber wheel handle, which also provides an attached tactile orientation pin for position readings for VIB users. It is directly connected to the shaft of the stepper motor, which actuates the wheel. The motor is driven through the use of a stepper motor control circuit, which is connected and controlled by the ESP 32 micro-controller. The stepper motor is then connected to a rotary encoder via a rubber belt and the use of aluminium gear wheels, that are mounted at the shafts of the stepper motor and the rotary encoder. The rotary encoder provides precise readings of the movement of the wheel in order to calculate the position. To calibrate the wheel, a small magnet is mounted to the shaft of the stepper motor, which is then detected by a hall sensor mounted to the enclosure. The sensor readings are also used during operation to stabilize the measurements regarding the wheel position and revolutions.

The electric circuit is realized using a custom circuit board that fits the micro-controller and the stepper motor control circuit. The entire interface is provided with 12V, which is needed for the stepper motor and the rotary encoder. The voltage is then converted to 5V for the micro-controller, the hall sensor and the motor control circuit, by using

[19] https://www.arduino.cc/
[20] https://all3dp.com/2/esp32-vs-arduino-differences/
[21] Online ESP32 Simulator WOKWI. https://wokwi.com/esp32

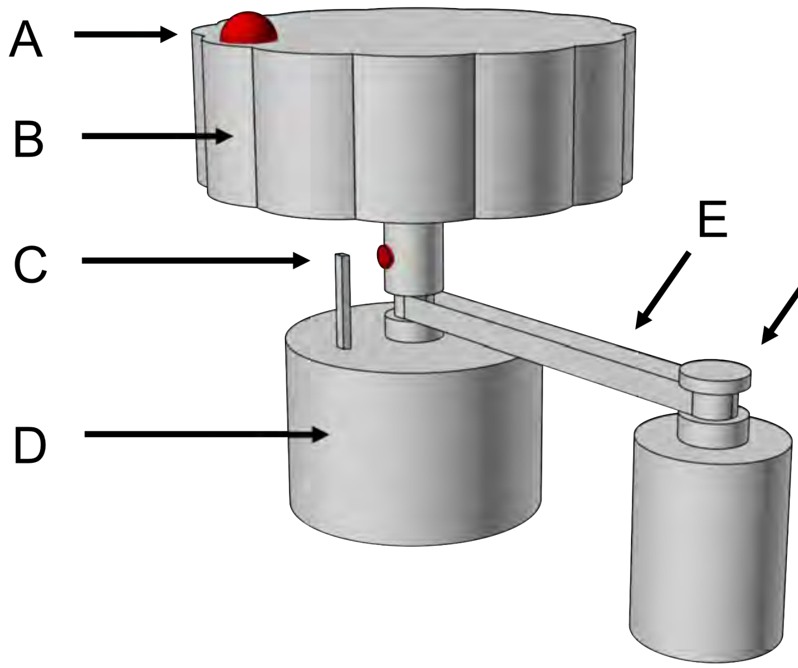

Figure 3.5.7: Tangible Wheel - schematic and components. (A) tactile orientation pin (B) rubber wheel (C) magnet and hall sensor (D) stepper motor (E) rubber belt (F) rotary encoder.

a DC to DC step-down converter circuit. Three tact switch buttons are mounted on the interface as additional controls, and are connected directly to the micro-controller, as well as a capacitive touch button (see all components in Fig.3.5.8). An off-the-shelf black plastic housing was modified to fit all components and external connectors.

The main components for the operation are the stepper motor and the rubber wheel mounted on top of it, as well as the rotary encoder that measures the changes of its position. Thereby the stepper motor is used to mechanically change the position of the wheel, and is switched of when reaching the final position, thus enabling smooth operation of the wheel without any mechanical blocking. The absolute position of the wheel is calculated by measuring the sensor readings of the magnet mounted on the motor shaft. The motor speed for updating its position is calculated using PID programming, which stands for *proportional*, *integral* and *derivative*, and is a method to interpret the distance from the current position towards the final position of the motor, and the subsequent adaptation of the motor speed and its acceleration and deceleration for a smooth operation. The detents, or haptic force feedback points, that are implemented as tactile feedback in the wheel interface, are realized by micro-powering the stepper motor at the respective positions, which results in a high torque blocking of

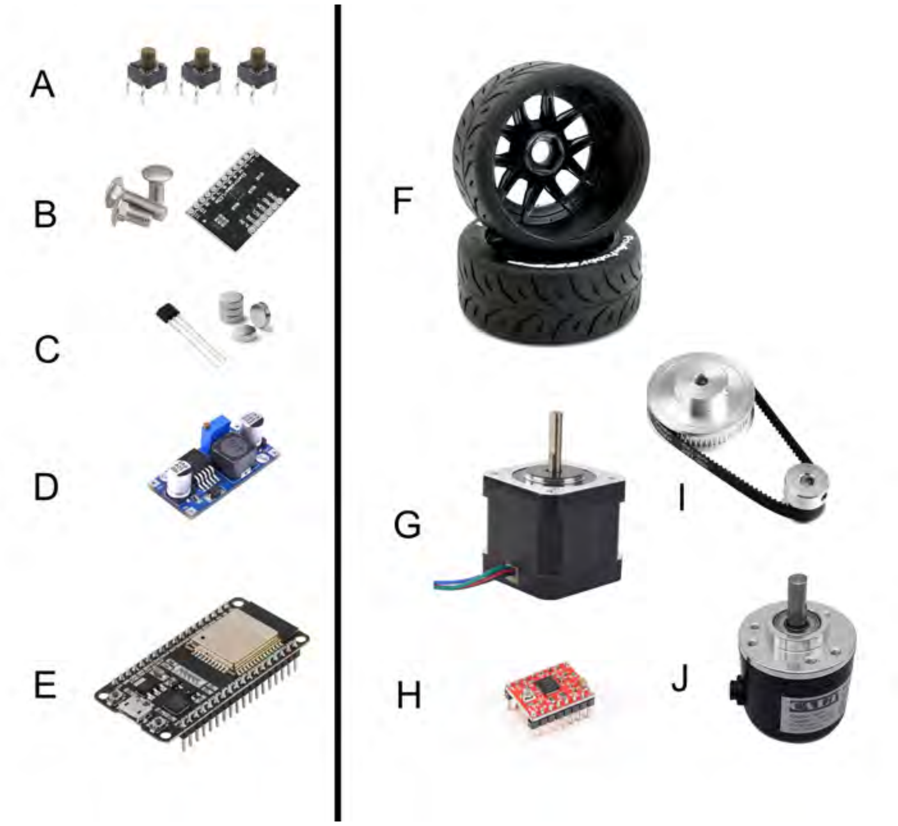

Figure 3.5.8: Tangible Wheel - components. (A) tact switch push buttons (B) capacitive touch board and steel screws (C) neodym magnets and hall sensor (D) DC-DC step down converter (E) ESP 32 micro-controller (F) race car rubber wheel (G) stepper motor (H) motor control board (I) aluminium gear wheels and rubber belt (J) rotary encoder.

the rotation of the wheel. This blocking does not effect the rotation of the wheel, but produces the sensation of a detent during the operation for the user.

3.5.6 Applications and Possible Use Cases

Various different application scenarios can be envisioned for the *tangible wheel* interface in relation to digital music-making. A basic usage of the interface could be the representation of continuous musical parameters such as the volume of instruments or panorama settings. The mechanical actuation thereby allows to update the wheel position when switching instruments or mixer channels. Similarly to the *Haptic Wave* interface it could be used to explore and navigate through an audio file, to set markers for editing, and to mechanically rotated the wheel back to previously set markers [Tanaka and Parkinson 2016]. Likewise, it could be used to navigate through step sequences or musical compositions, to enter or detect notes, or to edit the entire composition. As an interactive musical control it could be used to perform musical gestures in order to generate, record and store the generated data. The *tangible wheel* and its motorized interface could then be used to playback the previously recorded control data. Thereby this playback could be used both as an modulation source to affect musical parameter, as well as to visualize the data through tactile feedback and tangible interaction for VIB users.

3.6 INTERFACE - TANGIBLE PINS

This section will present the process and results of developing the *Tangible Pins* interface in detail.

This tangible musical interface is inspired by the concept of *alternation* and focuses on the idea of using discrete steps with binary states as musical building blocks for rhythmic patterns. It follows on one of the core concepts of digital and electronic music-making, namely the grid-based generation of rhythmic patterns through the use of step-sequencers, whereby a single step is used to set two different states. This grid-based design based on step-sequencers is also used for the music environment *Welle*.

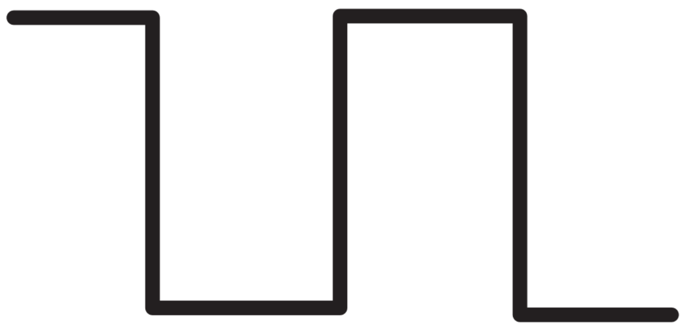

Figure 3.6.1: A square wave inspired experimentation with tangible sonic interactions based on *alternation*.

3.6.1 Prototyping an Actuated Switch

For the design of an interface that enables the physical switching of binary states in order to manipulate musical patterns, a first prototype was developed to explored a suitable mechanical switching mechanism. It was inspired by the functionality of a pen or a light switch, where the switch can pushed inwards to activate its function, as well as can be pushed outwards to deactivate its function.

Thereby, most physical switches used for controlling computers are input devices, e.g. the keys of a computer keyboard or switches of a computer mouse. These devices do not output any data. In contrast, a refreshable Braille display uses a pin-based display to output text in Braille notation, but its pin-based display itself cannot be used as input device.

The design of physical switches that are able to interact with the computer, and that allow both the use as input devices as well as to physically output data is more complex. First of all, the switch needs to provide sensors that detect the manual interaction. A mechanical actuator is needed to physically change the state of the switch automatically, e.g. to *"press"* the switch remotely and computer-controlled. The resulting physical position or state of the switch has to be measured with suitable sensors

In order to explore possible switches that would allow mechanical actuation, various different components and techniques were tested, e.g. various light switches, furniture closing mechanisms, the use of metal springs, DC motors to control mechanical switching, as well as electro-magnetic solenoids. The most promising setup was a combination of switches with pin-based design and strong solenoids to mechanically imitate finger pressing by pulling a reversely mounted string (see Fig.3.6.2). The string was pulled once for activation and once for deactivation. Unfortunately, the results were not reliable, the components were too big and heavy, and the solenoids were not strong enough to *"press"* the mechanical switches.

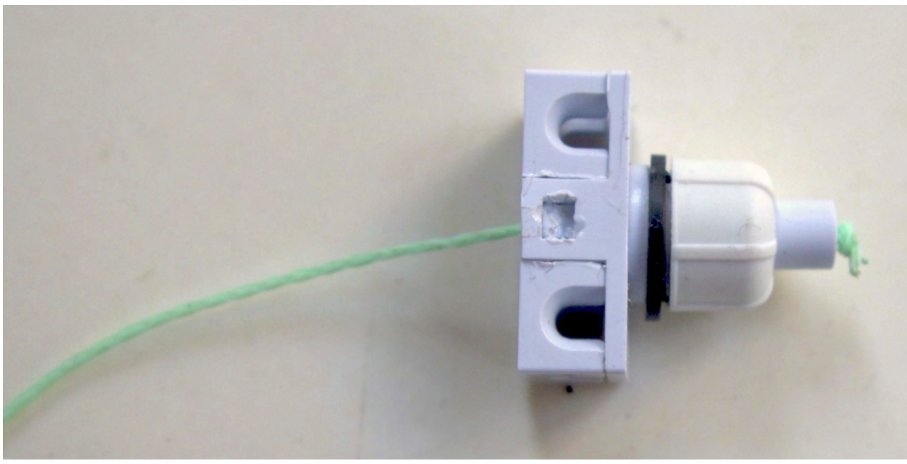

Figure 3.6.2: Prototype - mechanical on/off switch with a chord.

The key to design a working prototype was the use of electro-magnetic solenoids that are bi-directional, e.g. that are able to move their head in both directions inwards and outwards. Thereby the both resulting positions of the heads are stable even without the solenoids being powered, based on internal magnets. This way the bi-directional solenoid can be used to mechanically display two states through updating its position, similarly to a single pin in a refreshable Braille display.

A suitable user interaction could be based on the alternation of pressing the solenoids head down to achieve the binary state *zero*, and pressing the head again to achieve the binary state *one*. In an experimental setup, a tact switch push button was mounted below the solenoid to detect the manual pressing of the head of the solenoid. The solenoid is mounted in a *"flying"* position, which causes manual interaction such as pressing the head downwards to trigger the tact switch button, since the whole body of the solenoid is moved simultaneously (see Fig.3.6.3). The solenoid is powered and controlled by a micro-controller, that is used to detect the button presses and to set the solenoid in both directions.

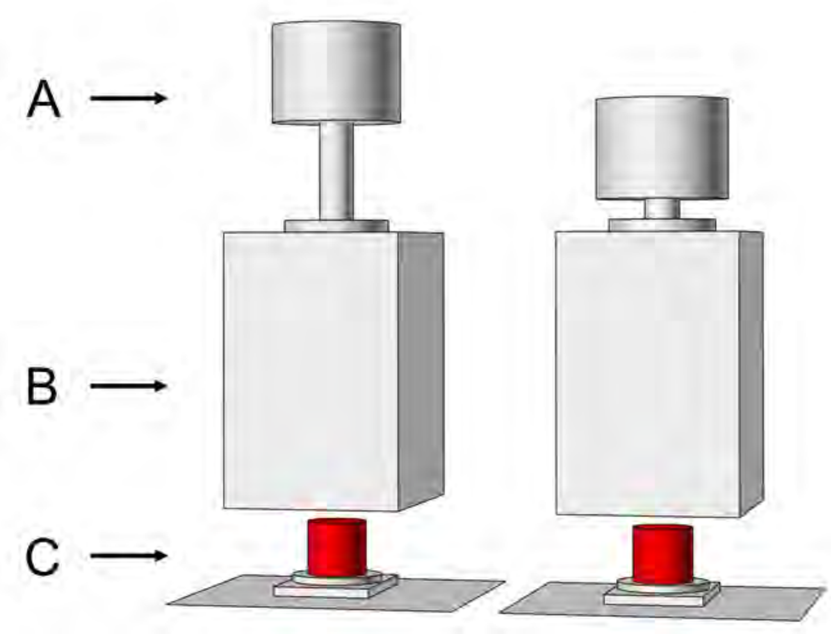

Figure 3.6.3: Actuated pin - schematic. (A) solenoid head (B) bi-directional push-pull solenoid (C) tact switch push button. Two states of the pin head are possible, e.g. outwards (left) and inwards (right). Interacting with the pin head pushes the solenoid down on the button.

As the final user interaction, the head of the solenoid can now manually be pushed down to achieve the state *zero*. The tact switch button mounted below registers this pressing and the new position is updated in the micro-controller. A next pressing of the solenoids head in its inwards position again triggers that tact switch button mounted below, which leads the micro-controller to send a command that lifts the solenoids

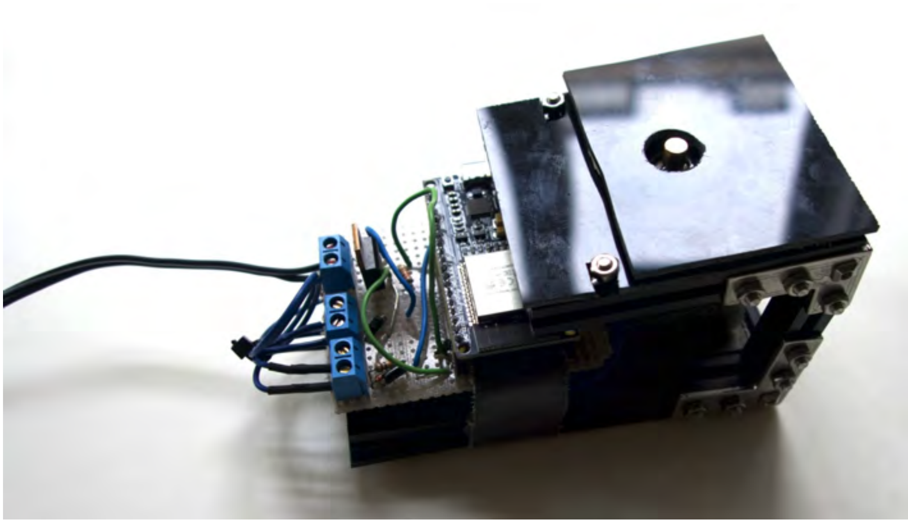

Figure 3.6.4: Prototype of a single tangible pin.

head outwards. In this way the bi-directional solenoid in its configuration with a button mounted below controlled by a micro-controller, can be used as a binary input device, as well as an interactive binary out device. This configuration was realized as a working prototype with a single interactive pin (see Fig.3.6.4).

3.6.2 Prototyping Tangible Pins

Following the development of the single *tangible pin* prototype, the next iteration of the interface used its technical design and created an arrangement of eight *tangible pins* in a row (see Fig.3.6.5). The decision to use the number of eight pins was made in order to provide a balance between technical complexity as well as meaningful musical interaction of a step-sequencer. To realize the interface, a custom circuit board was designed to host the micro-controller as well as motor controls for the eight bi-directional solenoids. The design of the housing allowed the solenoids to float freely, in order to physically transmit the manual pressing towards the buttons placed below the solenoids.

3.6.3 Main Features

The final version of the *tangible pin* interface (see Fig.3.6.6) provides following key features:

- **Pins.** Actuated pins enable bi-directional manual interaction and the physical display of binary digital data.
- **Pattern.** Eight interactive pins in a row can be used represent patterns of a musical step-sequence.

- **Serial Port.** Embedded micro controller for data processing, sending and receiving of serial messages, and for updating the pins.

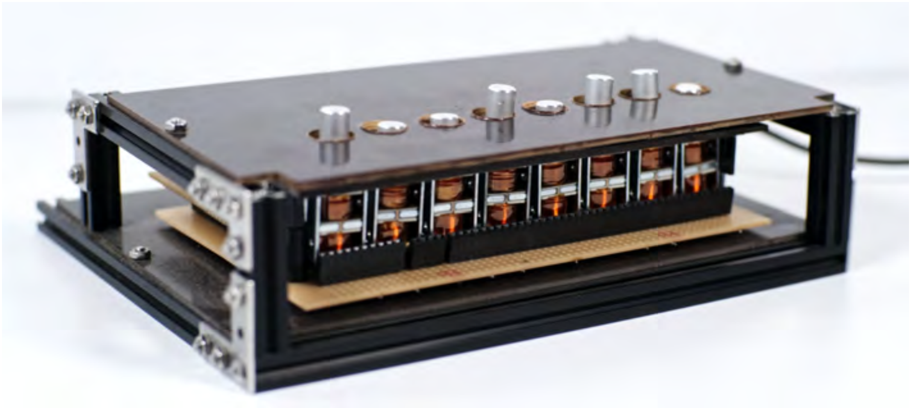

Figure 3.6.5: Prototype *tangible pins* with 8 actuated pins.

Figure 3.6.6: Tangible pins interface.

3.6.4 Technical Implementations and Hardware Design

The *tangible pins* interface was realized based on the use of the micro-controller ESP 32, which was programmed using the Arduino software. The used electro-magnets are bi-directional solenoids operating on 12V/DC from the type *"repelling and attracting"* with a power of 35W. The eight electro-magnets were controlled by four L293D motor driver ICs, which can be used to each control a set of two DC motors or electro-magnets simultaneously in any direction.

The electro-magnets were mounted in a flexible way into the device by using two layers of fixation. A bottom plate holds the electro-magnets in place with a fitting and prevents sliding and shifting. A top plate provides a guide for the shaft of the solenoid through centered holes, which defines their position. At the end of the shaft a custom-made aluminium head is mounted. The electro-magnets including their pin heads is mounted into the housing in a way, that the aluminium heads in their inwards position are leveling with the surface of the housing. Only when they are pushed outwards, they protrude above the housing.

For their operation the solenoids draw larger amounts of power, which is why a small latency of around 20 milliseconds was implemented for controlling all eight solenoids together at the same time. For instance, when all solenoids should be pushed outwards simultaneously, the latency leads to a chain-like operation, where one solenoid is pushed outwards after the other. When powering the device, a start routine sets all pin heads first high and then to their lower position to ensure that all pins start with the same state, independently of their previous positions. Likewise, latency is also used for the detection and operation after button presses. If a button press is detected, the software embeds a small latency to provide some delay to remove the finger before pushing the pin head outwards, which otherwise could interfere with the pressed pin head.

3.6.5 Applications and Possible Use Cases

The *tangible pins* interface is designed to represent and display binary states of digital data in a row of eight actuated pins. The primary use case is to represent eight steps of a musical step-sequencer. Thereby the device is designed to be connected to the computer as a tangible interface, but it could also be adapted to be used with stand-alone step-sequencers. Furthermore the eight available actuated pins could be used to represent other binary musical information, such as mute states of separate tracks in a music software. They could also be used to represent and control play states and mutes states of separate sample loops (see Chapter 3.10.2). An experimental usage of the eight pins could be is use as simplistic keys similar to a MIDI keyboard to trigger note-on and note-off events. The design of the interface could also be scaled up towards a higher number of pins per row as well as an arrangement in multiple rows. A higher number of pins and rows would permit the representation and control of more steps in a sequence, or the control of more than one instrument sound.

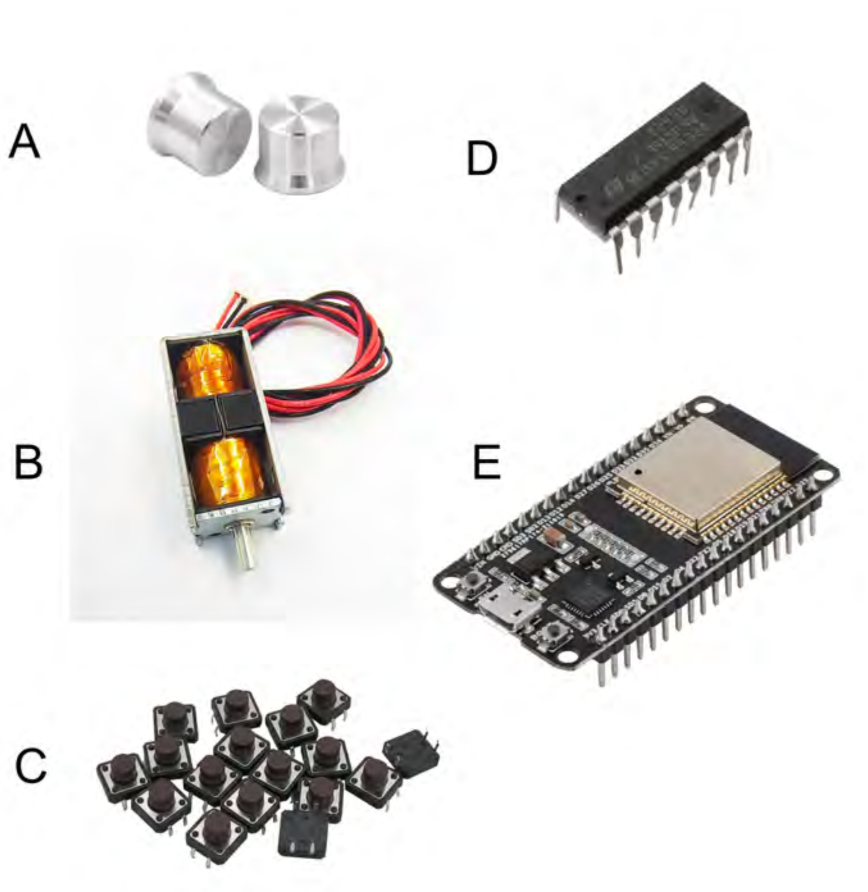

Figure 3.6.7: Tangible pins - components. (A) aluminium pin heads (B) bi-directional electro-magnets or solenoids (C) tact switch push buttons (D) motor control IC L293D (E) ESP 32 micro-controller.

3.7 INTERFACE - TANGIBLE STRING

This section will present the process and results of developing the *Tangible String* interface in detail.

The inspiration for the development of the interface and its sonic interactions is based on the concept of *modulation* as a musical strategy to alter sound and compositions through the manipulation of musical parameters, in order to add texture, contour and surprise to sound and music (see Fig.3.7.1). Modulation can be produced manually, e.g. the modulation wheel on a keyboard, as well as can be generated automatically through *low-frequency-oscillators* (LFOs) with respective waveforms, or other kinds of repeated control signals, e.g. noise as a modulation source.

The design of the prototype continues the initial research proposal of a multi-functional tangible prototype based on the arrangement of numerous motorized faders in a row, that are connected by a flexible

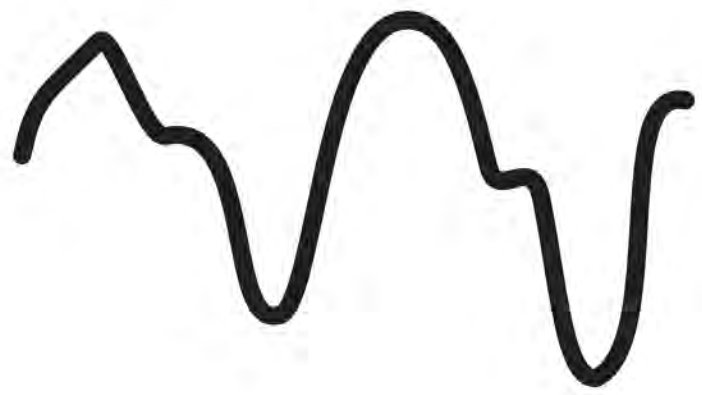

Figure 3.7.1: Noise as a waveform inspired tangible sonic interactions based on *modulation*.

band in order to abstract the single positions into one overall representation as a tactile curve or graph (see Chapter 3.1). Thereby the inspiration from the tactile waveforms shifted the focus away from providing *many discrete parameters to describe a waveform*, towards the contrary and somewhat simpler approach of using *few parameters to enable flexible sonic modulation*.

3.7.1 Prototyping Physical Waveforms

To investigate the physical shapes and manipulations of waveforms, a simple prototype was designed using multiple pieces of flat plastic, that were assembled using rivets as joints for the segments. The goal was to explore the mechanical behavior of this abstract and flexible form, and how it reacts in order to form different kinds of shapes or waveforms (see Fig.3.7.2).

The experimentation revealed a number of insights into the creation of a physical curve. It became clear that mainly two aspects influence the possible results, which are the number of segments of the prototype in combination with the length of the segments. The eight segments enabled the display of various different forms, as shown in Fig.3.7.2. But the total number and the length of the segments also limits the possibility of creating more complex waveforms.

Rather then adding more segments to create more complex waveforms, it seemed interesting to explore the reduction of the number of segments, in order to find the lowest number of segments, that would still allow to display a waveform. For instance, the *triangle wave* (B) or the *square wave* (C) shown in Fig.3.7.2 could have been described with fewer segments than used in the prototype. The minimum amount of

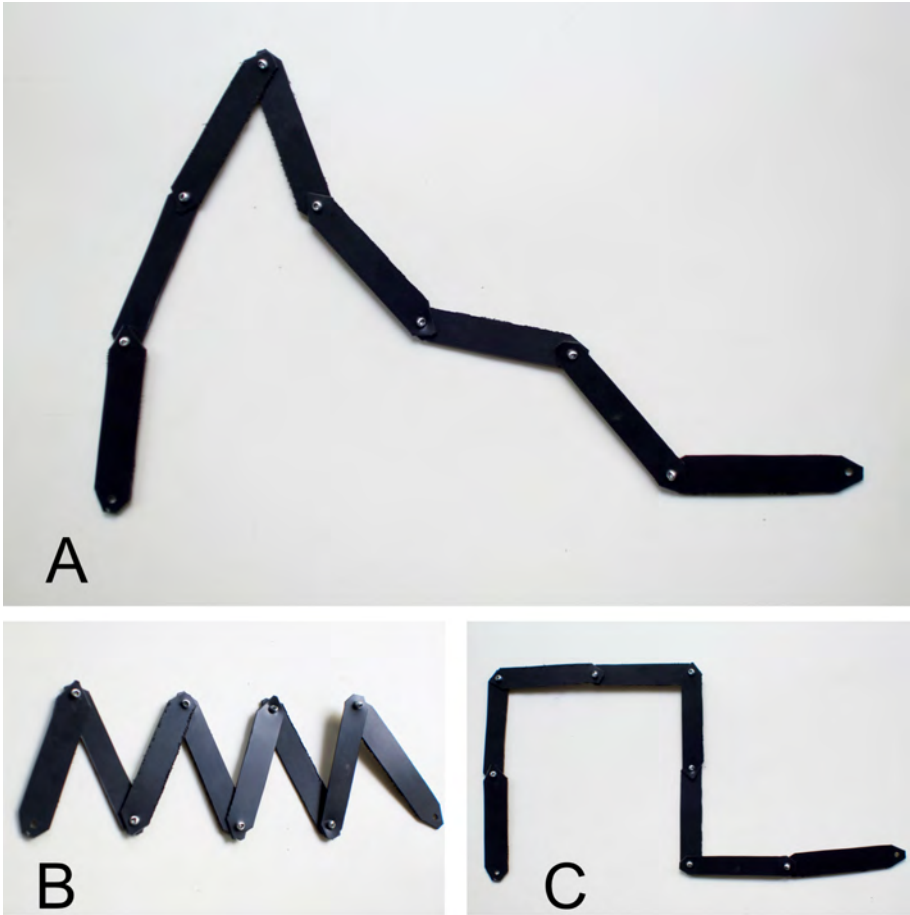

Figure 3.7.2: Prototype for experimentation with mechanical waveforms with 8 segments. (A) envelope (B) triangle wave (C) square wave.

segments necessary to describe waveforms seemed to be three segments and the according four variable joints. The result of this experimentation is the insight, that three segments are enough to represent a range of simple waveforms or graphs, e.g. square wave, triangle wave, or a simple *attack-decay-release* (ADR) envelope.

3.7.2 Prototyping Variable Graphs

The next iteration of the prototype focused on the creation of more diverse shapes and curves through variable length of the three segments. To accomplish variable lengths, different materials were tested, such as rubber bands or metal springs, but none of them was flexible enough to allow the necessary degree of stretching and contracting. Instead, a continuous string was used that replaced the separate segments. It was passed through the four joint points and thus enabled variable distances between them (see Fig.3.7.3).

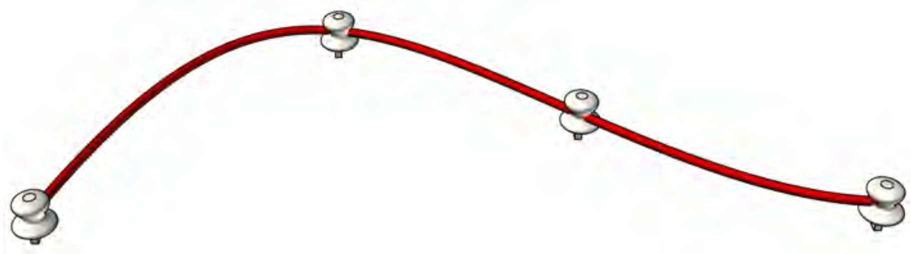

Figure 3.7.3: Variable waveforms - three segments with variable length through continuous string.

3.7.3 Prototyping Actuated Waveforms

In a next step the technical and mechanical realization of four movable points and the continuous string was explored. Thereby the use of off-the-shelf motorized slide potentiometers were considered as building blocks for the physical interface. These *"flying faders"* are commonly found in devices such as mixing decks of professional music studios, or motorized control surfaces for computer music setups.[22] The are equipped with potentiometers for the sensing of the fader position. Their motorization enables mechanical position changes, and their fader heads allow capacitive touch sensing to detect manual interaction.

A first simple prototype design was created based on the elastic string connected to four motorized points. To provide tension over the entire string length, a simple tension mechanism based on weights was added. To increase the position variability of the four motorized points, a 2D configuration was considered, in which the left and right points are mounted on fixed positions for vertical movement, whereas the two inner points are able to move both vertically as well as horizontally.

An experimental interface was developed, in which four *"flying faders"* were mounted vertically on rails, whereby the two inner motor faders were able to slide on the rails using rubber bearings. To enable horizontal movement, two additional motorized faders were mounted below to move the both inner motorized faders and thus enable their 2D positioning (see Fig.3.7.4). The resulting prototype and its 2D design enabled the display of simple graphs and waveforms with variable lengths based on four movable points and three segments.

3.7.4 Prototyping Tangible String

As a next step, a functional interface was created based on the previously describe configuration of motorized faders. The interface enabled

[22]https://learn.adafruit.com/flying-faders/overview

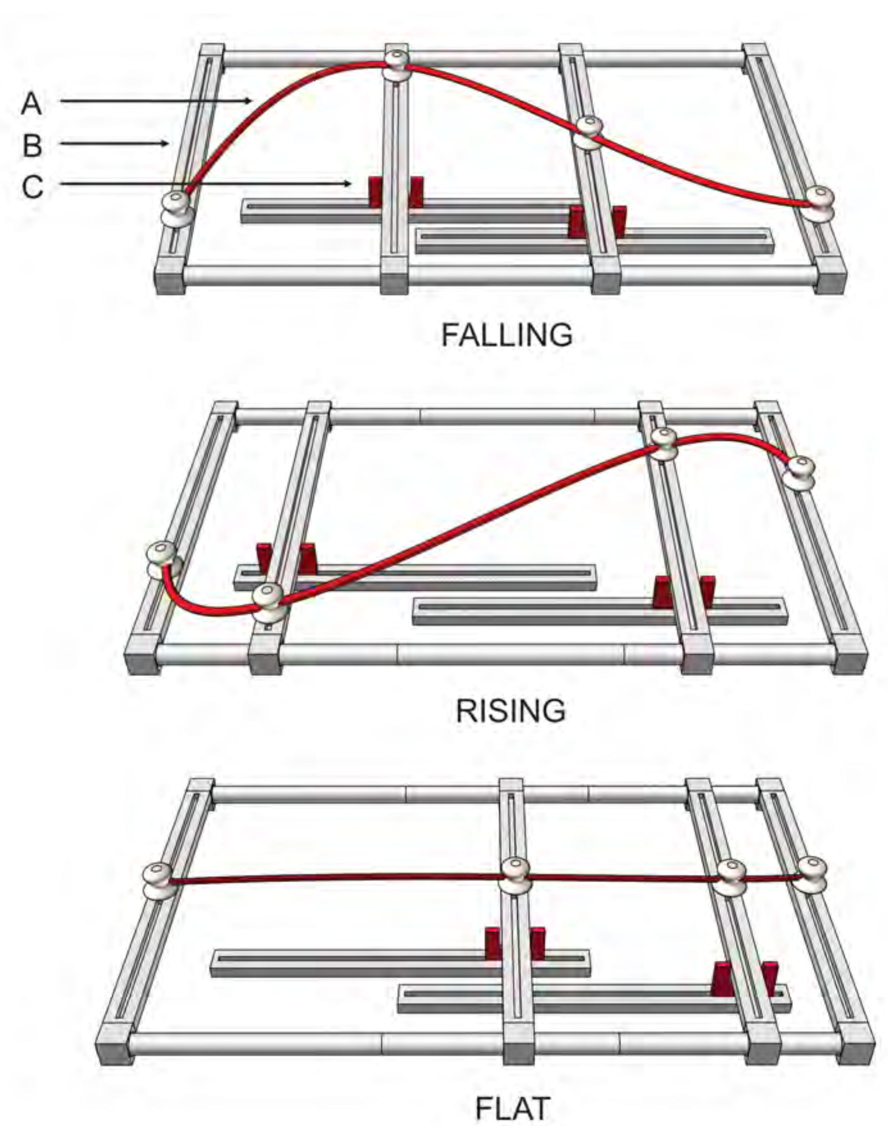

Figure 3.7.4: String interface schematic. (A) string connected to four fader heads (B) vertical faders with attached fader heads (C) horizontal motorized sliders. The effects of different fader and slider positions are displayed in three potential shapes: *rising*, *falling* and *flat*.

the physical representation of simplified waveforms. It also enabled manual re-configuration of single segments or the entire waveform (see Fig.3.7.5).

In order to ensure suitable tension of the elastic string, both ends of the string were mounted to a tension mechanism based on metal springs, which balanced the loosening and tightening of the string during its operation (see Fig.3.7.6).

The final *tangible string* interface was enclosed in a metal housing to ensure safety for the users as well as to protect the electronic components (see Fig.3.7.7). Furthermore it provides capacitive sensing

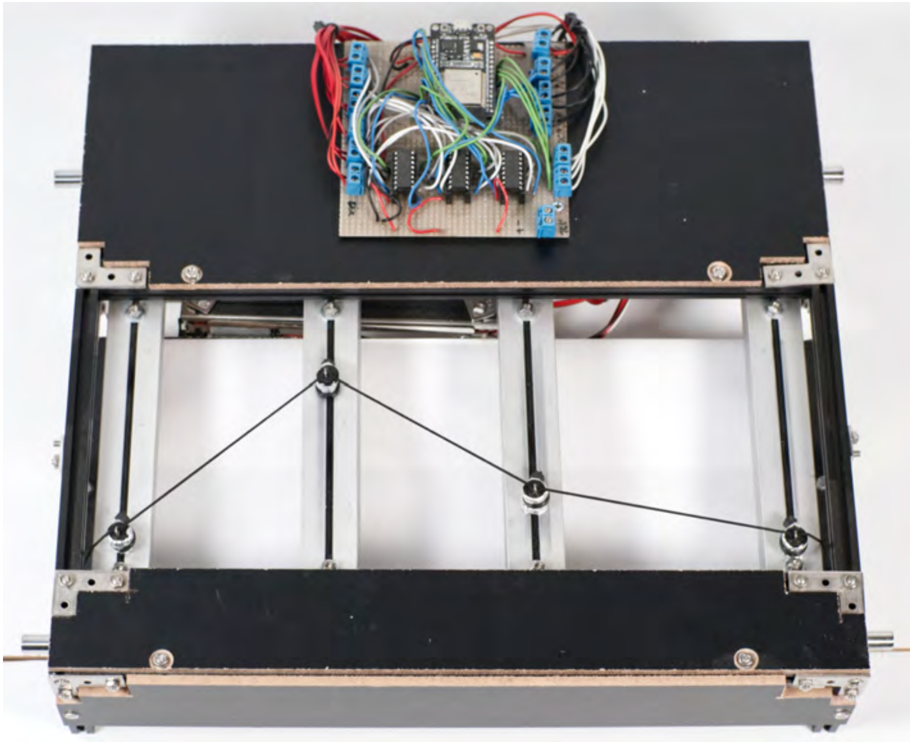

Figure 3.7.5: Prototype *tangible string*.

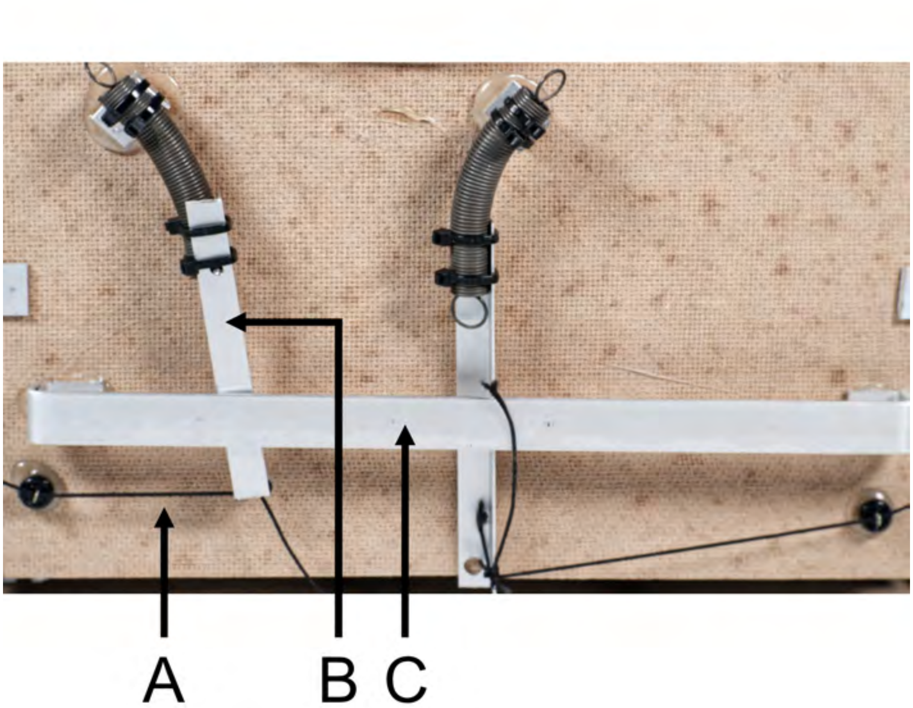

Figure 3.7.6: Prototype - spring tension mechanism. (A) string (B) extension arm connected to a metal spring (C) metal rail for the extension arms to reduce friction.

Figure 3.7.7: Tangible string interface.

for the custom fader heads, which allows manual interaction through deactivating the motorized faders as long as touch is detected.

3.7.5 Main Features

The *tangible string* interface provides the following main features:

- **Tactile waveform.** The interface uses an elastic string to display tactile waveforms and graphs by reconfiguring the four contact points.
- **2D display.** The interface enables the 2D movement of the two inner contact points, which increases the variability of the displays curves.
- **Serial Port.** Embedded micro controller for data processing, sending and receiving serial messages, and updating the waveform and motorized faders.

3.7.6 Technical Implementations and Hardware Design

The *tangible string* interface is build based on six motorized faders, that provide four fader head contact points, whereby the two inner fader heads are able to move both vertically and horizontally. This horizontal movement is realized by moving the inner motor faders with additional secondary motor faders mounted below. The four motor vertical faders are mounted on custom carriages made of aluminium profiles. The carriages are then mounted on two rods of stainless steel with a diameter of 8mm, whereby the two outer carriages are fixed. The two inner carriages are moving with ball bearings on the steel rods. The four contact points are connected by a nylon string.

The total of six motor faders are connected to an ESP 32 micro-controller, which is programmed via the Arduino software. Three L293D motor driver ICs are connected to the ESP 32 micro-controller. They are used to control the six motor faders, and to move them in either direction. In the software, a PID algorithm was used to control the DC motors in order to enable smooth operation. PID stands for *Proportional Integral Derivative*, where the current speed of the DC motor is measured and compared with the desired speed.[23]

Each motor fader also provides position values, which are transmitted to the ESP 32. The fader heads enable to detect touch, which was implemented by using an external circuit board for touch detection connected to the ESP 32 board. The fader heads are custom made to provide both an eyelet for the nylon string as well as a touch sensitive handle for the operation. For the network communication of the ESP 32 with computers, the serial port of the micro-controller was used. It was made accessible via a mini jack plug at the housing of the interface.

A string tension system that is mounted below the motor faders ensures constant tension of string in all positions. To support smooth tensioning, PTFE Teflon tubes are used to guide the nylon string at both sides of the interface, where the string is bend to reach the bottom area. At the bottom area a custom spring-based tension system is mounted, consisting of two springs that are extended with 10cm aluminium profiles to regulate the tension.

The housing was realized by adapting an aluminium box of approximately 30cm width, 24cm length and 5cm height. The opening in the box cover was milled with a CNC machine.

3.7.7 Applications and Possible Use Cases

The *tangible string* interface is build to enable tangible interaction and physical representation of musical parameters, for instance to control the amplitude envelope of audio samples. For that purpose, the interfaces displays parameters of an amplitude envelope such as *attack*, *decay*, *sustain* and *release*. Another use case is the representation of a parametric equalizer curve. Therefore the left side of the string represents lower frequencies and the right side represents the higher frequencies. This use case resembles the initial proposal of a *tangible equalizer*. Likewise the interface can also be used to represent and control *wavetable synthesis*, as initially proposed as application for a

[23] https://www.instructables.com/Speed-Control-of-DC-Motor-Using-PID-Algorithm-STM3/

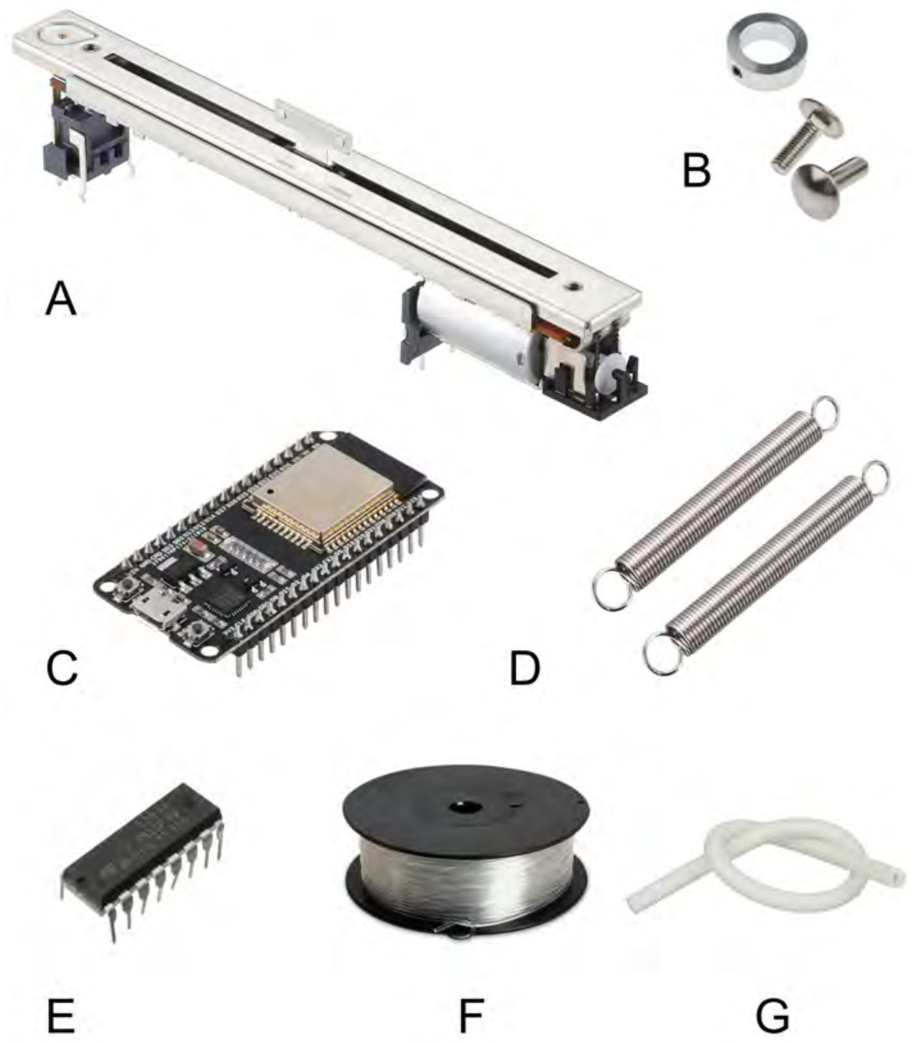

Figure 3.7.8: *Tangible string* - components. (A) motor fader with capacitive touch (B) shaft and stainless steel screw for custom fader head (C) ESP 32 micro-controller (D) metal springs (E) L293D motor control IC (F) nylon string (G) PTFE tube for low friction string tension.

multi-functional tangible prototype. The *tangible string* interface and its display of variable graphs and tactile curves could also be used to visualize other abstract forms such as mathematical functions or physical waves.

3.8 TANGIBLE INTERFACES SETUP

This section presents various attempts to integrate tangible musical interfaces into suitable computer setups. This includes initial experiments and finally the development of a MIDI connector interface.

3.8.1 Experimental Setup

During the development phase, the prototypes were connected to the computer using serial communication via the USB connector of the embedded micro-controllers and the computers serial ports. The serial communication was realized using a custom Python script, that enabled sending and receiving messages to the different tangible interfaces connected to the computers. The serial messages were converted to *Open-Sound-Control* (OSC) messages, a communication protocol that encodes musical control data for real-time communication with other software applications.[24]

A custom test software was developed in order to explore the tangible interfaces and their usage as interactive musical sound displays. The design of the custom test software was orientated towards the music environment *Welle* and its concepts of step-sequencer patterns, switching instruments and providing musical parameters such as volume or envelope settings (see Fig.3.8.1).

The software was written in SuperCollider, which was used for the sound generation and composition processes, to control the tangible interfaces and to provide a visual representation of the composition.[25] The experimental software consisted of four tracks, similar to the *Welle* sequencer design. Each track provided a fixed sample sound, a mute state control, a volume parameter control, an eight-step sequencer pattern and finally an amplitude envelope affecting the sample sound. In the graphical interface of the software, the different tracks were displayed as four rows on top of each other, providing the same elements. The volume parameter was displayed as a knob, while the mute state was displays as a checkbox. The musical pattern for the step sequencer was displayed as a sequence of buttons, of which the active steps were displayed with black color, whereas the inactive ones were displayed as white buttons. The envelope was displayed as a three-segmented line with four variable points in a rectangle, which displayed the combination of envelope values as a geometrical form. Below the four track rows an additional row of small, half-sized buttons changed their color from white to red in order to show the currently played step in a running sequence.

This experimental setup was used to explore the possibilities and limits of the tangible interaction with the interface during multiple sessions with VIB experts (see Chapter 3.9.1).

[24]https://ccrma.stanford.edu/groups/osc/index.html
[25]https://supercollider.github.io

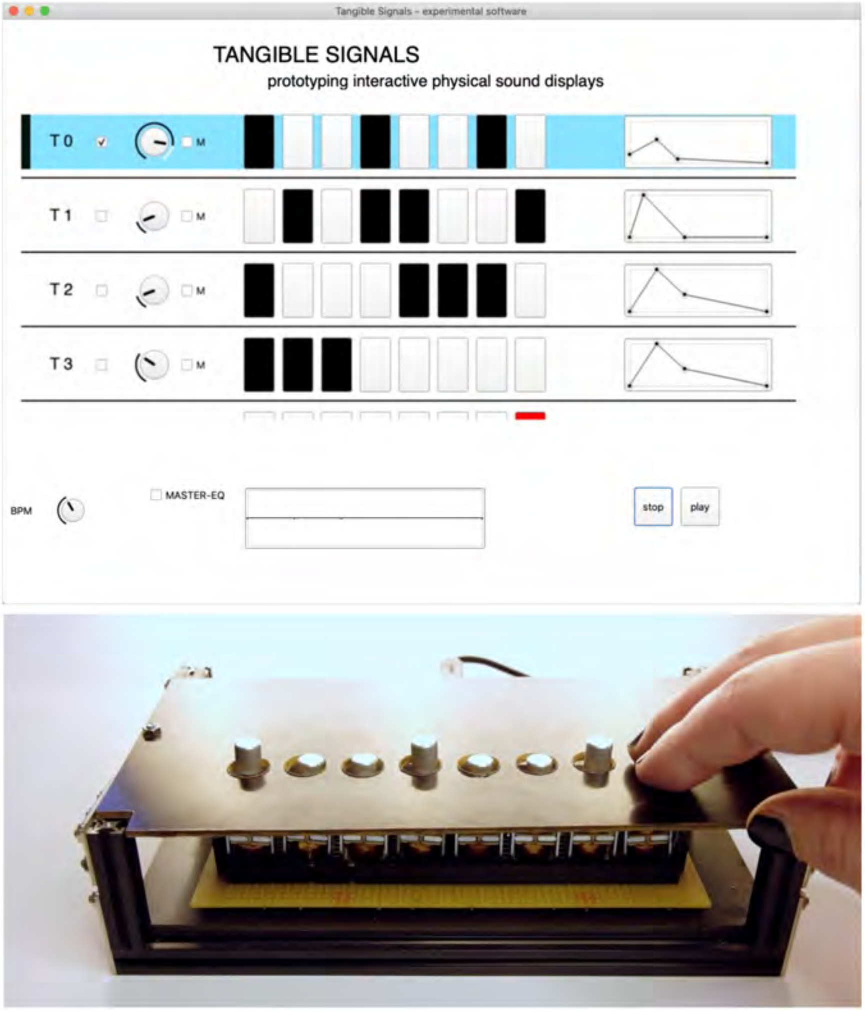

Figure 3.8.1: Experimental software (top) connected to the *tangible pins* prototype (bottom). Blue color in the software marks the current active track, whose pattern is represented at the pins interface.

3.8.2 MIDI Connector Interface

To provide a stable and robust connection between the tangible interfaces and the computer, a custom interface was developed based on MIDI communication. MIDI is a flexible and common way of sending and receiving musical data in music studios between music hardware and computer software. It provides commands for 128 possible notes, such as note-on, note-off, as well as 128 different control change messages (CC) with values from 0 to 127. Furthermore, USB interfaces for MIDI are often class-compliant and do not require any driver installation. The single tangible interfaces were connected to the MIDI connector device using their serial port connections. The MIDI connector device acts as a central messenger between computer and interfaces and was connected via USB cable to the computer. It was programmed to convert serial messages coming from the interfaces to outgoing MIDI for the computer, and MIDI messages coming from computer were converted to serial messages and send to the tangible interfaces (see Fig. 3.8.2).

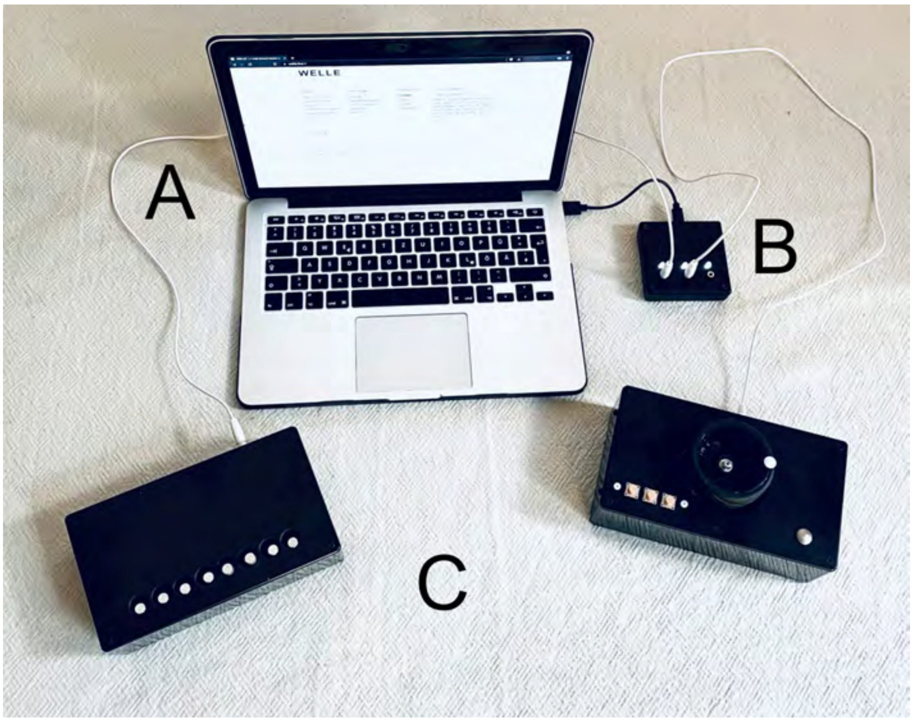

Figure 3.8.2: MIDI setup. (A) computer and music software *Welle* (B) MIDI connector box via USB to computer (C) two interfaces connected via a serial cable to the MIDI interface, *tangible pins* (left) and *tangible wheel* (right).

Figure 3.8.3: Development of MIDI interface using a micro-controller.

Figure 3.8.4: MIDI interface with two serial connections.

The MIDI interface was build using the micro controller Teensy 3.2, which is able to be configured as an *Human Interface Device* (HID) device (see Fig.3.8.3). The micro-controller is powered by the computer and its USB power. For the connection with the three tangible interfaces, the serial connection was realized via mono mini-jack cables, that can be plugged in the MIDI connector box (see Fig.3.8.4).

When an interface is plugged into one of the three sockets, the MIDI connector device confirms the detection of an interface by illuminating the according LED. The firmware of the tangible interfaces as well as the music environment *Welle* was updated towards the MIDI communication to correspond with the range of control change messages and available MIDI channels. This new hardware setup simplified the integration of the tangible interfaces into an accessible digital music setup, and also enabled a quick instrument setup. Especially when using different computers with different operating systems, e.g. Windows, macOS, or Linux, the setup is much easier and platform independent, since no drivers are required.

3.9 PRESENTATIONS, EXPERT FEEDBACK AND USABILITY

The following section provides an overview of the presentations of the music software and tangible hardware conducted with VIB experts and students throughout the research project. It also describes the preparation for a usability test.

A first series of meetings with VIB experts was conducted during the prototyping phase of the three tangible interfaces, with the aim to explore the overall interaction, as well as the accessibility of the prototypes and usability of the interaction elements. The expert feedback then informed the further development of the interfaces. A second series of meetings was organized after finishing the development of the tangible interfaces, during which VIB experts and musicians were able to explore the three tangible interfaces, the creation of musical patterns and the physical interaction with musical parameters. The inquiries and explorations by VIB experts are described in the following. The insights will be evaluated separately.

3.9.1 Prototyping Phase

During the prototyping phase the interfaces were presented, explored and discussed by VIB experts and musicians during two different meetings. Thereby a focus was on accessibility of the physical interfaces, their usability, as well as the underlying musical concepts. These meetings will be described in the following. The VIB expert feedback during the meetings was documented through notes and multimedia recordings.

VIB Experts and Studio Visit (2019)

The first meeting was conducted with the three blind experts and musicians Angela, Martin and Mario, who were associated with the BBI Vienna. Thereby Mario is an experienced multi-instrumentalist, programmer, as well as a digital and electronic music creator with his own music studio. The meeting was organized in November 2019 in the studio space of the author, where the VIB experts were presented with the three prototypes in their early states (see Fig.3.9.1).

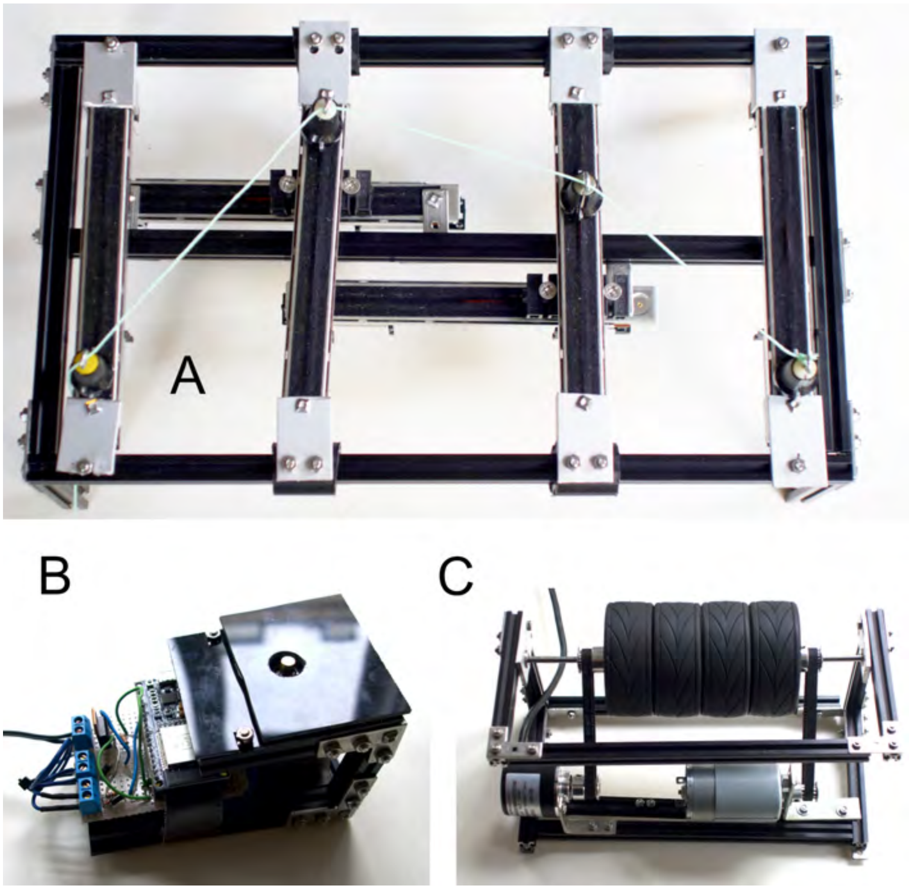

Figure 3.9.1: Tangible prototypes presented at first meeting with VIB experts. (A) "flying" waveform prototype (B) actuated switch prototype (C) vertical wheel prototype.

They were presented with the wheel interface in its early vertical form, with the rotary encoder attached (see Section 3.5.2). They also were presented with the single pin prototype, which already allowed functional interaction based on pressing the pin to switch between two alternating states (see Section 3.6.1). Lastly, the string interface was presented during this explorative feedback session. It was already actuated by motorized faders, and was able to move an elastic string (see Section 3.7.3). The prototypes for tangible interfaces were presented and discussed over a time of 3 hours. Their physical interaction elements were discussed, e.g. the rubber wheel, the metal pin and the elastic string of the string interface. Likewise, the interaction with the various elements was explored through touching, turning, rotation and pressing the interfaces and their interaction elements. Their interaction with a music software had to be imagined, since at the time of the meeting the interfaces were not fit for computer interaction.

The overall discussion touched on general aspects of research on accessible interfaces for the computer use for VIB users. The group discussed benefits of assistive technology such as refreshable Braille displays or devices such as the tactile computer mouse from *Virtouch*, technical aspects such as refresh rates of pins in Braille displays, as well as financial factors of assistive technologies.

Regarding the three tangible prototypes, the group commented on each of the interfaces, formulated suggestions for improvements, and shared their opinions on aspects of the interfaces that seemed ambiguous. In addition, the group proposed various possible use cases and application scenarios. Also, Angela described a desired imaginary device, that involved a combination of all the functionality of the prototypes.

Exploration and Feedback by Erich Schmid (2021)

The development of the prototypes continued after the inquiry and exploration of the VIB experts at the artists studio. The feedback received at this first studio session from the VIB experts was taken into consideration, and was then implemented in the next iterations of the development of the tangible interfaces.

After a number of subsequent iterations in the development of the prototypes, the devices evolved into functional tangible interfaces. These tangible interfaces were then presented to the VIB expert Erich Schmid. The exploration of the interfaces was conducted at the BBI in March 2021. It lasted approximately 1.5 hours and was documented on video (see Fig.3.9.2).

Schmid explored the updated tangible interfaces and their interaction elements, as well as accessibility aspects. Subsequently Erich Schmid used the tangible interfaces in combination with the experimental music software. He explored the creation of musical patterns, the control of the overall sequences as well as the control of parameters such as volume of the amplitude envelope of the according sample sound. During this explorative session, Erich Schmid commented on the overall impression of creating musical sequences with tangible interfaces

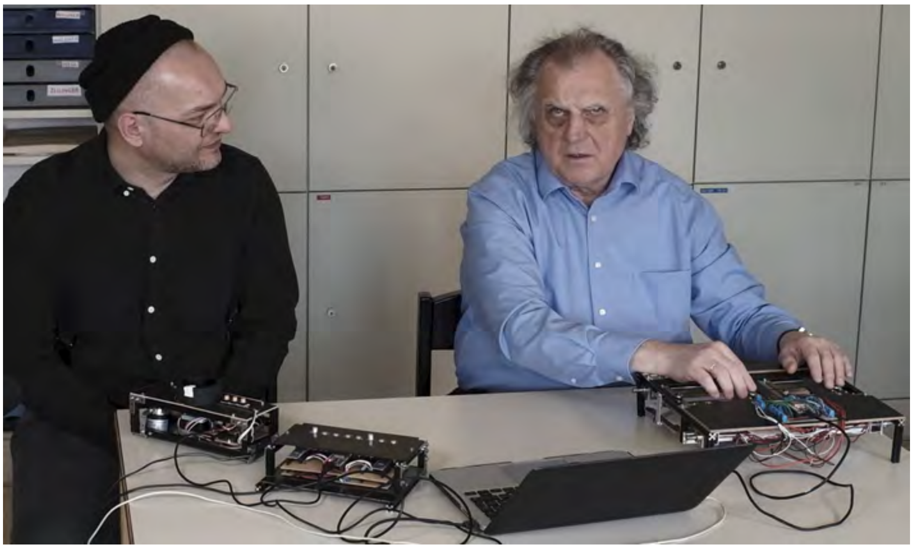

Figure 3.9.2: VIB expert feedback on the tangible interface prototypes with Erich Schmid.

Figure 3.9.3: Feedback on the *tangible pins* and *tangible wheel*.

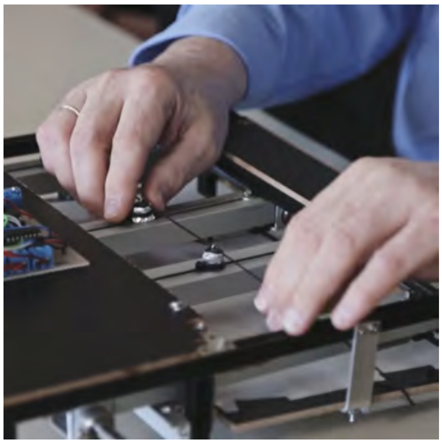

Figure 3.9.4: VIB expert feedback on the *tangible string* interface.

and commented on the various interaction elements and aspects of interface configuration and accessibility. Furthermore, he describe other possible use cases for the control of computer music software, as well as application scenarios besides their musical use, e.g. as general interactive computer controls in combination with the keyboard and the Braille display.

3.9.2 Explorations and Expert Inquiries

After finishing the development of the tangible interfaces, a series of artistic explorations and inquiries with VIB experts and musicians were organized, in order to investigate the use of tangible musical interaction as a means for accessible digital music-making (see Fig.3.9.5).

Figure 3.9.5: Tangible interfaces - *tangible wheel*, *tangible pins* and *tangible string* (top to bottom).

Explorations during OCC 2023

A series of meetings with VIB experts was conducted during the Austrian Computer Camp 2023 at the BBI Vienna. A studio desk was prepared with a Laptop computer and a connected stereo sound system. An additional third speaker was prepared in the room, to enable a basic multi-speaker surround sound setup with three loudspeakers. The three tangible interfaces were positioned at the desk in a row, starting on the left with the *tangible pins*, then the *tangible wheel* in he middle and on the left the *tangible string* interface (see Fig.3.9.7). This arrangement was chosen based on the relevance of the sonic features in regard to musical composition and performance from left to right, e.g. starting with creating patterns in a step-sequencer, adjusting the respective instrument volume, and manipulating the envelope for amplitude or effects. The tangible interfaces were then connected via the MIDI connector box to the computer, which provided access to both the music environment *Welle* as a musical platform, as well as the custom

Figure 3.9.6: Explorations with Erich Schmid at OCC 2023

Figure 3.9.7: Explorations at OCC 2023 - devices

Figure 3.9.8: Explorations at OCC 2023 - pupils.

music software developed for Erich Schmid and his music composition and stage performance (see Chapter 3.10).

Two explorative sessions with the VIB experts Erich Schmid and Ben Hofer were conducted and documented as an audio recording. During approximately 1 to 2 hours, both VIB experts were presented with the tangible interfaces. Each tangible interface was introduced, both as a physical interface with the respective interaction elements, as well as an interactive physical representation for musical aspects and sonic features related to the computer music software. Both VIB experts had time to create musical patterns and explore musical interaction of the according instruments and sounds with the interfaces (see Fig.3.9.6). Unstructured interviews were conducted based on questions regarding the tangible interfaces, the combined instrument setup including the music software, as well as questions regarding possible other use cases and general related topics.

Another explorative session was conducted with the VIB expert Martin Mayerhofer, who was already familiar with the concepts based on meetings during the prototyping stages of the interfaces (see Chapter 3.9.1). The tangible interfaces connected to a laptop computer were prepared on a table in the same configuration as described above (see Fig.3.9.7). During approximately 30 minutes, he explored the tangible interfaces and their musical interaction. Thereby the separate interfaces were explored, the combined setup was discussed, as well as possible other use cases.

Additionally, a 1 hour workshop was conducted with a group of three pupils aged between 12 and 15 years, that participated the OCC 2023. The pupils were all experienced with music and actively playing acoustic instruments. The tangible interfaces were presented to the pupils, including their musical concepts and connection to the computer music software (see Fig.3.9.8). The pupils were asked about their impression regarding the tangible interfaces, as well as possible other use cases.

Explorations during Studio Visit 2023

Another explorative session was organized with the blind expert and musician Mario Lang, who already encountered the first iterations of the tangible interfaces during the prototyping stage (see Chapter 3.9.1). The session was organized in his music studio and lasted approximately 3 hours. The session is documented as audio recording.

For the inquiry of the tangible interfaces and their integration as physical representations into the music software, a setup consisting of a computer and the three tangible interfaces was prepared, similarly to the previous setup at the OCC 2023 (see Fig.3.9.9). Thereby the computer was running both the music environment *Welle* as digital music platform, as well as the custom music software that was developed for the artistic staging for Erich Schmid (see Chapter 3.10).

The session started with an overall discussion of the artistic practice of VIB musicians in a music studio centered around electronic and digital sound generation, and on the musical background of Mario Lang. Various acoustic, electronic and digital instruments were discussed, as well as how they are used by VIB musicians, especially regarding accessibility aspects. This included computer music software, software instruments, and approaches and hurdles regarding accessible digital music-making. After this general discussion, a practical exploration of the three tangible interfaces followed. The devices and their tangible interaction were explored both separately as well as in a combined setup with the music

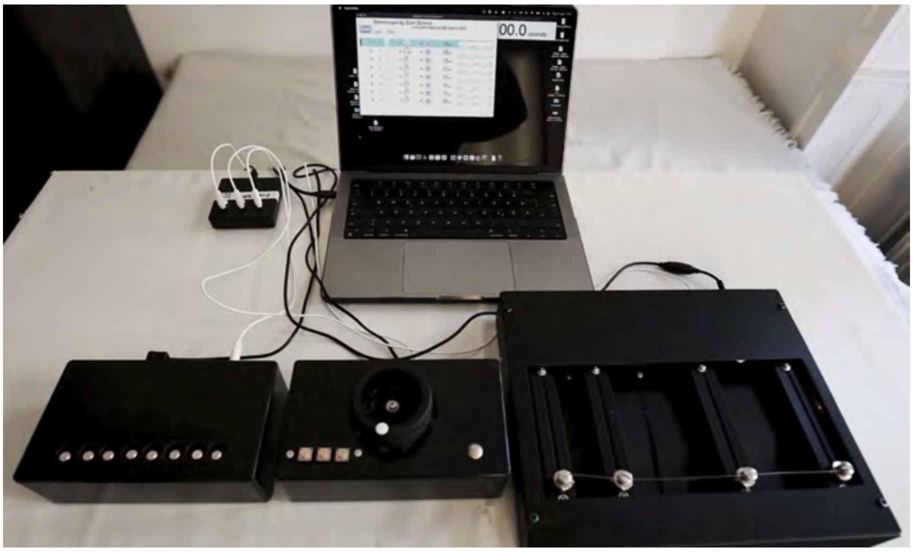

Figure 3.9.9: Setup for the exploration of accessible digital music-making, using tangible interfaces and various computer music software.

environment *Welle* and the custom loop-based music software. Lastly possible use cases and application scenarios were discussed.

3.9.3 Usability Test

In order to further explore the tangible interfaces, a usability test was prepared to investigate the musical interaction with the tangible interfaces connected to the music software *Welle*. The aim was to learn more about accessing musical sequences with music software and to compare them to tangible counterparts. As a result, the usability tests were abandoned in agreement with Erich Schmid, as described below.

Test Setup

A test setup was prepared to compare the interaction with an 8-step instrument pattern, using both the software *Welle* as well as the *tangible pins* interface, which were connected through the MIDI connector box (see Fig.3.9.10). Thereby the laptop computer running the music software *Welle* was placed on a table. The *tangible pins* interface was placed on the left side of it. A video camera was mounted above both devices in order to document the interaction, as well as spoken instructions and feedback as audio recording. A first usability test was conducted with a sighted person, in order to test out different tasks, before conducting regular tests with VIB musicians.

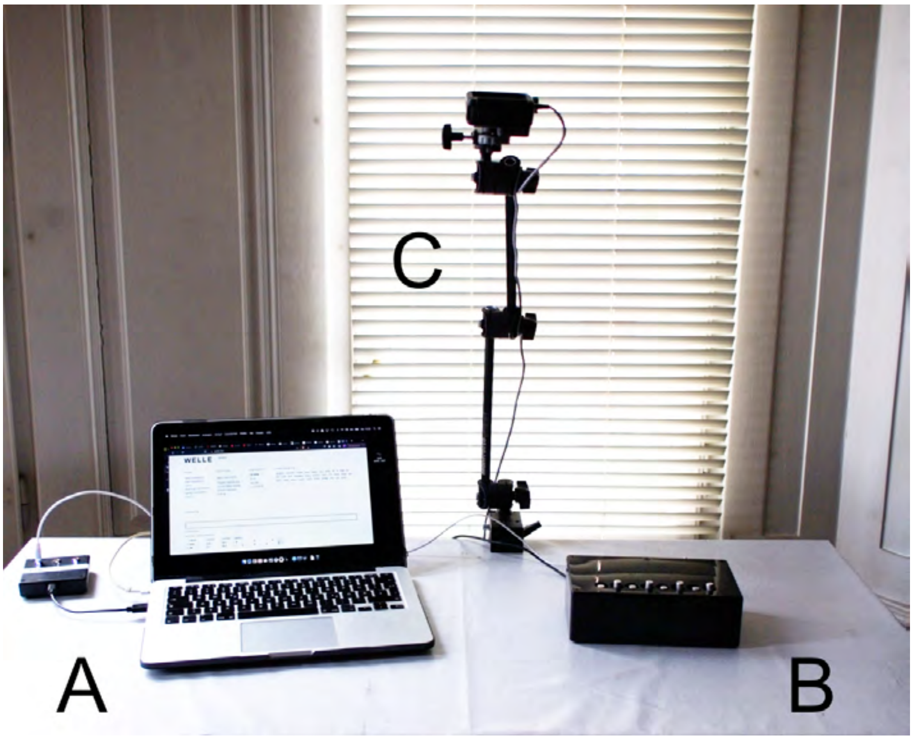

Figure 3.9.10: Setup for usability test. (A) computer with music software *Welle* (B) *tangible pins* interface (C) video camera to document the interaction with software and hardware, including audio recording.

Tasks

The sighted test person was asked to execute the following tasks with the provided software *Welle* and the *tangible pins* interface:

- As a first task, the sighted test person was asked to enter a rhythmic pattern into the music software *Welle*. Thereby the pattern was described verbally with *"hit, pause, pause."*, which the test person had to enter into the input field as the following notation: "# - -"
- As second task, the sighted test person was asked to configure the pins interface by setting a pattern at the available eight pins, that again was verbally announced as *"hit, pause, pause."*. This pattern had to be extended to fill all eight steps.
- The next task was to again enter a rhythmic pattern into the music software *Welle* and the hardware interface *tangible pins*. This time the pattern was not announced verbally, but was written down on a paper, and was described in the following notation: "# - - # # - - #"

- the last task was to change a running pattern into another pattern in both the music software and the tangible interface. The new pattern was announced again as written in the *Welle* notation: “# # # - - # - -”

Results

As a result of this preliminary usability test the sighted test person was able to accomplish all tasks such as to enter the patterns in both the music software *Welle* as well as setting the pattern at the *tangible pins* interface. As a feedback, the test person commented a *“feeling of just copying patterns”*. Other than that, the user test and the given tasks did not promise to reveal other relevant aspects of tangible interaction since the overall functionality and accessibility of the *Welle* music software and the tangible interfaces had already been tested during the prototyping and development phase. The usability test was then proposed to the VIB expert Erich Schmid. But in a discussion on potential insights, Erich Schmid preferred the use of artistic practice and the realization of musical compositions as a means to investigate tangible interaction and accessibility. Likewise, the author agreed to focus on the artistic practice instead of pursuing usability tests. Subsequently, the usability tests were discontinued.

3.10 ARTISTIC STAGING

As an integral component of the artistic research project, this section provides a detailed description of the artistic staging that incorporates the developed tangible musical interfaces. It covers the artistic concepts, preparations, technical setup, and final stage performance.

Incorporating tangible musical interfaces into artistic practice is essential to evaluating their impact on musicians’ ability to compose and perform a musical piece. To this end, blind musician Erich Schmid agreed to compose and present a musical piece as a stage-based live performance using the tangible musical interfaces. This artistic staging was documented, and the insights gained from this activity will substantially contribute to answering the research questions. The artistic process, creation of the audio loops, musical setup, and final performance will be described below.

3.10.1 Preparations and Accessible Music Setup

For the realization of the artistic project by Erich Schmid, a number of preparations were necessary, including support for the creation of sound recordings or assistance for the studio setup (see Fig.3.10.1).

Figure 3.10.1: Erich Schmid working in his music studio.

Schmid's studio setup consists of a studio computer running Reaper with OSARA as accessibility extension. OSARA enables access to various musical elements of Reaper, such as information on tracks, transport controls or sound items. As MIDI keyboard, Schmid uses the Native Instruments *Komplete Kontrol* that also provides accessibility features, e.g. built-in speech output and integration of the various controls into the local screen reader software. During multiple meetings with the author, Schmid's studio setup and the software configuration of Reaper was adjusted, and additional audio plugins were installed.

3.10.2 Artistic Process

As musician, Erich Schmid has a musical background in playing the piano, composing various pieces for church choirs, as well as conducting choirs and various music groups. He combines experimental approaches with traditional music composition, which is complemented by his interest for computer technology.

Inspired Sounds

Regarding the sonic material for his composition, Schmid focused on the *echolocation* technique used by many VIB individuals for orientation and navigation. This technique uses echoes from clicking sounds that bounce off objects and surfaces in the environment. This behavior is also observed in animals such as bats and dolphins. *Human echolocation* also receives continuous attention based on new insights into neuroplasticity and how the human brain processes novel sensory information [Thaler and Goodale 2016]. As Schmid explains, he grew up in the Austrian countryside and had been using this orientation technique since his youth. He had practiced producing sharp, short clicks with his tongue. He then listened to the echoes of these sounds and trained himself to distinguish walls and doors and to perceive other obstacles. He perfected echolocation to such a degree that he could ride a bicycle despite being blind.

Schmid recorded himself producing a series of sharp clicking sounds and edited them into short audio samples. He then used these samples as the sole musical material for his compositions.

Figure 3.10.2: Human echolocation [Thaler and Goodale 2016]

Audio Loops and Music System

Schmid created multiple audio loops based on his recorded sample sounds. The loops ranged in length from four seconds to two minutes and were grouped into three compositional parts. Each part consisted of eight loops. To evoke the idea of echolocation and spacial environments, Schmid used a multi-channel sound setup that enabled the use of variable room sizes and sound reflections.

A custom music software was prepared by the author, that enabled the control of multiple audio loops in the multi-channel sound setup (see Fig.3.10.3). The software was written in SuperCollider. In addition to playback controls for audio loops, the software provided access to panorama and volume controls. Lastly, the software implemented an audio delay effect to explore echolocation as a musical practice artistically by using room reverberation.

Schmid's composition consisted of three parts that could be stored in the software and recalled using the first three number keys on the computer keyboard. The three tangible devices were integrated into the custom music software to control different audio tracks and their respective parameters. Various computer keyboard keys could also be used to select audio tracks or switch the functionality of the *tangible wheel* interface (see below).

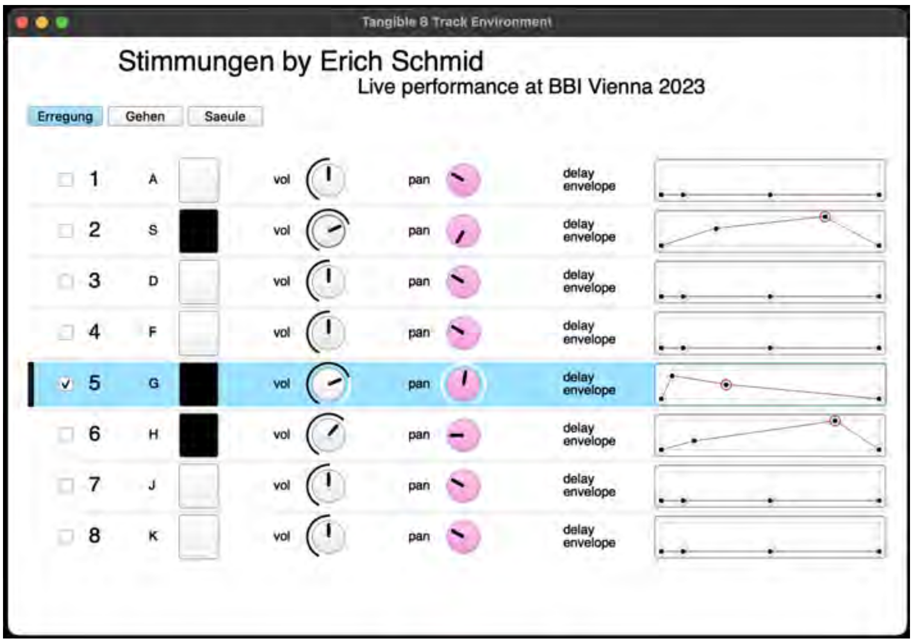

Figure 3.10.3: Screenshot of custom music software for the composition and performance of the piece *Stimmungen* by Erich Schmid.

Hardware Setup

The hardware setup for the stage-based performance was based on using a laptop computer including an external audio interface with four output channels. A three-channel speaker setup was prepared in a triangle arrangement, where two speakers were placed on the left and right side on the stage, and a third speaker was placed at the back of the audience to enable the most amount of depth.

Figure 3.10.4: Hardware setting for the stage performance, including a laptop computer, a computer keyboard and three tangible interface.

The musical controls, sound parameters and effects settings were both represented visually in the GUI display, as well as represented physically through the three available tangible hardware interfaces, e.g. the *tangible pins*, the *tangible wheel* and the *tangible string* (see Fig.3.10.4).

Each tangible interface controlled a different aspect of the music software composition, according to the following description:

- *Tangible pins.* The interface controlled the playback of eight audio loops. Each pin indicated either a running or stopped playback. Activating the pin by pressing it started the underlying audio loop. Starting an audio loop automatically selected the respective track for the interaction with the other devices.

- *Tangible wheel.* The interface controlled volume and panorama of the selected audio track. As a panorama control, the wheel enabled continuous movement of sounds across the three speakers in the room.

- *Tangible string.* The interface provided access to the Delay audio effect. Thereby the envelope curve controlled effect settings, such as the amplitude, the delay time, the delay feedback and the dampening of the signal.

The music software stored the settings for each audio track. The hardware devices were updated with the respective settings when selecting a new track. This way it was possible to use the tangible interfaces as displays for the respective selected track and its settings.

3.10.3 Staging and Live Performance

Over a period of three months in 2023, Erich Schmid prepared and composed the musical elements for his piece *Stimmungen*. During the composition, Schmid focused on improvisation and the musical freedom to perform spontaneous breaks and changes. The piece was first presented during an evening event at the Austrian Computer Camp (OCC) in 2023 in the auditorium of the BBI in Vienna.

Figure 3.10.5: Performance and audience at the OCC 2023.

The stage was prepared with stable metal table as a stand for the musical instruments and the computer. The multi-channel sound system was installed using two speakers on the stage as well as a third speaker in the back of the audience. The instrument setup including the computer, audio interface and tangible interfaces was prepared as described above (see Fig.3.10.4). Erich Schmid used paper notes with embossed Braille to organize his performance. He placed these notes on the table next to the tangible interfaces. In the audience were ap-

Figure 3.10.6: Artistic performance Erich Schmid at the OCC 2023.

proximately 40 persons, mainly pupils, teachers and other participants of the OCC (see Fig. 3.10.5).

At the beginning of the stage performance, Erich Schmid welcomed the audience and introduced the musical piece by describing the artistic concept of *echolocation*. This was followed by the eight-minute live performance of his piece *Stimmungen* (see Fig. 3.10.6). The performance can be found online.[26] Insights from the video documentation, subsequent interviews, and observations will be used for the evaluation.

3.11 SUMMARY

This chapter summarizes the practical work realized during the research project. It details the initial research proposal, discusses the development of the accessible music platform Welle, and sketches the inspiration for the various interactive devices, as well as their development and technical implementation. Additionally, the chapter summarizes the presentations, expert feedback, and artistic explorations of tangible interfaces. It also describes the preparation and realization of a musical composition and stage-based presentation of an original musical piece by Erich Schmid.

[26] Erich Schmid, *Stimmungen* live: https://youtu.be/QqHM-HToAug

Chapter 4

Evaluation

This chapter evaluates and discusses the various activities, obstacles, and insights gathered in the course of the practical work. Using qualitative analysis, it aims to answer research questions, formulate critical perspectives, and identify specific problems. The evaluation is based on insights from initial workshops at BBI Vienna, observations during sonic experimentation and the development of the music environment *Welle*, and musical explorations and the artistic process of VIB expert Erich Schmid. Experiences from the development process of the tangible interfaces, as well as inquiries and explorations by VIB experts, will be included in the evaluation. Likewise, unstructured interviews with VIB experts and musicians will be included in the evaluation, along with their insights. The discussion will cover various aspects of accessible digital music-making, such as the computer as an accessible musical instrument, inclusive music software design, assistive technology, sonic interactions with tangible interfaces, observations of artistic practice, and suggestions for further use cases.

The following material for the evaluation was collected during workshops and practical sessions throughout the research period:

- Observations of accessible digital music-making and discussions during lectures and workshops with VIB pupils at BBI Vienna and OCC between 2018 and 2019 (memorandum)
- Inquiry of tangible interaction for computer music including exploration of the first iteration of tangible prototypes and discussion with VIB experts in 2019 (memorandum)
- Exploration of tangible interaction for computer music, and inquiry of the second iteration of tangible prototypes with Erich Schmid in 2021 (video recording)

- Inquiry of tangible interaction for computer music, exploration of the three tangible interfaces, and interview with Erich Schmid in 2023 (audio recording, memorandum)
- Exploration of tangible interaction for accessible digital music-making using the three tangible interfaces, and interviews with VIB experts Ben Hofer, Mario Lang and Martin Mayerhofer in 2023 (audio recording)
- Demo with three tangible interfaces and feedback from VIB pupils during OCC 2023 (audio recording)
- Observation of artistic practice and stage performance by Erich Schmid, his use of tangible interaction and the three tangible interfaces in 2023 (video and audio recording)

4.1 STUDY FRAMEWORK AND LIMITATIONS

To further contextualize the research project, this section reflects on its study framework, limitations, inclusion critera and participant diversity, as well as an ethics statement. The research project was conducted at the Tangible Music Lab of the University of Arts Linz in collaboration with Erich Schmid and the BBI Vienna. It involved the participation of multiple groups of VIB pupils and experts. The following section describes the inclusion criteria, formulates an ethical statement and comments on study limitations.

4.1.1 Inclusion Criteria and Diversity

The inclusion criteria for the participation in the research project was an association with Erich Schmid, the BBI Vienna as well as the Austrian Computer Camp (OCC). The participating pupils were either studying at the BBI Vienna or participating the OCC computer camp in 2019 and 2023. Other participants were teachers of the BBI and associated VIB experts, such as Ben Hofer, Mario Lang or Martin Mayerhofer.

Regarding the diversity of the participants, the VIB experts were all Austrian white male persons between 30 and 65 years. The participating pupils were between 9 and 16 years old. In total 25 VIB persons participated the research project from its beginning in the autumn of 2018, until the last activities during the OCC 2023. From those 25 VIB participants, 48% were male and 52% were female.

4.1.2 *Ethical Statement*

The research project was realized in collaboration with the BBI Vienna and was based on a close work relationship between the author and the VIB expert Erich Schmid, who worked as a teacher at the BBI Vienna. Schmid invited the author to conduct research activities in two of his classes at the BBI, which were the classes *"Kreatives Gestalten"* from 2018 and *"Praktische Grundlagen"* from 2022. The pupils in the two classes were between 14 and 16 years old, with a total of 11 pupils. None of the pupils was forced to participate the research activities, e.g. digital music-making using the music environment *Welle*, or exploring the various tangible musical interfaces. The engagement in the research activities was voluntary. The work with the pupils was based on mutual respect, respectful communication and awareness towards personal rights and boundaries. Multi-media documentation such as images, audio recordings or video recordings were only taken with permission.

Erich Schmid also invited the author to participate at the Austrian Computer Camp 2019 to conduct a workshop on accessible digital music-making. This workshop was realized with eight participants, of which six were VIB pupils aged 9-16 years, and two participants were VIB teachers, who chose to participate voluntarily. During the next Austrian Computer Camp in 2023, another workshop with VIB pupils was realized, which was also based on voluntary participation. As part of the research project, Erich Schmid offered to realize a musical composition using the tangible musical interfaces and to perform it live on the stage during the OCC 2023. All other VIB experts also participated the research activities voluntarily.

4.1.3 *Study Limitations*

The research project faced a number of limitations and constraints. One of the limitations was the low number of VIB participants involved. In particular the pupils at the BBI Vienna had no prior experience in using the computer for musical expression, neither as an audio recording device, nor for the composition of musical pieces or as a platform for musical performance. This situation shifted the focus at the beginning of the research project away from tangible interaction and towards accessible computer music software, which was both insightful but also limited the time and resources projected for the exploration of tangible musical interfaces.

Another limitation was the constant changing groups of pupils during the research period of 5 years at the BBI Vienna and at the Austrian Computer Camp. Four different groups of pupils participated the workshops and explorations, which had to be introduced to the concepts anew each time.

A major disruption of the research project regarding the organization of personal meetings, workshops and musical explorations was the occurrence and the implications of the COVID-19 pandemic. The pandemic and its substantial threats to health started in the beginning of 2020, which was the third year of the research project. All workshops and meetings at the BBI Vienna had to be canceled and the school closed its doors for external persons for two years entirely. Likewise the OCC computer camp, which proved to be a great place to explore musical tools and interaction with VIB pupils, was suspended due to COVID-19 in the years 2020 to 2022.

4.1.4 Conflict of Interest

Regarding the realization of research project as part of the *Tangible Music Lab* at the Institute for Media Studies at the University of Art Linz, and the collaboration with Erich Schmid and the BBI Vienna, there exists no conflict of interest. There exists neither any financial conflict of interest or intentions regarding the outcome of the research project, nor exist any conflicting personal relationships with one or more participants of the research project.

4.2 ACCESSIBLE DIGITAL MUSIC-MAKING

This section discusses accessible digital music-making as one of the evaluation's main topics and attempts to answer a new research question that emerged during the process. It also summarizes the resulting findings.

4.2.1 Music Practice and Computer

During the first lectures on sound theory in 2018, the VIB pupils were asked if they are experienced in music making, for instance if they played a musical instrument (see Chapter 3.2). Almost all pupils answered, that they did play instruments such as flutes, piano or the guitar. Only one pupil did not play any musical instrument. Secondly, the pupils were asked, if they ever used the computer for anything related to create music, for instance to record their instrumental playing for documentation, to create overdubs and tracks, or to compose new musical pieces. The answers revealed that none of the pupils ever used the computer for musical tasks, even though they would be interested to create *electronic music* or *Hip Hop*.

Blind expert Mario Lang confirms that the situation regarding accessible music software is difficult and time consuming. Lang has a background as multi-instrumentalist. He studied acoustic instruments such as the guitar, transverse flute and the piano. He also explored synthesizer and the computer as an instrument for music making. He says that platforms like FL Studio or Ableton Live are not accessible at all: *"Because the main software platforms are not accessible, children are not using computers to make music."* As a main problem he sees an interface problem, since computer screen and mouse are not usable for VIB users, and therefore other approaches have to compensate for that such as Midi controllers. Lang tested Csound and SuperCollider for digital music-making, as well as using the Terminal. For programming in the Terminal, Lang used Emacs with the add-on EmacsSpeak, which is a text-to-speech environment for Emacs. He started to write custom music software that is adapted to his own needs and provided a sequencer, and integrated external MIDI devices and the Braille display. But he points out, that programmings custom personal software takes time and energy, which has to be balanced with its creative purpose of music-making. Lang says, that projects bigger then 10.000 lines of code are too big for personal programming and require professionals. A main musical device that Mario Lang is missing is an accessible sequencer for MIDI notes and control parameters, both as accessible software or hardware solution. But no accessible sequencers are available, which according to Lang is a consequence mainly due to small demand and therefore low potential profits for manufacturers. For him, the issues with computer music software regarding accessibility, as well as availability and integration of external motorized MIDI hardware led to re-focusing on hardware synthesizer and drum machines for composition and music-making. The computer as a platform is still part of the musical setup, but instead of being used as a creative compositional tool, it is used for recording, post-processing, and to provide multi-channel sound distribution in the studio via SuperCollider.

Erich Schmid confirms the difficulties regarding accessible music software. He is using Reaper as a music software for recording and composition. Reaper comes with basic accessibility features but allows to use of additional scripts such as OSARA to increase accessibility and customize the interaction. Observing Schmid and his workflow while using Reaper with OSARA, it becomes obvious that this software requires dedication and practice, and involves a steep learning curve to use the software intuitively. For beginners such as the pupils at the BBI, Reaper is neither the right tool for interactive and playful music-making, nor easily accessible and usable.

Ben Hofer, a visual impaired musician, composer and teacher at the BBI, uses the audio software Logic Pro for Mac for his musical practice. But like Reaper, Logic Pro is not a suitable platform for beginners, since it requires a steep learning curve for intuitive handling. Also, it only runs on Mac computers, whereas the school provides Windows computers.

4.2.2 Question: How to Enable Accessible Digital Music-Making for Non-Trained VIB Individuals?

Based on the experiences with the pupils at the BBI during the first workshops, the lack of experiences of using the computer for music-making, and the difficulties of finding a suitable accessible digital music-platform, the following new research question appeared: *How to enable non-trained VIB individuals to practice digital music-making and to use the computer as a musical instrument?*

4.2.3 Findings

The insights during practical workshops at the BBI and OCC, discussions and interviews with VIB experts revealed the following findings:

- **No accessible music platforms are available**, that enable simplified, interactive and performative digital music-making, and enable non-trained VIB musicians to use the computer as a musical instrument with a focus on interactivity and performativity.

- A **zero install paradigm** enables access to the music software without the hurdles of software installation, since most web browsers already provide accessibility features.

- **Text-based interaction** is a suitable interaction paradigm, since it follows *universal design* principles and prevents accessibility barriers resulting from vision-centric software design. A simplified music programming language inspired by live coding platforms can be used to control the musical interaction, composition and performance.

- A **web-based music environment** based on a simplified step-sequencers design, the use of sample sounds and controls over volume and randomization as well as textual interaction, is a suitable accessible music software and enables non-trained VIB individuals the artistic practice of digital music-making.

4.3 PHYSICALIZATION AND SONIC FEATURES

This section presents a discussion of physical representations of time-based sound signals and their abstraction into sonic features. It attempts to answer another new research question and provides the findings. The section highlights how the focus on sonic features served as a starting point for developing tangible interfaces.

4.3.1 Time-based Signals and Symbolic Descriptors

Sound is a time-based signal. For the generation of sound, synthesizers provide a number of features, such as sound sources, modulation sources, envelope generators, filters or rhythm generators. These features are not only based on time-based audio or control signals, but they can also be static parameter values or rhythmic patterns. Synthesizer features can be summarized as *sonic features*, that create and define the resulting sound and rhythm. They symbolize sonic aspects that will define the generation of the resulting sound including the according settings of the synthesizer.

4.3.2 Question: Which Aspects of Sound and Music to Choose for Tangible Interaction, and How?

The initial research proposal to develop a *tangible wavetable synthesizer* was informed by sound synthesis and the physical representation of time-based audio signals. This attempt to physicalize time-based audio signals changed during the first lectures at the BBI Vienna, when it became clear that the pupils had no experience with digital music-making, and thus advanced sound synthesis techniques such as *wavetable synthesis* were too specialized. A new research question emerged regarding the exploration of tangible musical interaction: *Which aspects of sound and music to choose for the development of tangible interfaces, and how to realize them?*

The resulting selection of sonic features, the respective tangible musical interfaces, as well as the feedback from VIB experts will be summarized below.

Tangible Pins - Sequencer

One approach towards sonic features was inspired by *square waves* and their inherent concept of *alternation*. This focus on the binary switching of states was already embedded in the music software *Welle* as an 8-step sample sequencer. Alternating switches can also be used for other sound controls such as playing notes, the switching of effects or the muting and unmuting of audio loops. They are easily understandable, powerful and allow the creation of musical compositions. The focus on alternation and the development of an according interface finally resulted in the *tangible pins* interface. The interface provides 8 actuated tangible pins, that are arranged in a row as step-sequencer layout. The pins can be switched manually, as well as remotely controlled and adjusted by the computer software (see Chapter 3.6).

Tangible Wheel - Continuous Controls

Another approach towards sonic features was inspired by *sine waves* and the concept of *oscillation*. Continuous movement and controls are used in sound synthesis for gradual parameter changes instead of simple binary switches, e.g. the gradual control of volume, frequencies, filter or effects. In *Welle*, parameters such as volume allowed continuous control. Subsequently, the focus on *oscillation* resulted in the development of the *tangible wheel* interface, a device the enables actuated continuous parameter control. It enables haptic feedback through programmable feedback points and can be used to control musical parameters such as volume, panorama, filter values or scrubbing through an audio file (see Chapter 3.5).

Tangible String - Envelope

A third approach towards sonic features was inspired by the waveform of *noise* and the concept of *modulation*. Modulation is the periodic change of sound parameters in order to make the sound more interesting, organic and to create rich timbres. Similarly envelopes are descriptions of parameter changes over time, for instance to control the amplitude of a sound through the parameters of attack, decay, sustain and release (ADSR). Envelopes can be applied to various different sonic aspects of sounds, such as sound sources, filters, other modulations, etc. In *Welle*, the volume of the sample sounds are shaped with amplitude envelopes. Based on this focus on amplitude envelopes, the *tangible string* device was developed. The interface enables the tangible interaction with sonic features, such as envelopes or parametric equalizers. It provides an elastic string, whose position and shape is controlled by a set of four motorized points. The motorization of the *tangible string* interface allows to store and recall previously save settings (see Chapter 3.7). The interface resembles the initial proposal of a device for wavetable synthesis and equalization, but simplifies the hardware design through its reduced and more flexible fader layout.

4.3.3 Findings

The findings in regard to this research question are the following:

- **Sonic Features instead of Time-based Signals.** The use of sonic features for tangible musical interaction is suitable for non-trained beginners and enables playful experimentation, e.g. higher-order symbolic descriptors such as amplitude envelope, volume and rhythmic patterns.

- **Tangible Pins - Sequencer.** Based on inspiration from the concept of *alternation* as well as the 8-step trigger sequencer implemented in the *Welle* software, the *tangible pins* interface was developed, a device based on eight switchable pins.

- **Tangible Wheel - Continuous Control.** Based on the concept of *oscillation*, the *tangible wheel* interface was developed, a motorized interface that provides continuous parameter control and haptic feedback.

- **Tangible String - Envelope.** Inspired by the concept of *modulation* and the amplitude envelopes on the sample sounds in *Welle*, the *tangible string* interface was developed, a device that enables the display and interaction with physical curves, e.g. envelopes or equalizers.

4.4 TANGIBLE INTERACTION AND ACCESSIBILITY

This section evaluates the effects and implications of tangible musical interaction as a means towards accessible digital music-making. It provides a detailed answer to the corresponding research question and summarizes the findings. With a perspective on assistive technologies, a number of benefits of tangible musical interaction for accessible digital music-making will be presented.

4.4.1 Assistive Technology and Digital Music-Making

Digital music-making for VIB musicians requires assistive technology such as screen readers, refreshable Braille displays or accessibility features in the respective audio software. While access to textual information is available through text-to-speech synthesis or the displays of the text on the Braille display, visual contents of digital music-making are more difficult to access, e.g. audio waveforms, equalizer curves or multi-track compositions. Music software and DAWs such as Logic, Pro Tools or Reaper, are based on a vision-centric design approach, which favors graphical representations and designs before accessibility. Additional scripts and extensions increase accessibility, yet the practical workflow takes more time and effort and some features remain inaccessible. For instance simple tasks such as controlling the mute states of multiple tracks in a project can be checked at a glance by a sighted person, but can already require a relatively big effort by a VIB musician, as Erich Schmid describes: *"In a DAW, I would have to go through the tracks one by one and check whether they are activated, and then I still don't know whether any audio is actually playing in the track."*

As Mario Lang points out, the interaction with the computer is limited for blind musicians such as himself, since the GUI display and mouse as a pointer device are not available for him. This becomes especially clear when comparing the computer with an Eurorack synthesizer that provides many separate physical modules for different tasks of sound synthesis. The modules provide numerous hardware knobs and switches that can be used to quickly adjust parameters, while compared with this direct interaction, accessible music software has to be programmed in a relatively static and lengthy process via text input. And even though DAWs allow the integration of external MIDI controllers such as motorized faders, these external MIDI controllers are limited to a certain amount of knobs, faders and switches in order to externalize musical parameters. Nonetheless, for Lang the motorization of MIDI controllers is a key feature, which allows him to use the MIDI controller as output device, e.g. to display parameters or simple waveforms such as sine waves. For him, *"the motorized MIDI controller Behringer BCF 2000 was an eye-opener"*, since it allowed to use external faders to control musical parameters, but without sudden jumps of values because motorized faders update their position autonomously. But despite the various accessibility features of music software, as well as the availability of motorized MIDI controllers, Lang states: *"For blind musicians, an interface problem still exists."*

4.4.2 *Question: What are the Benefits of Tangible Musical Interaction for VIB musicians?*

As described above, VIB musicians that practice accessible digital music-making still facing accessibility barriers due to a vision-centric software design, limited or absent accessibility features and a reduced range of interaction possibilities compared with vision-based interfaces. On the other hand, tangible musical interaction provides valuable physical access to digital music data, and has been widely explored in the context of digital music making for sighted musicians. Its physical and tactile interaction seem to be ideal for enabling accessible digital music-making. Unfortunately, respective research projects are rare, which led to the following research question: *"What are the benefits of tangible interaction for visually impaired and blind musicians?"*

Direct Physical Manipulation

The first key aspect that could be identified as a benefit of tangible interaction for VIB users is related to the interaction paradigm of *direct manipulation*. The concept of *direct manipulation* is well-known in HCI and constitutes the success of the GUI based on the WIMP paradigm and the desktop metaphor. Most personal computers, tablets and smartphones are based on this interaction paradigm using windows, icons, menus and pointers (see Chapter 2.2.2). But because the concept of *direct manipulation* is so closely related to GUIs and their visual representation, VIB users cannot take advantage of this interaction paradigm.

However, during the explorations of the interfaces by VIB experts it turned out, that VIB users benefit from tangible interaction in a way that resembles *direct manipulation*. But instead of the interaction of windows, icons or menus, the tangible interfaces enable *direct physical manipulation*, which provides physical and tactile access to the state and configuration of the various sonic features. For Erich Schmid, who previously used text input to change discrete parameters one after the other in his DAW, the use of the tangible interfaces and the ability to physically manipulate digital data increases the speed and intuition of the interaction with the digital musical material. According to Schmid, the *direct physical manipulation* with the tangible interfaces impacts the work process: *"In contrast to the DAW, it is quicker and easier to make adjustments with the interfaces."* It also makes it easy to understand the positions and settings of the digital data such as sequencer and other parameter values. He continues that: *"the changes are also immediate"* and adds that in contrast to the tangible interaction with musical parameters, *"the DAW means real work, in the sense of thinking and planning."*

During an exploration session, Mario Lang comments on the *tangible wheel* interface and says that he could envision the interface not just as a tool to adjust volume or parameter settings, but also as a tool for scrubbing through audio files, setting markers and reviewing them later for editing. This proposal also illustrates the potential of the interface for *direct physical manipulation*, since in this application scenario the *tangible wheel* represents the position of the pointer in an audio file, and also enables haptic feedback to display the respective markers.

In summary, tangible interaction enables *direct physical manipulation* for VIB musicians, an interaction paradigm that offers similar advantages as the traditional *direct manipulation* with its related WIMP paradigm, but now includes also VIB users, who benefit from a intuitive, faster and more convenient interaction with digital data.

Space Multiplexing

The second key aspect of tangible interaction is related to working with multiple interfaces in a grouped configuration to interact with music software. The developed tangible musical interfaces allow to control rhythmic sequences, volume settings or amplitude envelopes. This externalization of sonic features into the physical space provides access to several musical interactions at the same time, which is known as *space multiplexing*, in opposition to time multiplexing, an approach that focuses on execution of tasks one after the other in time (see Chapter 2.3.2). This spacial layout is especially interesting for VIB musicians that have little or no access to the visual layout in the GUI.

The participating VIB experts appreciated the simultaneous access to the various sonic features. They mention that the setup with three separate interfaces is large and somewhat complicated, but having access to the various music aspects is worth it. In this regard Mario Lang says that he likes haptic approaches in general and could imagine to combine the three devices into one device: *"Combining the interfaces would be super cool."* Also Angela Videbis says she could imagine to combine the devices in order to create an accessible DJ controller, using the *tangible pins* and two *tangible wheel* interfaces. Likewise the musician Ben Hofer could envision a combined interface, that provides access to all the separate sonic features at once: *"I would build every-*

thing into one device including sound output, where the envelope would be placed at the bottom, the wheel at the top right and the sequencer at the top left, plus respective Braille displays at the top and bottom. That would be a dream for a VIB composer." This feedback confirms, the all VIB participants valued the simultaneous spacial access to the various features of sound and music, so much so that they immediately started to envision future iterations of the interfaces, that make tangible musical interaction even more usable and suitable.

Furthermore, this spacial layout enables the participation and collaboration of multiple musicians in order to interact with the various aspects of sound and music. Erich Schmid comments during the rehearsals for his stage performance, that he could easily imagine to use his live setup in a group of two or even three musicians, where each one would operate a tangible interface and perform a tasks related to the sound performance. In fact, during the workshop with VIB pupils at the OCC 2023, three pupils were simultaneously playing on the tangible interfaces to explore tangible musical interaction (see Fig.3.9.8). This brief exploration did not result in any musical composition, but it shows the possibility of musical collaboration.

In regard to the artistic and musical practice, *space multiplexing* can be especially important for interactive and improvised live stage-performances. Having access to multiple parameters at once enables the VIB musician to interact with the musical composition on a more direct level, increasing the contact area of the musician with the computer as musical instrument, as well as with the audience through an expressive live performance. Erich Schmid is convinced that: *"The setup with the tangible interfaces makes the performance more diverse. I would not go on stage only with a computer recording. ... This way I can respond to the audience, for example by repeating effects or sequences."*

In summary, the availability of three separate tangible interfaces enables *space multiplexing*. This simultaneous access to the various sonic features is beneficial especially for VIB musicians. This configuration also enables collaborative digital music-making and supports stage-based live performances by enabling improvisation and spontaneous interaction with the audience.

Bandwidth of Interaction

The third key benefit is related to the bandwidth of the interaction between the VIB musician and the computer as musical instrument, especially in regard to input and output communication channels.

VIB musicians use screen readers, TTS or Braille displays for data output, e.g. to convey software settings, parts of musical compositions and other musical parameters. But unlike the GUI that visually displays multiple settings at the same time, the data output using the screen reader or Braille displays is consecutive, and one information is transmitted after the other. Similarly, VIB users mainly use the computer keyboard to input data. In general, the bandwidth of musical interaction for VIB musicians is limited compared to GUI-based workflows. Data output is consecutive, while the input of data is mainly realized by entering discrete steps with the keyboard. In this regard, tangible musical interaction can increase the bandwidth by opening up additional communication channels. Each actuated tangible interface represents both an additional input and output channel, that enables accessible musical interaction without occupying existing channels such as loudspeakers, Braille displays or the computer keyboard.

The increased bandwidth can be observed with the three available tangible interfaces. The *tangible pins* interface enables the display and interaction with rhythmic patterns, the *tangible wheel* provides access to continuous parameters such as volume, and the *tangible string* interface enables the display and control of envelopes or other multiple data points. These interfaces add simultaneous musical functionality and increase the amount of data that can be send and received.

The performance of Erich Schmid's musical composition *Stimmungen* was based on the availability of the three actuated tangible interfaces. Each interface provided access to separate sonic features, such as custom audio loops, panorama settings and effects envelopes, and also served as physically actuated displays for respective parameter changes. Regarding his experiences with the tangible interfaces, previous feedback from Erich Schmid also applies here, when he confirms that: *"In contrast to the DAW, it is quicker and easier to make adjustments with the interfaces."* When asked weather it is faster to perceive the mute states of eight audio tracks via screen reader software or via the *tangible pins* interface, Erich Schmid responds: *"The interface certainly wins. It is quicker to use your fingers than to query eight tracks with the arrow keys."*

In summary, tangible musical interaction with actuated interfaces increases the bandwidth for VIB musicians, compared with otherwise limited bandwidth due to consecutive data output and discrete data input with computer keyboards. The increased bandwidth supports accessible digital music-making and stage-based live performances.

4.4.3 Findings

The findings in regard to this research question are the following:

- **Direct Physical Manipulation.** Tangible musical interaction enables the direct physical manipulation of musical data, which increases the immediacy of musical interaction and enhances intuitive music-making through more direct access to digital data.
- **Space Multiplexing.** The externalization of sonic features through multiple tangible interfaces enables simultaneous access to the respective aspects of sound and music for VIB musicians. It also enables collaborative music-making, and enables musical improvisation and spontaneous interaction during stage-based live performances.
- **Bandwidth of Interaction.** Tangible musical interaction increases the bandwidth of the interaction for VIB musicians. Actuated tangible interfaces serve both as data input and output channels. They increase speed and intuitive interaction with music software, which benefits accessible digital music-making and stage-based live performances.

4.5 ARTISTIC EXPRESSION AND PERFORMATIVITY

This section will evaluate the effects of tangible musical interaction on artistic expression and musical performativity for VIB musicians, particularly with regard to musical improvisation and stage-based live performances. The corresponding research question will be addressed in detail, and the findings will be summarized. Thereby the concept of *artistic expression* refers to the ability, richness and variability of communicating emotions and stories through musical interaction, including musical phrasings and improvisations. The concept of *musical performativity* on the other hand refers to the process of transmitting the artistic vision through using the computer as a musical instrument and the ability to include bodily movements and gestures.

4.5.1 Using the Computer as Musical Instrument

Computers can be used for musical tasks such as sound synthesis, the composition of musical pieces, audio recording, music editing or stage-based live performances. This ability is related to the question of how to interface and communicate with it in order to convey musical vision and artistic gestures. The interaction with the computer becomes even more important when using it as a musical instrument with a focus on musical expression, the access to sonic features and the virtuosity of the musical performance. While this question of musical interaction is relevant to all computer users, it is especially relevant for VIB musicians, since their computer music setup is non-visual and involves assistive technology such as screen reader and Braille display, as well as the computer keyboard, MIDI keyboards or MIDI controllers.

One way of using the computer for digital music-making based on non-visual interaction is the use of programming languages for the creation of sound and music. Audio programming environments such as Csound, SuperCollider, Sonic Pi or Tidal Cycles can be used to compose musical pieces, as well as to perform *live coding*, a real-time approach for sound-generation and music composition (see Chapter 2.4.5). Despite the fact that many live-coding platforms are not accessible, the use of audio programming languages and textual interaction reflects *universal design* principles for music software, and can make digital music-making accessible to all musicians (see Chapter 3.3).

The most popular means for digital music production are advanced audio editors and DAWs, which enable the composition, recording, and editing of sound and music (see Chapter 2.4.4). These music platforms are mostly based on a vision-centric software design, which favors a WIMP-style interaction and the use of GUIs and pointers. This focus on GUIs presents accessibility barriers for VIB musicians due to the use of graphical representations and visual interactions (see Chapter 2.4.7). To complement visual with non-visual interaction, HCI modalities such as haptic interaction or tangible interaction can be used to interface with the computer. In regard to digital music-making, these interaction modalities can offer physical access to musical features, as demonstrated numerous novel musical interfaces, such as the performative and collaborative synthesis platform *Reactable*, the accessible tactile rhythm sequencer *Beatbearing* or the interactive waveform display *Haptic Wave* (see Chapters 2.3.3 and 2.4.9). Especially tangible interaction seems to enable more accessible, expressive and performative interaction with digital data, which potentially could enrich the tactile and physical user experience of VIB musicians.

4.5.2 *Question: How does Tangible Musical Interaction contribute to the Artistic Expression and Musical Performance of VIB musicians?*

As shown above, VIB musicians who attempt to use the computer as a musical instrument benefit from tangible musical interaction on a technical level, since it provides the ability for *direct physical manipulation*, enables *space multiplexing* and increases the *bandwidth* of the interaction. However, technical implications are only one aspect of musical interaction and digital music-making, which leads to the following research question: *"How does tangible musical interaction contribute to the artistic expression and musical performance of visually impaired and blind musicians?*

Immediacy, Intuition and Performativity

The first musical key aspects that appeared during the various sessions with VIB experts are the immediacy of the expression of musical ideas, as well as the intuitiveness of working with music software.

Erich Schmid says: *"Compared to the DAW, it is quicker and easier to make changes with the interfaces. This is important to me. In the DAW, all inputs are frozen immediately. With the interfaces, there are far more possibilities for changes and the changes are immediate. I don't have to think about which adjustments I want to make beforehand. ... It therefore allows me to work more intuitively."* Regarding the artistic practice with the actuated tangible interfaces, Schmid continues: *"I really think it is fun because it is more intuitive than working with a DAW. The DAW means real work, in the sense of thinking and planning."* He adds: *"Creativity is stimulated in a different way. That is the advantage of these interfaces."*

Likewise, Ben Hofer confirms that the tangible musical interaction makes digital music-making more immediate and intuitive. In regard to interactions like setting single steps in rhythmic sequencer or controlling the mute states of audio tracks with the *tangible pins* interface, he says: *"I really think that this is quicker, simpler and more helpful."*

The immediacy and intuitiveness of musical interaction became especially apparent during the stage-based live performance of the piece *Stimmungen* by Erich Schmid, where he used a music setup centered around the three actuated tangible interfaces (see Chapter 3.10). Erich Schmid states: *"The interfaces make the performance more interesting. As an artist, you don't need to sit on stage with just a computer recording. But when I realize from the audience's reactions that an ef-*

fect or a sequence was fun, then I can repeat this sequence again, which otherwise wouldn't be so easy." He especially liked the *tangible wheel* interfaces as a control of the panorama settings in the multi-speaker setup.

Explorative Interaction

Another effect of tangible musical interaction is the ability to explore sound and music through interactive physical displays. Immediate feedback and physical access to the musical material enables sonic exploration instead of calculating and enter discrete values with the computer keyboard.

For instance, the *tangible string* interface was used to control the envelope of a Delay effect during Schmid's live performance, with access to parameters such as delay amplitude, delay time, delay feedback and the dampening of the delay signal. Erich Schmid confirms that the *tangible string* increases the understanding of the musical possibilities of the respective audio effect by exploring its impact on the individual sounds. Schmid says: *"All these parameters are available in the DAW too, but if I want to set a 'small room' for a delay effect and there is no ready-made preset in the corresponding plug-in, then it is difficult for me to achieve this 'small room'. With the interface, you can explore suitable settings and are more likely to find one. ... In the DAW, I always have to change one parameter at a time and listen to the result each time. It's much less immediate."*

Also Ben Hofer appreciates the interaction with the *tangible string* interface and its ability to manipulate multiple parameters at once: *"It's great that you can immediately hear a change in the sound. That is a very exciting experience. Especially as the string connects one point to another, which makes it easier to navigate."* Regarding the adjustment of parameters of sound effects such as reverb or delay he says, that in his studio he has to change every parameter separately, which is more complicated: *"The string interface offers more musical possibilities and it is also faster than having to change one parameter at a time."*

Playful Experiences

Another aspect that was emphasized during the artistic explorations with VIB experts is the playful experience of using the actuated tangible interfaces. The participants underlined the joy of the tactile and haptic experiences, the motorization of the interface and the resulting intuitive and playful access to musical interaction. Erich Schmid comments, that it is a joy to use the tangible interfaces, especially compared to computer keyboards and the relatively slow workflow in the DAW. Mario Lang appreciates the *tangible pins* interface for its playful possibilities, and would immediately integrate it into his Eurorack synthesizer. Jakob, one of the pupils that explored the interfaces during the OCC 2023, said: *"They are so cool, especially moving sounds through the room. ... If I had such interfaces I would use them at Halloween to make scary noises."* Martin Mayrhofer, teacher at the BBI, likes the sensory perception of the interfaces and how they interact with each other: *"I like the haptic feeling when the pins bounce out. I like their sound, I think it's great when something sounds so mechanical. ... Generally I love motorization, devices that adjust themselves and things that move, simply out of a playful childlike instinct."*

4.5.3 Findings

The findings in regard to this research question are the following:

- **Immediacy, Intuition and Performativity.** For visually impaired and blind musicians, tangible musical interaction enables intuitive interaction with sonic features and musical controls, and increases the immediacy of compositional variations or parameter changes. It increases the performativity by enabling musical improvisation and spontaneous reactions during stage-based live performances.

- **Explorative Interaction.** Tangible musical interaction benefits the exploration of sound and audio effects for visually impaired and blind musicians by providing access to multiple musical parameters through a combined physical interaction element. This sonic exploration can used for discovering new audio effects settings in the studio, as well as for musical improvisations on the stage.

- **Playful Experiences.** Tangible musical interaction provides playful experiences for visually impaired or blind musicians. The tactile use of the interfaces is perceived as joyful interaction, and creates a playful musical experience, that stimulates curiosity and playful experimentation.

4.6 CRITICAL REMARKS

During the discussions and inquiries critical remarks were made by the participants in regard to the *Welle* software, the interfaces and integration of the three tangible musical interfaces, as well as research in AT in general.

The music software *Welle* was criticized as not suited for more advanced and professional musical composition and performance due to its limited and simplified musical possibilities. Likewise, the complicated technical setup of the tangible interfaces was criticized. It was mentioned, that the amount of available physical controls needs more experience and familiarization. One participants expressed the wish for plugins, that could simplify the integration of the tangible interfaces into the DAW, as well as allow custom assignments of the various interface controls into a custom musical setup.

The interaction elements of the tangible interfaces were also criticized. The rubber wheel of the *tangible wheel* interface was considered to be too big by some participants. The interface was also considered as too exaggerated for a simple volume control. The *tangible pins* interface was criticized in regard to the amount of available pins, e.g. more rows of pins would make it more flexible and significant. The *tangible string* interface was criticized in regard to the low number of faders. A higher number of motorized faders would increase the significance of the tangible interaction with the string.

Lastly, some participants mentioned that research projects such as this create hope and expectations with regard to novel interfaces and technical solutions. However, these expectations often remain unfulfilled since the respective interfaces are never commercially available. This can lead to frustration and a reevaluation of participation in and support of further scientific research projects.

These criticisms on *Welle* and the tangible hardware interfaces were received and noticed. They underline the fact that the tangible interfaces are prototypes and have plenty of room for improvements. Some of the points mentioned are related to individual preferences while others could have been improved with additional time and resources. Features like VST plugins could be developed to integrate the interfaces into the DAW, the musical possibilities of *Welle* could be increased, the interfaces could be scaled up and interaction elements could become customizable, e.g. exchangeable rubber wheels and more rows of tangible pins. However, these critical remarks underscore the importance of further research into assistive technologies. Such research depends on time and resources to advance existing knowledge and continue developing accessible musical platforms.

4.7 DISCUSSION

This chapter evaluates the insights and feedback collected during the research project using qualitative analysis and organizes them into four key topics that address the research questions. These topics range from exploring accessible music software to localizing sonic features and their physicalization as tangible musical interfaces. The chapter further investigates tangible musical interaction in the context of assistive technology and its impact on artistic expression and performativity. The final results are derived from interviews and artistic explorations with VIB experts alongside the creation of an accessible, web-based music environment and three tangible musical interfaces. The findings in each topic provide comprehensive insights into the use of tangible musical interaction as a means of digital music-making for VIB musicians.

Chapter 5

Conclusion

This final chapter provides a brief summary of the research project and concludes the thesis. The chapter gives an overview of the practical work including the development of the tangible interfaces and the various artistic explorations by VIB experts and musicians. It summarizes the findings, which are categorized in four key topics. Furthermore, the contributions of the research project will be listed, followed by remarks on the research methods. Finally, possible future directions will be indicated.

5.1 SUMMARY

The research project *Tangible Signals* centers around sound and music generation with computer technology, as well as the HCI modality of tangible interaction for musical expression. Thereby, the focus is on accessible digital music-making for visually impaired and blind musicians, which rely on assistive technologies in order to access music software and face accessibility barriers due to its mostly vision-centric design. Inspired by various research projects that focused on haptic interfaces for VIB musicians, such as the *Moose*, the *Haptic Wave* or the *HaptEQ*, the research project *Tangible Signals* explores tangible musical interaction as a means for accessible digital music-making for visually impaired and blind musicians, which has been little explored so far [R. B. Gillespie and O'Modhrain 1997; Tanaka and Parkinson 2016; Karp and Pardo 2017]. To that end, the research is conducted in collaboration with the blind musician, expert and teacher Erich Schmid, and other teachers, pupils and associates of the *Institute for the Blind* (BBI) in Vienna, Austria.

5.1.1 Music Software and Accessibility

The research project started with a series of workshops with pupils at the BBI Vienna. The workshops revealed a need for an accessible music software to complement the exploration of tangible musical interaction. This led to the development of a custom, simplified and accessible music software to convey principles of digital music-making, as well as to serve as a platform for the exploration of tangible interaction. This process revealed valuable insights regarding accessible music software platforms for non-trained VIB pupils. It showed, that none of the available music software platforms were suitable and accessible. It also showed, that a combination of a *zero-install paradigm*, *textual interaction via a music programming language* and a simplified *sample-based step-sequencer design* enables a suitable and accessible musical interaction.

5.1.2 Sonic Features and Tangible Interfaces

The insights of the research project shifted its initial focus from the physical representation of time-based sound signals towards the exploration of sonic features as meta-controls. Thereby sonic features describe components of audio synthesizers that are involved in the sound creation, such as oscillators, LFOs, filters, envelope generators or trigger sequencers. In an artistic process, inspired from tactile waveforms and different aspects of the music software *Welle*, a number of sonic features served as starting points for the development of three different tangible interfaces. Stimulated by the musical concepts of *oscillation*, *alternation* and *modulation*, this process resulted in the development of the *tangible pins* interface, that served as a 8-step trigger sequencer. A *tangible wheel* interface was developed, that focused on the tangible interaction with continuous control signals including haptic feedback. Finally, the *tangible string* interface enabled the interactive physical representation of an envelope curve based on the use of four motorized faders connected by an elastic string. These tangible musical interfaces were subsequently used for the investigation of tangible musical interaction as a means for accessible digital music-making.

5.1.3 Benefits of Tangible Musical Interaction

To explore the implications of tangible musical interaction, multiple explorations and interviews were conducted with VIB experts. Likewise, Erich Schmid used the tangible musical interfaces to composed and perform his piece *Stimmungen* live on stage. The evaluation of the collected material identified three key aspects in which tangible interaction has significant benefits for accessible music-making. It revealed, that tangible musical interaction enables *direct physical interaction*, an interaction approach that is traditionally related to visual representation, GUIs and the WIMP paradigm, and which enhances intuitiveness in music-making by providing a more direct access to digital data. Furthermore, the externalization of sonic features into multiple tangible interfaces creates *space multiplexing* by providing simultaneous access to different aspects of sound and music creation, instead of consecutive data input or output. This encourages and supports collaborative music-making and stage-based performances, and thus enables improvisation and spontaneous interaction with the audience. Lastly, VIB musicians benefit from increased *bandwidth* of interaction with the computer. Multiple tangible interfaces provide additional data input and output channels for musical interaction, and thus increase speed and intuitive musical practice.

5.1.4 Artistic Expression and Performativity

Lastly, the research project investigated the question wether tangible musical interaction contributes to the artistic expression and musical performance of visually impaired and blind musicians. Insights from expert feedback, artistic explorations and stage-based performances provide a number of key findings. Firstly the research shows that tangible musical interaction increases *immediacy, intuition and performativity*, especially when used live on stage. It enables faster and more intuitive workflows with the DAW. The ability to immediately perform musical changes provides benefits for artistic live performances, e.g. allows musical improvisation and spontaneous reactions to the audience. Secondly, tangible musical interaction enables the *explorative interaction* with sound and audio effects. Tangible interfaces support the physical sonic exploration, which is particularly relevant for VIB musicians and can be useful for musical exploration in the studio, as well as for stage-based live performances. Combining the control of multiple parameters into one interaction element such as the *tangible string* further increases its ability for sonic exploration. Lastly, tangible musical interaction enables *playful experiences* due to its tactile sensation and intuitive use. It can stimulate curiosity and playful exploration.

5.2 RESULTS AND CONTRIBUTIONS

The main contribution of this research project is the exploration of tangible musical interaction as a means for accessible digital music-making for VIB musicians. Thereby the research project exposes shortcomings in the field of music software and accessibility for non-trained VIB musicians, it presents the design and development of three tangible musical interfaces, and it investigates and analyses tangible musical interaction as a means for accessible digital music-making through artistic practice.

- The research project shows, that digital music-making can be a challenge for non-trained VIB musicians, especially due to a lack of accessible music software for playful and explorative real-time music-making (see Chapter 3.2).
- It describes the development of *Welle*, a text-based accessible digital music platform, that enables simplified music composition and real-time interaction. The resulting music environment *Welle* can be used as a music composition tool, as music production studio including audio recording and presets management, as well as an interactive control for external software and hardware MIDI instruments (see Chapter 3.3).
- Three actuated tangible interfaces were developed in an user-centered and iterative design process: *tangible pins*, *tangible wheel* and *tangible string*. The interfaces are inspired by sonic features derived from concepts of audio synthesis and the *Welle* software. They are described in detail, including their underlying sonic concepts, the development process and the application scenarios (see Chapters 3.5, 3.6, 3.7).
- An in-depth exploration of tangible musical interaction as a means for accessible digital music-making was realized during multiple sessions with VIB experts and musicians, including the composition of a musical piece and its stage-based live performance (see Chapters 3.9 and 3.10).
- The research results highlight tangible musical interaction as an expressive and intuitive modality for performative musical expression, especially for visually impaired and blind musicians. The research underlines the benefits and artistic value of tangible musical interaction as a means for accessible digital music-making (see Chapter 4.4 and 4.5).

5.3 REFLECTIONS ON RESEARCH PROCESS AND METHODS

The results of this research project are largely based on the collaboration and the stimulating encounters with professionals, pupils, musicians and other researchers. The research mainly focused on a deeper understanding of accessible digital music-making, on the development of appropriate software and hardware tools, and on the best possible investigation of tangible musical interaction for visually impaired and blind musicians. The research activities resulted in numerous valuable insights and knowledge in regard to the posed research questions. Nonetheless, the research practicalities, methods and the overall framework could be improved to enable more in-depth explorations and to generate more detailed insights.

A fundamental aspect of the research project is the collaboration with VIB experts in order to explore tangible musical interaction. This was realized based on the collaboration with Erich Schmid and other teachers, pupils and associates from the BBI Vienna, in great respect of the *"Nothing about us without us"* approach [Harpur and Stein 2022]. For more comprehensive investigation, a higher number of participating experts and musicians would be preferable. It would also be beneficial, if more of the participants would already have a background in digital and electronic music-making and experiences with stage-based performances. In this regard, also the work with the non-trained pupils at the BBI Vienna was rewarding, especially to observe their advancements in digital music-making. But unfortunately, the groups of pupils involved in the research project changed over the years, which interrupted the progress in the group as well as the research process. To gain a deeper understanding of accessible digital music-making and the effects of tangible musical interaction, it would be preferable to collaborate with the same group of pupils over a longer period of time.

Another aspect that could be improved is the balance between the efforts of developing appropriate software and hardware in respect to the amount of time available for practical explorations, meetings and artistic sessions. The design of the music software *Welle* as well as the development of the tangible interfaces was necessary for the research process. But in respect to the overall research period, these developments consumed a large amount of the resources. It could be beneficial to share or outsource the software and hardware development, in order to regain more resources for practical explorations and expert feedback sessions.

Lastly, the research project focused on the realization of artistic practice, musical composition and stage-based performances in order to gain insights in the practical implications of tangible musical interaction. In that regard, it would be beneficial to enable more artistic works and to collaborate with a bigger and more diverse group of external VIB artists and musicians. The subsequent documentation and feedback could provide a more in-depth understanding of the effects and the potential of tangible musical interaction as a means for artistic expression and digital music-making.

5.4 FUTURE PERSPECTIVES

This thesis illustrates the potential of tangible musical interaction for visually impaired and blind musicians, and how it can complement common musical computer workflows that are based on screen-reader and Braille display. The research project attempts to raise awareness for the benefits, and provides insights for future developments of musical interfaces that include tangible interaction. The focus on accessible workflows is especially relevant regarding existing access barriers in digital music technology due to vision-centric design of music software and hardware, as well as insufficient accessibility features, while in fact these musical environments should be grounded in *universal design* principles and provide equal access for all users. Artist-researchers in the field of new musical interfaces, such as the author of the thesis, have a special responsibility to investigate suitable musical approaches, new technologies and interaction modalities for accessible music-making.

In the future, the music software *Welle* will remain accessible online as an educational and creative tool. It can be used to explore pattern-based electronic music, to experiment with the simplified music programming language, to record sounds and music, and to perform live on stage.

Likewise, the tangible musical interfaces remain available for musical experimentation, possible live performances, and further exploration of tangible interaction. The *tangible pins* interface received special interest as an accessible trigger sequencer, such as for Eurorack synthesizer. In the future it could be adapted and made available as a DIY kit.

Ideally, the pupils that participated the research project benefit from their experiences gained through the various workshops, and are encouraged and inspired to continue to practice digital music-making for their musical journey.

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List of Figures

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