Improving Digital Audio Workstation Accessibility for Blind and Visually Impaired Music Producers through Vibrotactile Feedback

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"Recognising the inevitability of conflict does not justify inaction; it creates opportunities for innovation"

Hofmann et al., 2020

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Abstract

Music production has become central to modern music-making, enabling digital creativity and distribution of music through technological tools. While early analogue studios relied on tangible interaction with devices such as mixing desks, encoders, and faders, the move toward fully digital production has shifted these tactile controls into visually demanding interfaces within Digital Audio Workstations (DAWs). This transition broadened access for many people; however, it introduced significant disadvantages for blind and visually impaired (BVI) music producers. The skeuomorphic visual representations in DAWs require constant visual attention, creating significant barriers to audio editing and processing. Accessibility tools such as screen readers provide essential text-to-speech functionality, enabling access to and interaction with DAWs. However, they also introduce challenges, including increased cognitive load and workflow inefficiencies, particularly when voice feedback overlaps with the processed musical audio. Inspired by the tactile benefits of earlier studio equipment, haptic feedback presents a promising non-audio-based interaction method. Vibrotactile feedback, specifically, has been used to support BVI users in tasks such as navigation and everyday interactions, and is widely used to enhance audio-visual experiences. However, its integration into music production remains underexplored, and there is limited guidance on designing vibrotactile feedback to convey complex creative tasks in DAWs.

This thesis investigates how BVI music producers can benefit from vibroatactile feedback to enhance DAW accessibility through human-centric methods. Starting with interviews with 19 participants, insights were gathered regarding how BVI music producers utilised existing haptic technologies to enable a more accessible workflow. Findings demonstrate the benefits of haptic feedback, the key accessibility barriers and the opportunities for vibrotactile feedback support. Through the interviews, initial design requirements were gathered regarding a new wearable haptic device and the potential vibration patterns mapped to DAW functionalities. A complementary review of wearable haptic devices identified the arms as the most suitable location for a vibrotactile feedback display in a music production context.

The collected design requirements, based on users' needs and existing literature, led to a study focused on an interactive process of designing, developing, and evaluating a vibrotactile feedback armband with five, and finally three, motors around the arm. The experiment with 12 participants testing their ability to identify the location of the vibration excitation accurately showed a 96% success rate, providing evidence that this device can effectively and precisely convey spatiotemporal patterns to convey information about the DAWs. To evaluate this, 6 two-parameter Tactons were tested in presenting EQ information to 6 BVI participants. This haptic feedback method was evaluated in a study that compared information recognition and time between the existing screen reader method, the new haptic method, and a hybrid of both. The results showed that participants could understand the information from the haptic method as well as from the screen reader, demonstrating the potential of this new method, as evidenced by their positive qualitative feedback and suggestions for further improvement and application.

Diverse vibrotactile feedback design techniques were also explored in the context of interaction with a volume fader in the absence of a screen reader. Three vibration-mapping strategies, based on vibration intensity, location around the arm, and vibration duration, were developed and evaluated with BVI music producers in realistic mixing scenarios. Results from 7 participants showed that mappings based on rhythmic cues and precise motor localisation were more usable, accurate, and efficient than alternative approaches, enabling participants to perform mixing tasks without reliance on audio-based accessibility tools.

This thesis contributes to understanding accessibility barriers in DAWs for BVI creatives and how the current use of haptic technologies can inform the future design of accessible music production tools. Furthermore, it provides insights into a specific way of utilising vibrotactile feedback as an alternative accessibility method, demonstrating the method's validity and effectiveness in supporting BVI creatives. This work presents design strategies for vibrotactile feedback and a wearable haptic prototype tailored to music production workflows. Finally, it guides future research toward inclusive, adaptable, and multimodal interaction designs using haptic technologies to enhance accessibility in music production for BVI creatives.

Declaration

I confirm that the work contained in this PhD project report has been composed solely by myself and has not been accepted in any previous application for a degree. All sources of information have been specifically acknowledged and all verbatim extracts are distinguished by quotation marks.

Signed ..... Date 13/07/2026

Christina Karpodini

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Chapter 1

Introduction

1.1 Motivation

The advancement of technology has enabled the digitalisation of human activities such as education (Raja and Nagasubramani, 2018), social life (Chayko, 2014), daily activities like banking (Rahi et al., 2020) and shopping (Taher, 2021), as well as entertainment like gaming and music (Tófalvy and Barna, 2020). This increasing adaptation of technology advantages individuals and industry by providing new opportunities for efficient task completion, networking and innovation (Hamideh Kerdar et al., 2024). Music and arts, a traditionally physical and analogue domain, have been equally influenced by this progress of technology. Music making with the use of computers began alongside the early development of computing itself. In the 1950s, Max Mathews produced the first computer-generated sound for musical purposes, pioneering the field of 'computer music' (Wang, 2017). Since then, music production has become increasingly reliant on digital tools with software like Digital Audio Workstations (DAWs) enabling the production of music without any use of physical musical instruments but only the use of the computer (Izhaki, 2017). A similar direction has been followed by fine arts, which gradually incorporated computational techniques into artistic practices. This shift led to the formalisation of 'digital arts' in the 1980s with pioneers such as Aaron Cohen who developed AARON, a machine that produces abstract drawing (Bramantyo, 2021). Nowadays, a big part of artistic expression is being mediated by digital tools, reflecting the influential role of computer systems in contemporary human life.

In this new digital age, people with disabilities are often excluded (Hamideh Kerdar et al., 2024). Interaction interfaces with technology are frequently designed without considering the diversity of users. People with disabilities have inadequate access to digital

information, or they face many challenges while interacting with technological systems. To address these barriers, companies often use ad-hoc solutions by adding accessibility features to existing software and hardware. This approach reflects aspects of the medical model of disability by positioning impairments as a problem that needs to be compensated for, rather than addressing the systemic design barriers that produce disability. In contrast, a more effective approach would adopt the social model of disability, which supports the view that it is society that disables people. The social model of disability emphasises designing systems that are inherently accessible to everyone, promoting equality and inclusion (Retief and Letšosa, 2018).

This thesis focuses particularly on people with visual impairments and their use of Digital Audio Workstations (DAWs). According to the World Health Organisation (WHO), 217 million people worldwide live with moderate-to-severe vision impairment (WHO, 2023). In the UK, the Royal National Institute of Blind People (RNIB) reports that 2 million people live with sight loss (Royal National Institute of Blind People (RNIB), 2023). The lack of access to digital information challenges blind and visually impaired people's access to employment, social inclusion, access to education, healthcare, entertainment and other elements of life, as well as self-expression through music and arts. The employment rate among blind people in the UK is 27% against the 76% of the general population (RNIB, 2021). In music, barriers are similar, Baluji Shrivastav OBE (Baluji, 2023) states:

> 'Being great at music isn't enough to get you employed as a musician. I have experienced this myself. I have lost jobs or been made to feel that including me on a tour would be an inconvenience because of my blindness - the music doesn't even come into it.'

Advances in technology have provided many accessibility tools that are now advanced enough and widely used (e.g., braille displays, screen readers), making digital information accessible. Additionally, guidelines and regulations have been created to ensure the design of new systems that comply with the inclusive design principles. The UN Convention on the Rights of Persons with Disabilities included access to the web specifically as a fundamental human right. Laws have been established (Equality Act 2010), which oblige organisations to make the appropriate adjustments and ensure equal access for people (United Nations and Affairs, 2008). For instance, Web Content Accessibility Guidelines (WCAG) offer a unified framework for the development of accessible digital technologies ((W3C), 2023). These laws and guidelines support the day-to-day lives of people with visual impairments; however, there are still many elements in the interaction with digital media that challenge the efficient and productive access (Hamideh Kerdar et al., 2024). Individual studies explore the challenges in accessibility of digital technology for blind

and visually impaired (BVI) users; however, there is a lack of a unified overview of the accessibility factors that influence stakeholders and can enable the creation of a better and consistent accessible interaction model for digital environments. This research focuses specifically on music production as a professional pathway and as a hobby. It is motivated by the imbalance between the potential of technological advancements and the existing efforts to leverage them to create inclusive software and hardware, as well as by the fundamental right of BVI people to be part of the digital music-making and performing community.

Digital music production is supported by software that tends to be visually demanding. There is a shift towards a more skeuomorphic representation of hardware studio equipment on screen, making it harder for blind and visually impaired (BVI) users to interact. With the availability of software and online applications, 'bedroom' music production has made a significant leap in recent years (Burgess, 2014). As a result, many digital audio workstations (DAWs) have made the use of bespoke studio hardware, such as effect racks and mixers, redundant in their physical form. For BVI individuals, the heavy dependence on visual representation in new DAWs (e.g., sliders, buttons, and menus) makes music production more challenging. Music hardware devices (e.g., surface controllers and MIDI keyboards) improve workflow efficiency by offering a multimodal experience that allows interaction with sound through both visual and tactile means; however, many accessibility barriers remain in software-based workflows. Accessibility methods such as screen readers use text-to-speech to provide information on the screen verbally. This can create multiple challenges, such as slowing down navigation through an extensive list of parameters and causing voice feedback to overlap with the audio content of the music being processed (Saha and Piper, 2020; Harrison et al., 2023).

Haptic feedback has been explored as a method to reduce the barriers in music production. Both industry and academia have specifically provided methods through tactile interaction to enable a more effective way of accessing DAWs and processing audio. Haptic feedback has also been utilised in the day-to-day activities of people with BVI, with examples such as navigation assistance and accessing other types of graphic information (Jiang et al., 2025).

Haptic feedback is a technological tool that involves various technologies, designs, and use cases. Understanding the most appropriate choices in the design process is vital for creating a practical, accessible tool. Designers need to choose from the type of feedback (i.e., force, vibrotactile, pressure), as well as the type of device and its level of wearability, which gives numerous opportunities for adaptable and inclusive designs. Vibrotactile feedback has been used to provide various information such as notifications, alerts and

numerical values (Choi and Kuchenbecker, 2013). It is suitable due to the size of the actuators and the available opportunities for wearability and unobtrusive feedback they provide. Cases such as navigation tasks for BVI people, sound experiences for the d/Deaf and hard of hearing (DHH), and realism in virtual environment (VE) experiences have provided evidence of how vibrotactile feedback can enhance an experience by providing information through a complementary modality. However, the plethora of available design opportunities hinders the standardisation of a hardware device design or the vibration stimuli design. For example, the choice of body part that will accommodate a wearable device is still debatable and open to exploration (Zeagler, 2017). Nevertheless, this level of flexibility in vibration design indicates how suitable such a tool is for assistive technology, particularly for designing complex information systems like those of the DAW and enabling non-visual dependent interaction for the BVI.

The lack of human-centred design in the development of those accessible tools creates barriers to achieving an efficient and fully accessible music production workflow (Lucas et al., 2025; Payne et al., 2020; Saha and Piper, 2020). Although previous literature has explored the use of haptic feedback for accessibility, very few examples have resulted in viable solutions that can be integrated into everyday practice. This is due to the diversity of designs and the lack of established guidelines for integrating haptic feedback into assistive technology (Breitschaft et al., 2022; Jiang et al., 2025). Vibrotactile feedback, specifically, offers an embodied, flexible, and obtainable solution, showcasing a great variety of designs suitable for accessibility. Nonetheless, limited research has been undertaken on the use of vibrotactile feedback in music production and the accessibility of DAWs by BVI creatives. Finally, the presence of audio in the process of engagement with DAWs elevates the complexity of any task within the software. There is an increased mental demand produced by the need to process two audio materials, the music and the accessibility method that is based on voice feedback (Cauchard et al., 2012). This research aims to investigate how BVI users utilise haptic feedback in their current workflow, identifying their current needs, and exploring how vibrotactile feedback can enhance DAWs interactions (Research Question (RQ) 1). Additionally, this thesis evaluates the effectiveness of haptic feedback integration in DAWs compared to existing solutions and suggest novel haptic interaction designs (RQ 2).

1.1.1 Accessibility and disability position statement

This research aims to contribute to an inclusive design framework that enables people of all abilities to participate in a creative technology network, specifically in music technology and production, offering equal access to employment opportunities and self-expression. It approaches disability studies through the lens of the Social and Cultural

model of disability.

Literature has identified the four main limitations across studies in accessibility and assistive technology using haptic technologies: (1) the 'lack of user group diversity considerations', (2) 'lack of customisation', (3) 'limitations of user study' and (4) 'haptic device distrust' (Jiang et al., 2025). A lack of user-centred design in the research approach leads to most of these limitations. Studies that overlook individual differences and diversity make users feel underrepresented and excluded from the design process. The applied technosolutionism approach uses technology as a universal 'fix' of the individual's 'impairment' , echoing the medical model of disability, which focuses on the individual's impairment rather than on society and the surrounding environment. Whenever such approaches are applied, they often overlook users' needs and feedback during the design and development process, leading to ad hoc, temporary suggestions. Duarte et al. (2023) suggested classifying assistive digital music interfaces (ADMI) according to medical, social, and cultural models of disability. With social and cultural models, users are more involved throughout the technology design process. This research adopts the social and cultural models of disability and uses these models as the foundation for its methodology. Table 1.1 presents how Duarte et al. (2023) dimensions of social and cultural disability model (i.e., User Participation, Disability View, Inclusion View, and Impact View) have been applied in this research. 'User participation' aims to understand users' needs and identify ways to lower barriers to accessing music production software. The 'disability view' is that the barriers stem from the non-inclusive design of DAW rather than the user's medical conditions, as well as from a lack of infrastructure and knowledge about available accessible solutions. The 'inclusion view' focuses on making technology inclusive and adaptable, enhancing people's different abilities and providing equal opportunities in life. From a cultural model perspective, the aim is to lower the economic barriers and promote knowledge and access to music production in countries and people with poorer infrastructures. This research 'impact view' is the social benefits in making music production tools more accessible, which will provide a better and fairer basis for collaboration for music producers and musicians regardless of their abilities or where they are coming from.

Throughout this thesis, the term Blind and Visually Impaired (BVI) is used as an umbrella term to describe individuals across a spectrum of vision loss, including those with no light perception, partial sight, and low vision. This reflects the diversity of the participant group, which included individuals with varying degrees and types of visual impairment. This research recognised that the terminology in disability studies may vary over time and that individuals may prefer different ways of self-identifying and being described.

Participants were informed about the use of this terminology and were given the opportunity to suggest an alternative. The term 'sighted' is used to refer to participants without visual impairment who took part in the device evaluation studies.

1.1.2 Methodology

Building on this positionality, this thesis employs a human-centred methodology utilising key participatory design methods to thoroughly examine and utilise participants' needs and preferences. Nevertheless, the journey involves a mixed-methods approach that combines participants' voices with measurable data from usability testing. This research is grounded in the need to include participants throughout the process and ensure that this is a new system that is grounded in their needs. According to John Kally (a self-taught musician, singer/songwriter and a Disability and Human Rights Campaigner fighting for the right to Independent Living.)

> *"If you go away and do it, for me, nothing changes, the inequality still exists. We need this to be about a partnership."* [1]

Participatory design is used in HCI to enable inclusive designs that are adequate to the user's needs. In particular, studies on the design of technology for people with visual impairments have highlighted the need for alternative methods that enable effective participant engagement (Albouys-Perrois et al., 2018). Such methods include speech-based techniques (i.e., interviews and scenarios) which can initiate productive communication with participants (Metatla et al., 2015) Example methodologies by (Metatla et al., 2015), (Tanaka and Parkinson, 2016), (Albouys-Perrois et al., 2018), and (Rector et al., 2015) utilise interviews at the beginning of their design process to understand how users interact with specific technologies, identify the challenges they face, and determine their needs. This way, they ensure that participants' voices are heard and that they directly lead the development of new technologies.

This research utilises qualitative data collection primarily through participant interviews and usability questionnaires throughout the process (Chapters 3, 5, 6, 7). While interviews provide direct, in-depth, and rich feedback on each aspect of the research, questionnaires provide a measurable depiction of their perceptions of the development, which allows comparison with prior and future work in the field. Additionally, this thesis utilises quantitative methods, such as measuring accuracy and time, in task-based studies (Chapters 5, 6, 7). This method primarily benefits the evaluation of the new system's technical functionality, providing numerical evidence on the system's performance by a specific group of people. Mixed methods, combining qualitative and quantitative

[1] https://www.designpartners.com/the-pursuit-of-sound-report/

Dimensions	Our Position	Practical Contributions
User Participation	BVI music producers are collaborators. User-centred design techniques are at the centre. Understanding the needs in music production, and for social access to music production tools.	Interviews (Chapter 3), Post-test interviews (Chapters 6,7).
Disability View	DAWs are non-inclusively designed. Music production went from tactile interactive to visual with skeuomorphic representations. Music Hardware devices and assistive tools are impractical and financially inaccessible.	Armband Design (Chapter 5) is adjustable, non-intrusive, and low-cost. Vibration feedback as an intuitive, offer non-audio-based way to perceive information (Chapter 6,7).
Inclusion View	Technology must remove social barriers: be adaptable and affordable, respecting different bodies and cultures.	Providing equal opportunities to music production as a hobby or occupation. Enable better communication and collaboration across musicians of different abilities and cultures.
Impact View	Inclusive Music production tools have a greater impact in the music industry, allowing all people to be part of it regardless of their abilities or cultural background.	

Table 1.1: Alignment of our research with social–cultural disability principles

methods, provide a rounded, holistic evaluation method that allows centring the research around participants, developed based on their needs and feedback and providing results that can be expanded in future work (e.g., ideas from qualitative data), and compared or replicated through task-based studies with different or larger participant groups.

All studies conducted in this thesis received ethical approval from Birmingham City University. Participants provided informed written consent prior to their involvement and were made aware of their right to withdraw at any time without consequence, and all data was anonymised and stored securely in accordance with GDPR requirements. All study designs were accessible, respectful of participants' time, and sensitive to the lived experiences they shared.

1.2 Research Questions and Objectives

The following research questions are explored in this thesis, leading to the Objectives that underpin this research.

1. **How do BVI music producers currently use haptic feedback in their DAW workflows, and how do their unmet needs inform the design of new haptic devices?**

   To answer this question, a thorough exploration of the existing literature on the challenges faced by BVI music producers in accessing DAWs is essential. Participatory design methods, such as interviews, will enable the understanding of the current use of haptic feedback in DAW workflows and how participants' experiences can inform the requirements for the design of a new haptic tool. The beginning of this thesis, Chapters 2,3,4, aims to answer this research question by achieving the following objectives:

   1. Review existing literature and identify challenges faced by BVI people in the accessibility of DAWs, and examine the existing strategies and technologies developed to address these challenges. (Chapter 2)

   2. Review the types of haptic technology and their perceptual and technological opportunities and limitations in supporting non-visual interaction with digital interfaces. (Chapter 2)

   3. Interview BVI music producers to identify how they are currently using haptic feedback in their workflow and brainstorm ideas for the design of a new haptic feedback device.(Chapter 3)

2. **What vibrotactile feedback design strategies are most effective for supporting DAW interactions, and how do they compare to existing accessibility solutions?**

   This research question explores the viability of using vibrotactile feedback to enhance accessibility of DAWs for BVI users. In order to do that, Chapters 4,5,6,7 explore the optimal location of wearable haptic device for music production workflows, suggest the development of a new vibrotactile feedback armband device, compares a series of prototype vibration patterns with the existing method of screen readers and explores the use of different design methods in the interaction with the DAWs. The objectives that facilitate answering this research question are:

5. Review the existing designs of wearable vibrotactile feedback technologies and identify the most suitable ones for music production scenario (Chapter 4)

6. Design, develop and evaluate a new vibrotactile feedback armband device to provide haptic feedback on DAW interface interaction. (Chapter 5)

7. Explore the potential of using vibration cues for conveying information in the DAW through a comparison task between screen reader, haptics, and screen reader and haptics. (Chapter 6)

8. Explore a series of vibrotactile feedback mappings to music processing interactions in a DAW. (Chapter 7)

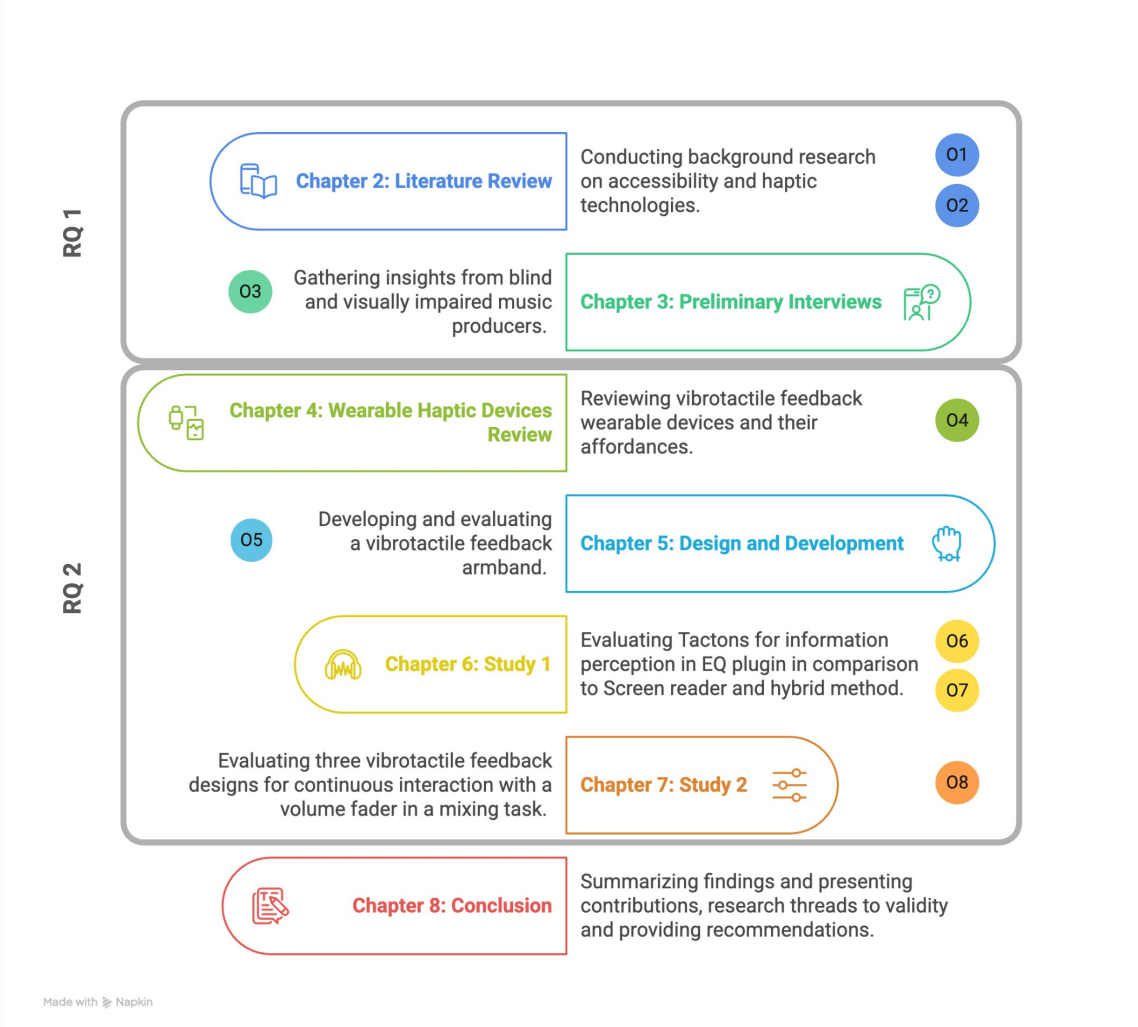


Figure 1.1: Thesis Structure

1.3 Thesis Structure

The thesis explores the use of vibrotactile feedback for lowering the barriers to accessibility of DAWs for BVI music producers. First, the existing challenges in DAW accessibility were reviewed along with the efforts to mitigate them through the use of academic or commercial haptic devices. Design methods of haptic technologies were established to facilitate the development of a new device. Through user-centred techniques (i.e., interviews), initial understanding of the use of music hardware for DAW accessibility was revealed, along with ideas on the areas of the DAW that would benefit from vibrotactile feedback and the establishment of the need for a wearable tool to convey information. Guidelines for mapping vibration feedback to DAW features emerged through the process of these interviews. After that, the literature review of the affordance of body parts in wearable technology design helps identify a more suitable location for the new device. Two evaluation studies of a prototype haptic feedback device facilitate the design of an armband with three vibration motors around the arm. Two further studies evaluated the use of vibrotactile feedback for the accessibility of DAWs using music production scenarios.

The structure of this thesis (Figure 1.1) is in two parts to separate the investigation around the participants' needs and technology's capabilities and limitations (Part 1), and the exploration of the use of vibrotactile feedback in music production (Part 2). Part 1, 'Requirements investigations', consists of Chapters 2, 3, and 4, and is designed to answer RQ 1. These chapters explore the research gap through literature review and human-centred research methods, such as interviews, with the aim of identifying the elements that contribute to the solution design. Part 2, 'Iterative Prototype Development and Evaluation', consists of Chapters 5, 6, 7 and addresses RQ 2. First, the design and development of a new haptic display (i.e., an armband with three vibration motors around the arm) is presented. Subsequently, two scenario-based studies were undertaken in which participants were asked to complete tasks situated within realistic use cases in order to examine the potential of using vibrotactile feedback to address accessibility challenges.

Chapter 2: Literature Review. This chapter focuses on the background research around accessibility, music technology and haptic technologies. The current methods of accessibility and trends in music technology have been reviewed. Barriers and challenges in the accessibility of DAWs have been collected and documented. Building on these limitations, the chapter then provides a detailed examination of haptic technologies, with particular emphasis on their wearability and potential contributions to accessible design. A particular focus is given to vibrotactile feedback, presenting how humans perceive this

type of feedback, the available technology, and the parameters that influence the design of the vibration stimuli.

Chapter 3: Preliminary Interviews with BVI music producers: Exploring Haptic Feedback for Inclusive DAW. In this chapter, 19 blind and visually impaired music producers were interviewed and provided insights into their workflow. More specifically, they explained how they use music hardware devices to lower the barriers of accessibility. They also expand on how they utilise vibrotactile feedback in other areas of their lives. Participants also provided extensive ideas on areas of DAW that require more accessibility and how they can benefit from haptic feedback. They presented design ideas of a new vibrotactile feedback device and described vibration patterns that could enhance interaction with the DAW. Through these interviews, an initial guideline for mapping vibrotactile feedback patterns to DAW features emerged and informed the following studies of this thesis. Participants' insights facilitate narrowing down the type of device that will produce vibrotactile feedback to a wearable device, leading to the next chapter that explores wearable technologies to identify the optimal case.

Chapter 4: The Affordances of Body Locations for Wearable Vibrotactile Feedback: A Literature Review. This chapter reviews existing wearable devices that provide vibrotactile feedback and the affordances of the body locations they are worn on. It explores how these affordances influence the most frequent use cases of these devices. Selected studies classified by their body location, worn, their motor arrangement and use cases were examined. This chapter facilitates the decision on the most suitable location for placing a wearable device with vibration motors, considering participants' requirements, the existing guidelines for the design of wearable technology and the comprehension of the body location affordances.

Chapter 5: Design and Development of wearable vibrotactile feedback display. This Chapter presents the process of developing and evaluating a new vibrotactile feedback armband. The design rationale based on literature guidelines around the design of wearable and haptic technologies is provided, followed by a detailed description of the production of the armband. Two evaluations, involving 24 and 12 participants, evidenced the validity or efficacy of the device, from the first device with five motors to the second with three motors.

Chapter 6: Study 1: Evaluating the use of Tactons for perception of information in DAW. This chapter presents the evaluation of vibrotactile feedback patterns (designed based on the technique of Tactons) using the armband device for receiving information in the pre-interaction stage. Six two-parameter Tactons were designed and evaluated in the presence of background music to convey the information that the

VoiceOver screen reader presents about the EQ frequency centre in Reaper DAW. The performance and cognitive load were tested across three conditions: a baseline screen reader method, haptics alone and a hybrid screen reader with haptics. Additionally, qualitative feedback was collected from participants regarding their perceived level of usability of this new system.

Chapter 7: Study 2: Interaction task: Comparison of Three Vibrotactile Feedback Mappings to the Volume Fader. In this chapter, vibrotactile feedback is presented and evaluated for the stage of continuous interaction with the slider interface element. Three methods of mapping vibrotactile feedback to a range of values in the presence of music were presented to users. In the scenario where the screen reader was absent, participants were asked to mix two music tracks to a certain level using the specific vibration feedback. Performance measurements and qualitative feedback provided information about the level of usability of the three proposed mappings.

Chapter 8: Conclusion. This Chapter interprets the findings of all the studies conducted in this research. Separated into three parts, the first part discusses the findings by highlighting the contributions of this research, but also reflects on their implications across two main areas: (1) accessibility studies, and (2) haptic technologies. The second part presents the threads to the validity of this research, which emerged after reflecting on the research methods used in this thesis and their limitations. The third part offers concrete recommendations for future technological and design developments to improve accessibility and the user experience of inclusive music production tools.

1.4 Contributions

The primary contribution of this thesis is a deeper understanding of the potential of using vibrotactile feedback for the accessibility of digital audio workstations for BVI music producers and the suggestion of preliminary guidelines for the design and development. The key contributions are detailed below and categorised in two areas: (1) Accessibility, and (2) Haptics, which answer the two Research Questions respectively.

1. Accessibility of Music Production using Haptic Technologies: Expanding the current knowledge on accessibility barriers in DAWs for BVI creatives by examining how tactile and vibrotactile feedback, already used in music production workflows and everyday tasks, can inform the design of more accessible music production tools. (Chapters 2, 3)

2. Haptics: Utilising a wearable vibrotactile feedback device for inclusive music production software.

- Mapping of Vibration design techniques to DAW interface interaction (Chapter 3)
- Exploring Body Location Affordances for Wearable Vibrotactile Feedback in Relation to Use Contexts and Performed Interaction (Chapter 4)
- A design framework for a vibrotactile feedback wearable device for BVI DAW users. (Chapter 5)
- Identifying Rhythm and location as the most useful parameters in designing vibration patterns for presenting information. (Chapters 6 and 7)

1.5 Publications

The following papers have been published as part of my thesis:

- Karpodini, C., Michailidis, T., Creed, C., Stockman, T., & Williams, I. (2025, October). Vibration Or Voice? Enhancing EQ Information Accessibility for Blind Music Producers with Haptics. In Proceedings of the 27th International ACM SIGACCESS Conference on Computers and Accessibility (pp. 1-14). https://doi.org/10.1145/3663547.3746374
- Karpodini, C. and Michailidis, T., 2025, March. Less is more: Designing Wearable Vibrotactile Wristbands for Blind and Visually Impaired Creatives. In HCII (International Conference on Human-Computer Interaction). https://www.open-access.bcu.ac.uk/16227/
- Karpodini, C., Michailidis, T., Creed, C., & Williams, I. (2025). Haptic Feedback to Overcome Barriers for Visually Impaired Users in Digital Audio Workstations. International Journal of Human–Computer Interaction, 1–18. https://doi.org/10.1080/10447318.2025.2464899
- Karpodini, C. (2022). Evaluating haptic technology in accessibility of digital audio workstations for visually impaired creatives. In Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '22). Association for Computing Machinery, New York, NY, USA, Article 97, 1–5. https://doi.org/10.1145/3517428.3550414

Chapter 2

Literature Review

2.1 Introduction

This chapter reviews literature on music technology, accessibility and haptic technologies. Section 2.2 presents an overview of music technology applications, including both software and hardware tools. Section 2.3 showcases how BVI users utilise the available tools, particularly tactile interaction, to enhance music technology accessibility. Section 2.4 establishes the design considerations of haptic technology by exploring the haptic systems' perceived affordances, the types of haptic feedback based on users' interaction with them, and examining the wearability level of different systems. This section concludes by highlighting examples of the contribution of haptic technology to the accessibility of BVI individuals, especially in music production. Section 2.5 highlights the elements that influence the design of vibrotactile feedback tools (human perception, type of actuators, and vibration parameters).

Two vibrotactile feedback design methods are central to this thesis and reappear throughout the following chapters. Haptic icons are short vibration patterns resembling auditory earcons, designed to convey haptic feedback for tactile interactions (e.g., keyboard interactions on touch screens). Tactons are abstract vibration patterns that convey symbolic information (e.g., message notifications on smartphones). Section 2.6 presents a review of these vibrotactile feedback design methods, highlighting the existing definitions and taxonomies and presenting use cases.



Figure 2.1: Motorized Faders



Figure 2.2: Limited Range Encoders

2.2 Music Technology Applications and Practices

DAWs provide a comprehensive set of tools for music making, including recording, editing, and mixing. They are often accompanied by a plethora of external plugins, audio processing tools, and virtual instruments. This wide range of choices empowers producers to select the ideal sound processing tool for their needs. Mainstream DAWs include Pro Tools, Logic Pro, Cubase, Live, and Reason, all of which have large user bases and an established history within the field (Huber and Runstein, 2017). Other DAWs, such as GarageBand and FL Studio, also offer significant advantages for beginner users starting to explore music-making and production, such as simplified interfaces and preset workflows. Among industry standards, Reaper might be considered the most cost-effective option, which makes it more obtainable (Sarah Keith and Mesker, 2022).

Hardware plays a crucial role in enhancing DAW functionality, supporting creativity and user interaction. It encompasses a wide range of tools supporting music production, including analogue and digital synthesisers, audio effect processors such as equalisers, reverb units, compressors, and MIDI instruments like keyboards, drum pads, and surface controllers. A wide range of audio interfaces, mixing consoles, studio monitors, microphones, sequencers, and samplers are available on the market. De Man et al. (2019) highlight how each device has unique specifications, design and interaction methods, making them distinct and preferable to different users. MIDI controllers, for instance, offer physical interaction through knobs, faders, buttons, and sometimes modulator wheels, allowing for intuitive control of audio parameters during the music-making process. Such hardware devices offer users an alternative to traditional mouse and keyboard interfaces, which can be a less cumbersome and more accessible way of interacting with DAWs (Huber, 2020).

The technical specifications of each device influence the level of usability and the consequential accessibility opportunities. It is crucial to understand how specifications

that enhance accessibility shape the overall usability of a device when designing future tools. *Endless encoders*, like those found in MIDI Keyboards Komplete Kontrol (Native-Instruments, 2024) and the Avid S1 mixing board (Avid, 2024) can rotate continuously without any physical stop. Such controllers make the reassignment to multiple parameters possible, offering the flexibility to access various functions of a DAW with the same physical interaction element. They also possess the capability to store a parameter's value, allowing users to recall it based on their specific requirements. Similarly, *motorized faders* (Figure 2.1) like these found in Faderport 16 (PreSonus, 2024), and X-Touch (Behringer, 2024), although inherently possessing a fixed range of motion, can be assigned to multiple parameters, recall saved values and move automatically to the assigned value offering tactile feedback on the automation envelope of an audio track.

Surface controllers enable tactile interaction with DAW interfaces, providing multiple advantages, such as efficient workflow through precision and adaptability to the user's setup and interaction needs (Berthaut and Jones, 2016). For instance, motorised faders are commonly used for recording automation within the DAW, offering users a level of performative expression and accuracy that cannot be matched by a computer mouse or keyboard (Anthony, 2018). On the other hand, such hardware presents several drawbacks that impede its effectiveness within users' workflows. The cost and physical space required for these devices may prevent users from buying and integrating this type of technology in their studios. For instance, the MIDI keyboard controller Kontrol S88 costs £1129 and has dimensions of 80cm width and 32cm depth (Native Instruments GmbH, 2025). While these music production tools, software, and hardware are widely used in professional music production workflows, there is a notable lack of academic research into the features that enable usability and accessibility, highlighting the need for further investigation.

2.3 Accessibility in Music Technology

The accessibility of music technology for BVI individuals is provided both in software solutions (i.e., voice feedback) and hardware (i.e., haptic feedback). While a software solution is based on the concept of additional software that aims to 'solve a problem', most hardware solutions offer a new way of interaction tailored to users' needs, introducing a method of interacting with music production systems that accommodates users of diverse abilities. Among these solutions are commercial devices and academic projects. The study of both contributes to the understanding of the benefits and limitations of the tactile modality, as well as the potential improvements in haptic device design for

the future. This section delves into the understanding of the limitations of existing accessibility methods, mainly software-based, and explores the opportunities that tactile interaction presents to BVI practitioners.

2.3.1 Screen Readers for DAW Accessibility

BVI individuals access digital information on computers primarily via screen reader applications such as *JAWS*, *NVDA*, and *VoiceOver* (Nick et al., 2012). A screen reader interprets the displayed context and converts it to synthesised speech or braille output (e.g., Table 2.1). To function properly, developers must integrate additional code *scripts* that facilitate screen readers' access to the application's layout, text, and user interface elements (Leonardis et al., 2018). The majority of commercially available DAWs are not designed to be compatible with screen readers, which poses a significant challenge (Saha and Piper, 2020). Among the few DAWs that support screen readers are Logic, Reaper, and ProTools (Pedrini et al., 2020; Harrison et al., 2023) and most recently *Ableton Live*. Apple's *Logic* and the latest *Ableton Live* application have embedded screen reader capabilities, making them accessible 'out of the box'. In the case of *Reaper* and *Protools*, the required *scripts* are developed by individuals in the form of plug-ins such as *Osara* (Teh, 2024) and *FloTools* (Chi et al., 2016), to make applications accessible to screen readers. Pedrini et al. (2020) evaluated the accessibility of three DAWs, *Reaper, ProTools* and *Cubase* (no longer accessible), through practical tests of mixing practices such as the use of transport, track navigation, waveform editing, sound level mixing and file configuration. Overall, Reaper has been found to be the most accessible of the three in both macOS and Windows, with the macOS operating system performing better in supporting accessibility tools such as the voice synthesis used in the screen reader (Pedrini et al., 2020).

Action	**User Input**	**Screen Reader Output**
Add new track	`Ctrl + T`	"Track edit name." (an editable text box appears)
Name the track	Type a name, then press `Enter`	Confirms name entry, e.g. "Track 1: Vocal."
Skip naming (optional)	Press `Enter` without typing	Keeps default name (e.g., "Track 1").
Navigate tracks	Use `Up/Down Arrow` keys	"One zero items." (indicates no audio clips on the track)

Table 2.1: Creating a new audio track in Reaper using a screen reader.

Across all DAW platforms, screen readers introduce a range of usability issues for BVI users. Metatla et al. (2011) identified, through four case studies, that interactions with

screen readers are tedious and time-consuming. In particular, the authors reported that the voice feedback process highlights multiple irrelevant pieces of information before reaching the user's desired point of interaction. Similarly, Saha and Piper (2020) and Harrison et al. (2023) also underline that the way information is presented through the screen reader is not sufficient enough, given that information is being presented in a linear way (e.g. lists of parameters), thus causing delays and cognitive overload by requiring multiple steps for task completion and a high level of memorisation. Pedrini et al. (2020), highlight how using a screen reader in DAWs results in two conflicting sources of audio feedback, one from the DAW's output and another from the screen reader, which increases cognitive load and decreases workflow efficiency.

Payne et al. (2020) highlighted the lack of the required *scripts*, resulting in users' inability to access the software or parts of it through a screen reader with no alternative. For instance, software updates often break accessibility features if new code is not accompanied by corresponding scripts for screen readers. Similarly, the majority of third-party plug-ins are not accessible for BVI users as the developers often do not consider inclusivity and accessibility due to extra cost and development time (Payne et al., 2020; Saha and Piper, 2020; Harrison et al., 2023). DAW's graphical interfaces also present additional accessibility constraints, as they often focus on visual cues, such as changes in colour or graphical icons, to convey information. Without providing alternative descriptive text, graphical information cannot be translated to text (Metatla et al., 2011; Saha and Piper, 2020; Harrison et al., 2023).

Given the limitations of screen readers, BVI producers often turn to hardware devices, including Braille displays and MIDI controllers, to create a multimodal interaction setup that reduces the cognitive load (Payne et al., 2020). Saha and Piper (2020) and Harrison et al. (2023) examined how users are 'forced' to combine different tools to develop efficient workflows (e.g., a computer and a MIDI keyboard. However, this makes workflows significantly more complex, as users have to manage several pieces of equipment simultaneously. Although hardware tools are considered useful, they are often expensive, and some rely on interaction systems such as touchscreens that lack screen reader support. As a result, a system that depends on compatibility with a screen reader can be unreliable and present further accessibility issues. Harrison et al. (2023) specifically highlighted the tactile affordances provided by analogue equipment to users and how they are lost in the digital domain. Nevertheless, BVI producers embrace the fact that tactile interaction (e.g., motorised faders, rotary encoders and buttons) allows the manipulation of the audio through bypassing a screen reader's voice feedback for certain tasks (Harrison et al., 2023).

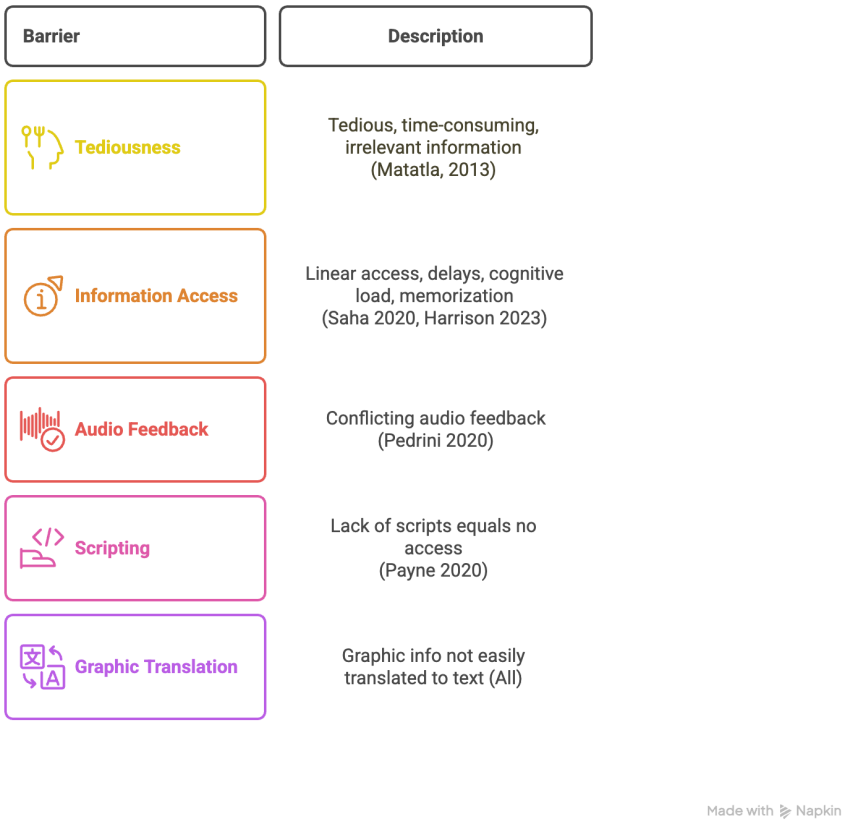


Figure 2.3: Accessibility in DAW: Barriers caused by screen readers.

Current research highlights patterns of inaccessibility in music production, with a predominant focus on screen readers and the efforts to address key challenges (Saha and Piper, 2020; Pedrini et al., 2020) (Figure 2.3). Harrison et al. (2023) examines the advantages of incorporating tactile interaction in the workflow of BVI users. Nevertheless, most existing studies (e.g., Payne et al. (2022) and Saha and Piper (2020)) do not adequately address the relationship between software accessibility barriers and benefits offered by hardware, highlighting a key research gap within the literature.

2.3.2 Tactile Interaction for DAW Accessibility

Studies by Kalantari et al. (2018) and Papetti et al. (2021) indicate that vibrotactile feedback can enhance the accessibility of music production tools by providing advanced non-visual interaction for understanding and manipulating sound. Many commercial companies leverage these insights to develop devices that promise an enhanced music experience (Figure 2.4). For example, wearable devices with vibrotactile feedback, such



Figure 2.4: Commercial Devices: a) **subpac**, b) Woojer (2025), c) Feelbelt (2025), d) bHaptics (2025), e) Microdrivers (2024) f) Not Impossible Lab (2024)

as the SubPac (SUBPAC, 2025) and bHaptics (bHaptics, 2025), vibrate at low frequencies to create a tactile sensation of sound. Similarly, the Woojer (2025) and Feelbelt (2025) are belt-style devices that respond to audio frequencies, delivering immersive vibrations to the wearer. The Music: Not Impossible (Not Impossible Lab, 2024) haptic suit is designed specifically to help deaf and hard-of-hearing individuals enjoy live performances through a full-body sensory experience. Meanwhile, the Soundbrenner (Microdrivers, 2024) wearable metronome transmits tempo information directly to the user's wrist, making it a valuable tool for musicians.

These devices show great potential for augmenting digital music environments such as DAWs and serve as valuable accessibility tools by introducing a new sensory dimension for perceiving sound. However, their functionality is still limited to conveying specific information within a DAW, such as sound intensity across certain frequency ranges. As a result, their primary applications remain focused on enhancing the experience of listening to or enjoying music in new sensory ways. Due to the physical constraints of these table-based haptic technologies (e.g., size, weight), these devices are not yet flexible or modular enough, and they are limited to specific use cases (Adilkhanov et al., 2022).

Examples of targeted accessibility features embedded in hardware devices are also presented in music technology companies such as Native-Instruments (2024) and Softube



Figure 2.5: Left: Native-Instruments (2024) Komplete Kontrol, Right: Softube (2024) Console One

(2024), which have attempted to integrate inclusive design methods and accessibility design practices into their product design to make their products accessible to BVI music producers (Figure 2.5). These devices not only utilise the tactile affordances of the hardware specifications, such as knobs and faders, but they also include embedded voice feedback to ensure that the device functions independently while also being well-integrated into a DAW or any workflow.

A variety of research projects explore the possibilities of alternative assistive tools to make DAWs more accessible by utilising multimodal interactions. The *Moose* by O'Modhrain and Gillespie (1997) suggested a motorised system that facilitates interaction in a 2D axis like the mouse. Haenselmann et al. (2009), with the *zero-vision sequencer*, proposed a MIDI instrument that combines performance and sequencing functionality, allowing users to avoid porting across platforms. Since 2010, several research projects (Karp and Pardo, 2017; Pesek and De Man, 2021; Lucas et al., 2019; Kaiser et al., 2018; Tanaka and Parkinson, 2016; Karpodini and Michailidis, 2022; Payne et al., 2019) have highlighted the need for tangibility in music processing and production. They explore existing and emerging technological advances, combining them with users' feedback to suggest directions for the future development of music production tools. Several projects focus on specific interactions in the DAW - for instance, *HapticEQ* by Karp and Pardo (2017) suggests an interaction with a flexible chain that can generate an EQ curve which is then interpreted through computer vision (Figure 2.6 a)); *TouchEQ* by Pesek and De Man (2021) uses *TanvasTouch* (Tanvas, 2024) (Figure 2.6 b)), a surface haptic interface that offers localised and textural haptic feedback for interacting with EQ parameters. Lucas et al. (2019) tested bespoke 3D-printed knob caps (Figure 2.6 c)), and Kaiser et al. (2018) used an Xbox 360 controller to interact with transport functions (i.e. play, stop, pause, rewind, fast-forward, and record buttons). Tanaka and Parkinson (2016) developed a device, the *Haptic Wave* (Figure 2.6 e)), consisting of a motorised fader that moves in a 2D axis, providing information about the waveform parameters and facilitating the editing process. Alongside music production projects, haptic interaction

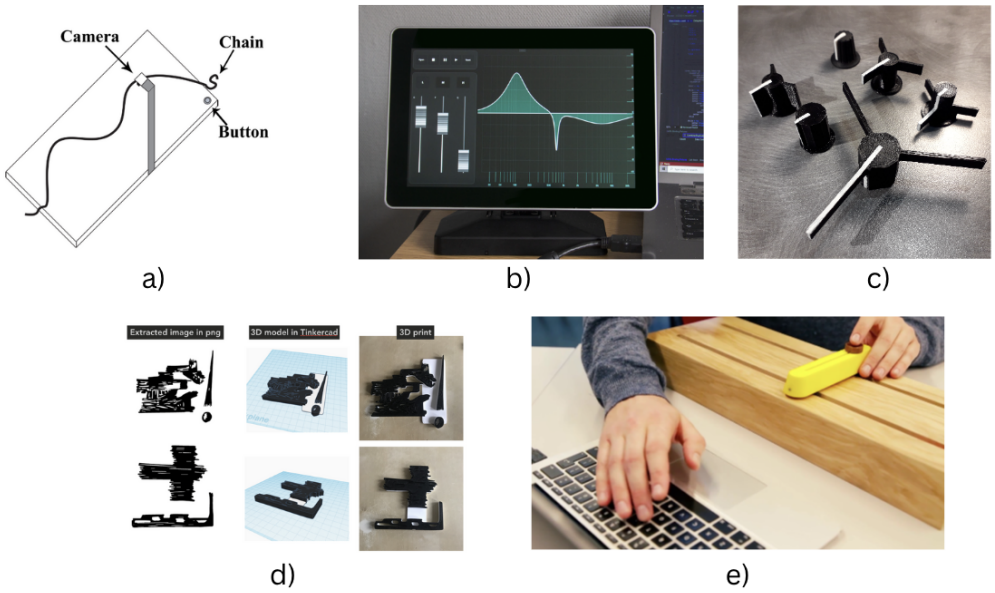


Figure 2.6: Research Projects using Haptic Technologies in Music Production: a) HapticEQ (Karp and Pardo, 2017), b) TouchEQ (Pesek and De Man, 2021), c) knob cups (Lucas et al., 2019), d) Accessible Graphic Scores (Karpodini and Michailidis, 2022) e) Haptic Wave (Tanaka and Parkinson, 2016)

has been utilised for compositional purposes. For instance, Karpodini and Michailidis (2022) proposed 3D-printed representations of graphical score parts in a table (Figure 2.6 d)), while Payne et al. (2019) redesigned the Groove Pizza application by adding keyboard interaction to make it more accessible.

Although individual case studies provide valuable information about the benefits of haptic feedback and multimodality in both assistive tools and music-making tools, they lack comprehensive research on how technology design and multimodal interaction synergistically contribute to the overall usability and inclusivity of these tools. Limitations of these projects are concentrated in three key areas: the methods of evaluation, sample size and lack of longitudinal evaluation.

Studies in the field heavily rely on qualitative and participatory design approaches, and are often unable to provide robust quantitative evidence to demonstrate a system's usability and the effectiveness of its design. On the contrary, mixed-methods offer a holistic assessment of system usability through comprehensive data collection (i.e., qualitative and quantitative. They help identify design issues in the early stages and provide ideas that guide future design (Dittli et al., 2023). Foremost, these methods increase the validity of the findings, as the results are cross-verified by different methods (Lynn Campbell, 2020).

Most studies have small sample sizes; the largest sample sizes reported were 11 participants in Tanaka and Parkinson (2016) and 15 participants in Pesek and De Man (2021). While the insights from these studies are informative and contribute to our understanding of the accessibility challenges faced by BVI music producers, there is a risk that they may not adequately represent the broader population. In conclusion, although small sample sizes provide valuable insights, they should not be used to present generalised conclusions (Oppong, 2013).

Another major limitation of these studies is the sustainability and a lack of longitudinal evaluations. Most projects remain at a research prototype stage and rarely transition into widely accessible, long-term solutions. According to Khurana and Hodges (2020), the reason for this limitation is often the researchers' lack of technical knowledge in manufacturing procedures and preparations, as well as a lack of industry and production networks, and according to Manzoor et al. (2018), the limited financial resources, ethical issues, and the complexity of the project. Thus, it is essential to consider in advance how any new device or system will be sustained, if there is potential for large-scale manufacturing, and what alternatives are available, such as utilising an existing design and working on its iteration and evolution. Nevertheless, work that remains at the research prototype stage still offers valuable insights and can inform subsequent work.

This section presents the existing accessibility tools that BVI music producers are utilising in their workflows. Literature has examined the limitations that screen readers pose to users (e.g. overlap of voice feedback and music and time-consuming navigation) and suggests that a multimodal approach would be more inclusive. Existing commercial and academic devices are being presented to and used by BVI people, revealing a plethora of benefits (e.g., non-intrusive and more precise interaction) but also challenges (e.g., cost, size, and task-specificity).

2.4 Haptic Technology

Touch is part of how humans understand their surroundings, complementing or replacing other senses, such as the texture of clothing and the temperature of food (Gao et al., 2021). Haptic technology aims to augment users' experience and facilitate their actions by adding a digital sense of touch. There is a wide variety of haptic feedback possibilities that reflect users' needs, ranging from simple vibration notifications about a text message on a smartwatch to heavy exoskeletons that assist people with physical impairments in walking (Manns et al., 2019). In the effort to digitise and reproduce the sense of touch, technology has been developed in many directions, offering a range of interaction types to users. This section presents the existing taxonomies of haptic technologies, enabling an

understanding of the considerations taken when designing a new system. The taxonomies explore the relation between the system and human from different perspectives, starting with how perceivable the tactile affordances are to the user, followed by the level of contact that the user needs to have with the system and finally, the position of the system in relation to the human body, also called wearability. This section concludes with the presentation of various haptic applications for BVI individuals, highlighting both the benefits and the limitations that arise when such considerations haven't been made during the design process.

2.4.1 Perceived Affordances of Haptic Feedback Systems

The first categorisation of haptics focuses on the degree to which the tactile affordances of haptic feedback systems are perceptible by the user. The terms that describe the level of percevability are the 'transparency' or 'passive/dynamic feedback' according to Vezzoli et al. (2022). Affordances that are directly perceivable without active interaction have low transparency, and they are considered passive feedback, while the tactile qualities are embedded in the object itself. Such examples are the keyboard buttons, knobs and faders on music consoles and any other physical structure where the tactile feedback is obvious and available at all times. On the other hand, High Transparency and Dynamic Feedback are characterised by the affordances being only perceived when the user interacts with the system. In this case, the feedback is digitally programmed or dependent on the input. Such examples include the resistance feedback received from a steering wheel or VR gloves (Wang et al., 2019), where there is no feedback unless the user interacts with the device by providing input. Another example is the digital tactile feeling when pressing a key on a touchscreen (Chen et al., 2011), touchscreens like phones and tablets provide a constant flat and smooth texture unless a user interacts with specific elements in the screen like buttons, which are programmed to provide a vibration feedback that substitutes the feeling of pressing a physical button.

Acknowledging the power of tactile affordances embedded in a device, designers can assess the level of perceptibility needed and make appropriate design decisions. When affordances are present, they provide a level of independence in interacting with the system; however, such physically demanding interactions often require large devices, which can be cumbersome or require a significant amount of space (e.g., music hardware devices). On the other hand, invisible systems that provide feedback when users interact with the system indirectly (e.g., using another modality or part of the system) can be less intrusive and require a learning curve, but they are more flexible and adaptable (e.g., smartwatches, vibration feedback wearables for music).

2.4.2 Type of user's contact and interaction with the Haptic Feedback Systems

The second categorisation of haptics (Vezzoli et al., 2022) is the type of contact and interaction the user has with a mechanism to perceive haptic feedback (i.e., the user needs to make a movement or apply force to the device, or the user is not interacting with the system at all) The two main categories are the *Kinesthetic* and *Tactile feedback*. *Kinesthetic feedback* activates mechanoreceptors and proprioceptors responsible for movement coordination and posture. It can be split into *Resistive* and *Active*. *Resistive* aims to obstruct the user's motion by providing a break or resistance (e.g., VR gloves prevent users to move their fingers further in order to provide a realistic sensation of holding an object), whereas *Active* aims to enable or motivate body movement by applying a force to a body part (e.g., a wearable exoskeleton that lifts a user's arm to assist with physical therapy exercises). Tactile feedback, also known as *cutaneous* feedback, is a passive type of haptic feedback, as users receive the feedback without the need to make a movement or interact with a device that produces the feedback. *Cutaneous* feedback activates the skin mechanoreceptors (section 2.6.1) (Fang et al., 2022), which are responsible for perceiving vibration, friction, and temperature. According to Vezzoli et al. (2022) *Tactile* feedback can also be divided into more specific types, *Spatial* and *non-contact spatial*, based on the technology and the way users interact with it and for what purpose. *Spatial* requires an interaction within a 2D or 3D space. For example, surface friction like in *Tanvas* touchscreen, where users received textural information while interacting with the touchscreen (Klatzky et al., 2019), skin indentation like in the use of pneumatic or fluid actuators where users feel the pressure in specific locations in their skin, like in *HaptX* (Shen et al., 2023) and *PneuFetch* (He et al., 2020), and involves applying electrical impulses to stimulate muscles or nerves (Guo et al., 2022), as demonstrated by the TeslaSuit (Caserman et al., 2021). Those are also Contact-related, as users need to contact the surface to perceive the feedback. Non-contact spatial haptics is an ultrasound-based technology that creates the sensation of touch in mid-air, allowing users to interact with virtual surfaces without physical contact, similar to Ultraleap (Hoshi, 2024). Lastly, vibrations are considered non-spatial, as they are not directly linked to interaction with a surface (section 2.6). Examples of vibration feedback can be found in notifications received in mobile devices or smart wearables. Thermal feedback, as in Peiris et al. (2019), which explores the use of thermal feedback to enhance notifications received on smartwatches, can also be characterised as non-spatial, as it is not tied to the user's interaction with a surface to provide feedback, without excluding the possibility of such use. The study of haptic technologies benefits the understanding of the most suitable technology for each use case scenario. Inclusive haptic tools need

to incorporate haptic technology and provide haptic feedback that reflects users' needs.

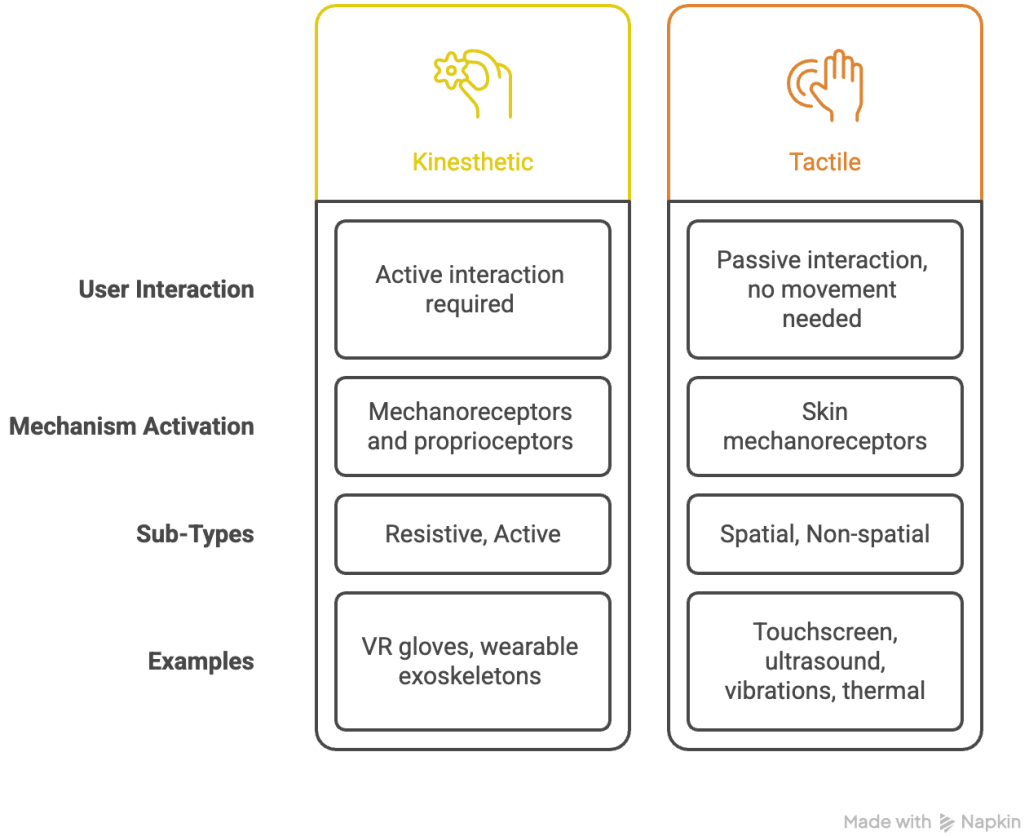


Figure 2.7: Categorisation of Haptic feedback based on the type of user's contact and interaction with haptic systems

2.4.3 Haptic Devices based on their Wearability

Existing literature reviews provide comprehensive overviews and taxonomies of wearable haptic technologies, adopting diverse approaches based on specific use cases. Some focus on the context of use of haptic technologies, others on the means of interaction with different devices and others on the type of technology used. For instance, some overviews focus explicitly on virtual environments (Rodríguez Ramírez et al., 2018; Patel et al., 2025), assistive technologies (Shull and Damian, 2015), and mobile augmented reality (Bermejo and Hui, 2021). Certain taxonomies emphasise specific types of wearables or feedback mechanisms, such as kinesthetic feedback (Wang et al., 2019), haptic gloves (Perret and Vander Poorten, 2018), or surface devices (Basdogan et al., 2020). Finally, broader reviews, such as those by Adilkhanov et al. (2022) and Culbertson et al. (2018),

and Pacchierotti et al. (2017), aim to categorise them based on how users interact with the devices, considering their design structure (i.e., wearable, non-wearable).

These reviews share a common focus on two aspects: the location and the device's wearability level. Thus, Adilkhanov et al. (2022), Culbertson et al. (2018) and Pacchierotti et al. (2017) categorise the technology into three primary groups: grounded devices, handheld devices and wearables. *Grounded devices* are defined as non-wearable systems that are fixed-positioned and touchable or graspable. These devices are often complex structures, limited by their size and weight; however, they provide highly accurate feedback. Depending on their structure, they can offer kinesthetic feedback through force feedback technologies or cutaneous feedback using vibrotactile feedback. Such examples are studies that incorporate vibrotactile feedback in chair-like structures (Plaisier et al., 2020; Vries et al., 2009; Cho et al., 2014; Branje and Fels, 2014; Baijal et al., 2012), touchscreen devices (Jamalzadeh et al., 2023; Okazaki et al., 2015; Palani et al., 2021; Singhal and Schneider, 2021) or other interactive surfaces like buttons (Park et al., 2020; Shim and Lee, 2018; Ogawa et al., 2015), sliders (Strohmeier and Hornbæk, 2017), and musical instruments (Jack et al., 2016; Marshall and Wanderley, 2011). In contrast, handheld devices can be held in users' hands but are still not worn. These devices usually provide both cutaneous feedback through vibrations and kinesthetics through force feedback. They are widely used in commercial applications (e.g., PlayStation, Xbox, Nintendo, VR systems, and other gaming controllers). Nonetheless, research in this domain has explored existing commercial devices, such as Sucu and Folmer (2014) who use Sony PlayStation Move steering wheel to provide tactile cues and guide blind users into moving the wheel to the indicated direction. Other examples include Nakada et al. (2018) that used Nintendo Switch controllers to represent musical scale with vibrations and novel experimental handheld systems. Cabaret et al. (2025) utilised the concept of the existing handheld gaming controllers and developed a multi-actuator haptic handle to provide spatial awareness in VR. Finally, wearable devices are defined as systems that can be comfortably worn by the user without hindering movement (Pacchierotti et al., 2017). They are typically lightweight, easy to wear, and compact (Vlam et al., 2023). They are most commonly used for providing cutaneous feedback using vibrotactile feedback technologies. An exception to this is the *grounded to the body-exoskeleton* devices (Pacchierotti et al., 2017), which are wearables but act like grounded devices aiming to provide kinesthetic feedback via force feedback, and they are usually heavy and uncomfortable to wear in the long term, like the SenseGlove (SenseGlove, 2025) or Dexmo (Caeiro-Rodríguez et al., 2021; Dexta Robotics, 2025). Based on these characteristics, a wide range of designs and haptic feedback arrangements is available, depending on the location worn. Examples include hats (Lordianto et al., 2024), wristbands (Lin et al.,

2024; Sabry and El-Atabany, 2024), belts (Gay et al., 2020), and vests (Richards et al., 2022), each employing different placement and configurations of vibration motors.

The diversity of haptic feedback system designs, including wearables and non-wearables, as well as the various parts of the body involved in perceiving the feedback, highlights the importance of involving the users in the design process. When user needs are considered (e.g., BVI individuals), the design choices become more targeted and refined. Users' insights should inform the design of the system's affordances, technological requirements, and device configurations.

2.4.4 Haptic Feedback in Assistive Technology for Blind and Visually Impaired Individuals

Haptic feedback in Assistive Technology for individuals with BVI is underexplored. Although individual studies have attempted to address certain barriers, very few studies have contributed significantly to lowering accessibility challenges or informing design frameworks for the use of haptic technologies in accessibility. Jiang et al. (2025) systematic literature review provides a clear overview of the use of haptic feedback in accessibility for people who are BVI. This review highlights the types of tools and their feedback based on the type of information or activity they assist with. Four use cases of haptic technology identified are: *Understanding graphical information, guidance and navigation, Educational and Training, and other life and work tasks*. The types of technologies vary from grounded to wearable; some are distinct for each use case, and some overlap as well. For understanding graphical information such as map information, chart information and figures, tools that convey pressure and kinesthetic feedback are used predominantly. These tools include tactile graphics, map displays, and 3D models. Tactile maps use the concept of raised dots or lines. For example, Hofmann et al. (2022) utilises tailored 3D-printed tactile maps to facilitate learning a new area based on users' preferences and needs, while Nagassa et al. (2023) employs 3D-printed maps to assist users in navigating multistory buildings. 3D models contain more details and are ideal for conveying information about objects familiar in the real world, such as the 3D printed icons from Holloway et al. (2023). The use of 2D or 3D structures, such as those used to perceive graphical information, are also used for education. For example, Melfi et al. (2020) uses the tactile pad system, along with braille and audio feedback, to help students understand graphical information in a school context and memorise information. Lu et al. (2024) explored the use of vibrations and 3d printed sliders and rotary encoders for assisting the learning and memorisation of music notation. Robotic arms are used for both educational purposes and to understand graphical information. Zhang et al.

(2017) uses a Force Dimensions haptic device (Inition, 2025) in which users use a stylus end to access depth and viscosity information of a histological image. This research aims to enable blind users to access certain types of science-related careers. Plimmer et al. (2011) suggests the use of SensAble Technologies PHANTOM Omni force feedback (Delft Haptics Lab, 2025) to teach BVIs to handwrite and, more specifically, be able to make a signature.

Navigation assistance facilitates BVIs' outdoor and indoor movement activities. The most common tools are the haptic bands, which mostly include vibration motors and feature white cases with attached vibration motors or thermal feedback. The information they provide usually includes guidance cues and information. For example, in Flores et al. (2015) and Cosgun et al. (2014), a belt with motors around the waist is used to provide information about foreseeable paths and the directions the user needs to take. In the case of the white cane, vibration cues also help indicate barriers; for instance, Kim et al. (2015) uses four actuators and Gallo et al. (2010) 3 motors in the handle of the cane to convey obstacle distance to the user.

Haptic technology has been extensively used to assist with various activities of everyday life and work. The most well-known haptic assistive tool is the braille display, which helps with writing and reading. This technology varies in size and cost. The largest Braille display has 80 Braille cells, allowing it to display a whole page of text, which facilitates more flexible navigation in a context broadly similar to vision (Pawluk et al., 2015). Similarly, Canute Console displays a whole page of text and supports access to spatial applications, graphs, spreadsheets, diagrams and schematics, maps, and tactile video games (Bristol Braille Technology, 2025). Another example is the Tangible Desktop, which evaluates ways of splitting information between audio and tactile feedback using 3D printed models, such as icons, faders and buttons (Baldwin et al., 2017). Similarly, in Tanaka and Parkinson (2016), a unique fader-type device is used to assist in understanding the sound waveform as it is represented in music production software through a graphical representation. Other applications are used to make games more accessible, as seen in Matsuo et al. (2021) and Jung et al. (2021), which enhance tactile interaction with game controllers and interfaces to present game information differently.

Although there are many applications of haptic feedback for accessibility, numerous limitations and challenges also exist. The technical elements, which comprise the hardware of the tools, present several barriers. Jiang et al. (2025) review argues that the fact that the devices are in physical contact with the user creates an 'environmental effect on sensors and actuators'. They argue that long-term use, diverse types of users' skin or body, and even environmental conditions like temperature and humidity are some of

the parameters that challenge the perception of haptic feedback (Jiang et al., 2025). Similarly, the size, weight, noise produced from vibration and overall design of the device can be noticeable in a way that creates discomfort for the user. Other limitations arise from the actual functionality of the devices and the level of accessibility they offer. Displays often lack flexibility and control over the way they display information (e.g., zoomed-in images, speed of sliders). Additionally, Jiang et al. (2025) points out that haptic displays do not provide detailed information. This is particularly common when displaying graphical information and complex structures, such as data visualisation or maps. Lastly, most examples offer only one way of displaying the information, hindering the presentation of multidimensional information. Haptic feedback assistive technologies often lack a user-centred design approach, aiming for one solution that fits all. The lack of consideration for diversity, including different visual impairments, age, educational background, economic barriers, and culture, often leads to short-term solutions tailored to narrow task-specific needs (Lundgard et al., 2019). New systems are often not adaptable, making users feel insecure, excluded and leading to a lack of trust in technology.

This section has provided an overview of haptic feedback technology, highlighting the different taxonomies and considerations that are taken into account when choosing the most appropriate technology and design. As discussed above, the wider literature extensively examines the opportunities and challenges of haptic feedback technology. However, individual studies tend to focus on specific angles in isolation, such as the perceived affordances, the type of interaction and level of wearability. The insights of the existing literature indicate that future studies need to prioritise understanding users' needs before conducting detailed investigations into the individual design structure of haptic feedback devices for accessibility of music production.

2.5 Vibrotactile Feedback

Vibrotactile feedback is distinguished from other types of haptic feedback (2.5.2) due to the small size of vibrotactile actuators, which allows them to be used anywhere on the body surface. Due to this practicality, they are ideal for conveying passive feedback, such as information, directions, texture, and other sensations. Vibrotactile feedback is preferred over other cutaneous feedback (Thermal, stretch, pressure) as it can act in mobile situations and perform well in a multimodal environment (Dim and Ren, 2017), enhancing the task performance (Vlam et al., 2023) and reducing the need for visual attention (Dementyev et al., 2021). The technology, which consists of vibrotactile feedback, is

small and often cost-effective, making it easily embedded in wearables, allowing for flexible designs. The extensive surface area of human skin offers numerous possibilities for designing and deploying wearable vibrotactile feedback systems. The combination of the human's body perception levels and the actuator's capabilities leads to the formation of the device's affordances. For instance, a belt-like device allows multiple motors around the waist, indicating the use of the device to provide directions (i.e., left, right, front, back). The design of such a tool is mutually influenced by the human characteristics, the technology used and the device functionality. The following paragraphs expand on how humans perceive vibrations, the types of actuators that are available to be used and the individual vibration parameters that form the vibration cues. Acknowledging the opportunities and limitations of technology facilitates the design process and the accurate transformation of users' ideas to haptic feedback applications.

2.5.1 Perception of Vibrations

For vibrotactile feedback to be perceived, actuators need to stimulate the skin's mechanoreceptors. The triggered signal is then sent and interpreted by the central nervous system via the dorsal-lateral column way, which is the fastest communication channel in the human body (100m/s) (Sziebig et al., 2009). There are four types of receptors: Pacinian, Meissner's, Merkel and Ruffini and each of them is responsible for perceiving different elements of haptic feedback. Ruffini is the only one not responsible for vibrotactile feedback but for skin stretching (Fang et al., 2022). Pacinian receptors are sensitive to high-frequency vibrations (40 - 400Hz); they can detect rapid vibrations as they have a quick adaptation rate. Meissner responds to low frequencies (5 - 40Hz), which have a high spatial resolution and a quick adoption rate in the glabrous skin. Lastly, Merkel responds to very low frequencies (≈ 5 Hz) with high spatial resolution but a slow adapting rate (Sziebig et al., 2009; Fang et al., 2022; Wang et al., 2020).

Further to the biological basis of tactile sensations, there are the psychophysical effects of vibrotactile feedback perception. Weber's Law refers to the way people perceive changes in stimuli. This is especially applicable to the perceived intensity and frequency of vibrations (Jones and Tan, 2012). The Just Noticeable Difference (JND) principle is used to measure this phenomenon. For example, in the frequency range 0 - 200Hz, the JND is 6Hz (Tran et al., 2023). Frequency and intensity are interlinked when it comes to the perception of vibrations. Thus, it is important to know the best-perceived frequency. Although the frequency range that can be perceived is from 0.3Hz to 1000Hz (Remache-Vinueza et al., 2021), the most sensitive range is between 150 and 300 Hz (Dementyev et al., 2021). Tran et al. (2023) tested different locations on the hands and arms and found that the sensitivity does not change across the different locations.

The study examined the fingertip (≈ 120 Hz), hand dorsum (≈ 120 Hz) and forearm (≈ 124 Hz. On the contrary, Wolf and Kuber (2018) suggests that the head has a sensitivity to lower ranges around 32 - 64Hz.

Spatial perception of vibrations has also been studied. The different body locations have different resolutions and minimum distances for positioning the stimuli due to the concentration of mechanoreceptors. For example, Cipriani et al. (2012) examined the minimum distance in the volar of the forearm and concluded that the different vibrotactile stimulation points should have at least 8cm separation. In contrast, Goldstein (2010, cited in Remache-Vinueza et al. (2021)) suggests 10mm for hands and lips. Meier et al. (2015) presents a concentration of the minimum perceived distance between stimuli for each body location (i.e., surface haptic resolution), as they have been stated in Deetjen (2005) (Figure 2.8). The understanding of the location depends on the frequency of the vibration, but also the duration of the stimulus (Remache-Vinueza et al., 2021), (Meier et al., 2015). Studies from Azadi and Jones (2014) indicate that a duration of 2.5s outperformed 1s and 1.5s. In the optimal scenario of 2s, participants can distinguish the vibrations if they have a minimum 150ms distance between them.

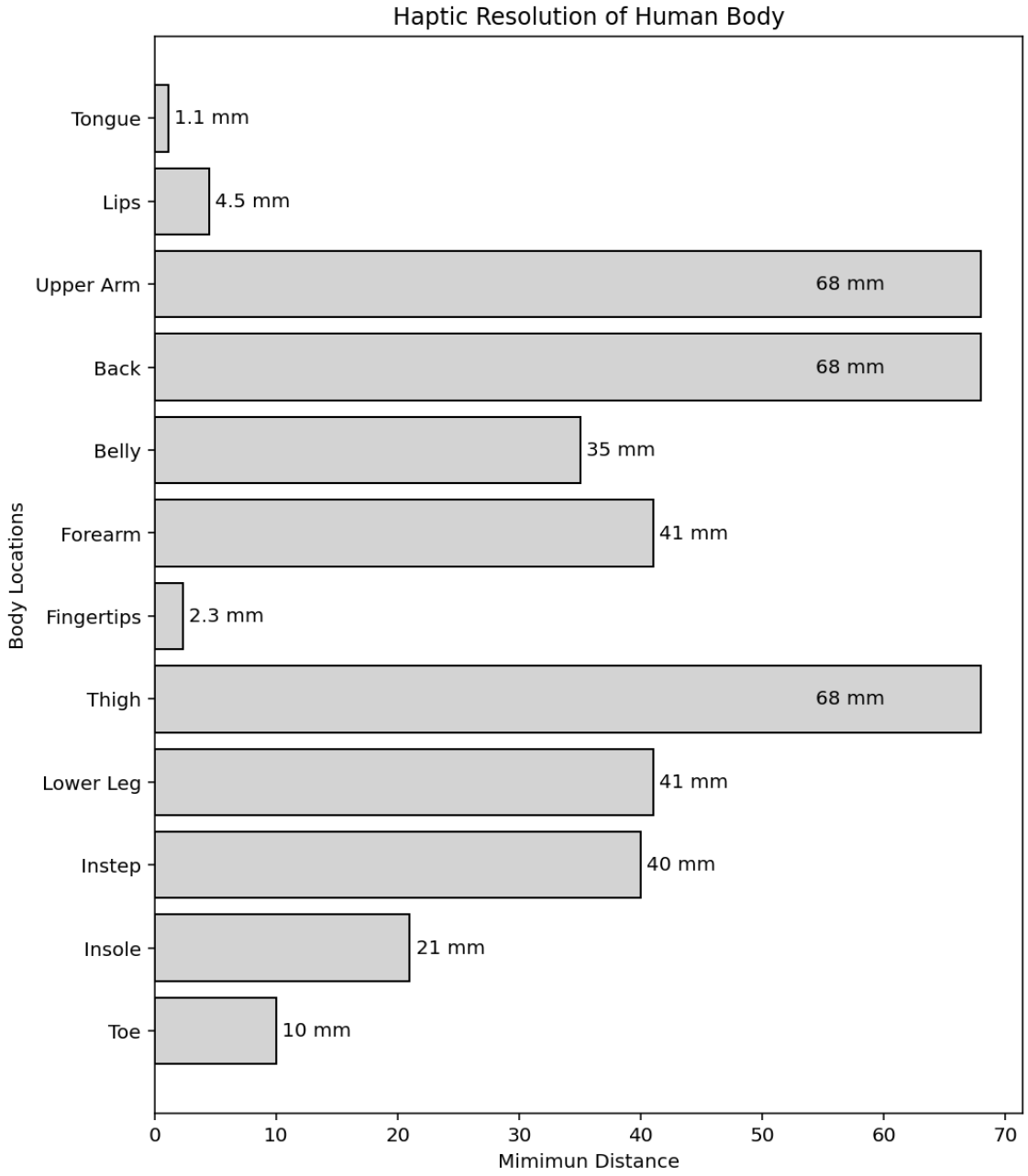


Figure 2.8: Haptic Resolution of Human Body (Meier et al., 2015)

Cognitive and psychological factors might also influence the perception of the vibrotactile feedback. Hong et al. (2017) demonstrates how vibrations can be perceived and provide benefits to interaction in the presence of audio stimuli. Vibrotactile feedback can benefit multimodal interaction, especially in environments with multiple distraction factors. For example, Kuriakose et al. (2020) reviewed the use of audio and vibrotactile feedback in multimodal approaches of spatial navigation. Information is also transmitted more easily and quickly through mobile phones and other touchscreen devices when vibrotactile feedback is present (González-Cañete et al., 2021), suggesting the perception is not

influenced by visual distractions. In the case of the absence of one of the senses, such as vision or audition, studies indicate that blind individuals (Horton et al., 2017) and those who are deaf (Mirzaei et al., 2021) have a better perception of vibration compared to those with full sensory function. Other factors that influence perception are the user's age, the tissue type at the stimulation location (fat, bone, muscle) (Sziebig et al., 2009), and in cases of circular arrangements (e.g., armbands, belts, leg sleeves), the circumference of the location.

2.5.2 Types of Actuators

Vibrations are produced by vibration actuators. The transformation of electrical signals to mechanical energy triggers this mechanism. In the case of vibration actuators such as eccentric rotating mass vibration motors (ERM), linear resonant actuators (LRA) and Voicecoils, this energy activates the movement of a mass inside a housing case. This very fast movement creates a slight displacement of the mechanism, which creates vibrations in the way humans perceive it. There is a great variety of actuators, also called vibration motors, which depend on the type of movement (e.g., linear, rotating) that occurs in the mechanism that produces the vibrations (Table 2.2). Other characteristics that distinguish vibration motors are their size, power consumption, frequency range, force output and response time, which are indicated in each motor data sheet and are provided by the manufacturers.

Eccentric Rotating Mass (ERM)

ERM motors are one of the most popular types of actuators. The displacement that produces the vibration is made through the rotating movement of the small unbalanced mass attached to the shaft in the centre of the motor. Their popularity derives from their small size and cost efficiency, which has made them suitable for wearable technologies and portable devices like mobile phones, toys, and game controllers (Hong et al., 2017). However, among their drawbacks, frequency and amplitude are interdependent (Remache-Vinueza et al., 2021), which means that the increase in either results in an increment in the overall vibration intensity. Additionally, they have a slower response time (start time) than other types of actuators ($\approx 20 - 30$ ms). Nevertheless, literature studies are using them extensively, proving their suitability, especially for prototyping. Due to their robustness, they can convey messages even above clothes (Remache-Vinueza et al., 2021), and additionally they are easily connected with Arduino systems, motor drives and other prototyping tools (Tran et al., 2023).

Linear Resonant Actuators (LRA)

LRA motors consist of a mass attached to a spring that moves back and forth. This displacement creates a sense of vibration. LRAs' frequency and amplitude can be controlled independently, but their frequency range is shorter than ERMs, and they depend on their resonant frequency ($\approx 150 - 200$ Hz) (Remache-Vinueza et al., 2021). On the contrary, their response time is quicker ($\approx 15 - 20$ Hz) than ERMs. Overall, they produce more discrete vibration cues than the ERMs; however, they are more complex in their wiring, their strength is weaker than that of ERMs, and they are more expensive, which makes them unsuitable for prototyping. LRMs are used in commercial devices, such as Apple's Taptic Engine on Apple smartphones.

Voice Coil Actuator (VCA)

VCAs work similarly to LRAs in terms of their way of movement. It consists of a coil suspended within a magnetic field, which moves up and down or back and forth because of the electric current flow. Their wider frequency range than the LRAs makes them popular among audio-driven haptic applications, particularly those related to music. Audio frequency and loudness are directly linked to the frequency and intensity of vibrations, providing a very easy way to haptify sound. Their cost-effectiveness adds to their practicality and consists of ideas for studies related to sound (Remache-Vinueza et al., 2021).

Piezoelectric Actuator

Piezoelectric Actuators consist of a material that generates mechanical motion when triggered by an electric voltage. They are durable over time since their mechanism does not produce friction from the moving parts. They are low-cost, have a wide frequency range and a quick response time. On the other hand, they have disadvantages, requiring high voltage input, which resolves the need for special driving electronics, making it harder for prototyping systems and minimal wearable device designs (Papetti et al., 2018).

Vibration motors come in many sizes and shapes, regardless of the aforementioned categories. A great variety of generic motors are used for generic purposes, but many companies are working on producing specialised motors, too (e.g., Boréas Technologies (2025), Actronika (2025), Tanvas (2025), Precision Microdrives (2025)). Table 2.2 demonstrates some diverse examples of motors.

Choosing the right actuator plays a considerable role in the usability of a wearable device. Giordano and Wanderley (2013) indicates three criteria for selecting the right

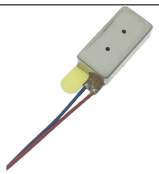
Motor Image	Type of Actuator	Model Number
	ERM.	310-003
	ERM	307-103
	LRA	C10-100,
	LRA	C12-003
	VoiceCoil	C2 Tactor
	Piezoelectric Actuator	AE1010D44H40DF
	LRA	Apple Taptic Engine

Table 2.2: Examples of Types of Actuators (Appendix: A.1)

vibration motor: 1) the purpose of vibrotactile feedback on the interface, 2) technology specifications such as the size or power consumption, and 3) the information that is conveyed. Smaller actuators provide an opportunity for creating arrangements of multiple motors, which create high-resolution haptic displays based on the understanding of the location of the vibration stimuli. Motors with smaller energy consumption and more straightforward wiring will provide more flexibility for multi-motor arrangements, too (Remache-Vinueza et al., 2021). Hong et al. (2017) evaluated both types of actuators, and the results indicated ERMs to have better performance in a wristband setup than LRA. Nevertheless, choosing a suitable actuator depends on the context of use; for wearable devices, the actuator needs to combine a low-cost and lightweight design and provide the preferred vibrotactile stimulation in balance with its size (Remache-Vinueza et al., 2021).

2.5.3 Vibrotactile Feedback Design Parameters

Setting and varying the values of the vibration parameters over time creates the vibration patterns. This enables vibrations to convey the sensations or information in each context of use. Different actuators work with different combinations of their parameters to provide a specific vibration pattern or sense. Nevertheless, when designing vibrotactile feedback patterns, it is essential to be aware of the capabilities and limitations of the provided technology. There are a number of parameters that define a vibration pattern, and depending on the types of actuators and the intended device design (i.e., number of motors, arrangement, body location placement) that need to be considered, designers also vary the naming of some of them. For example, Giordano and Wanderley (2013) and Brown (2007), and Hoggan and Brewster (2007a) associate these parameters with sound or music characteristics. Additionally, Giordano and Wanderley (2013) categorises these parameters according to *Temporal* (i.e., Pitch, Rhythm, Roughness, Timbre) and *Spatial* (i.e., Acuity, Pattern Recognition, Numerocity, tactile illusions, Attention).

Frequency/Pitch: Section 2.5.1 outlines how humans perceive the vibration frequency and the different capabilities of the varied actuators. For example, providing the same frequency and amplitude to ERM and LRA motors will produce different results. On the other hand, ERM intensity depends on the conjoined frequency and amplitude, and LRAs work best at their resonant frequency. Therefore, varying these parameters will also cause different haptic effects. Additionally, the perception of frequency changes relative to amplitude, as in the perception of loudness (Merchel and Altinsoy, 2020; Brown, 2007). In the case of voice-coil actuators, frequency discrimination is more efficient. Early studies by Brown (2007) suggest the ability to recognise nine values of frequency, while Giordano and Wanderley (2013) indicate specifically 3 to 5 different values in the

frequency range of 2Hz to 300Hz and 8 to 10 for the range 70 - 1000Hz. Depending on many factors (e.g., the amplitude, the training, location, and individual sensitivity), the frequency is the least preferred parameter for conveying information, and is most commonly set at the most perceivable level (≈ 250 Hz) for humans (Stein et al., 2017).

Amplitude/Intensity: The vibration amplitude, often perceived as intensity, is a useful parameter that works similarly to the sound amplitude. To be specific, if the amplitude of the vibration is too low, the vibration will not be detectable, and on the contrary, if it is very high, it will be irritating and uncomfortable to the user (Brown et al., 2005). Depending on the type of actuator, the amplitude can be controlled by the variation of the Voltage (for ERM, LRA, Piezoelectric actuators), the Current (for Voice coil actuators) or through Pulse Width Modulation (for ERM actuators). As discussed with respect to the Frequency, the perception of intensity may depend on other factors, such as the frequency level. Early studies indicate that four values are the maximum number of levels that should be used (Brown, 2007). In a different use case context, where absolute identification is not important, combining amplitude variation in time and space offers numerous opportunities to convey tactile sensations.

Waveform/Texture: Although one of the hardest to perceive, the shape of the wave/envelope of the vibration can provide meaningful information, such as texture. Hoggan and Brewster (2007b) indicates a 94% success rate in identifying three waveform variations (i.e., sine, square and sawtooth), based on a task where the user had to select among three buttons in the screen depicting three levels of urgency of an alert (very urgent, urgent, not urgent) based on the different types of vibration stimuli presented. This parameter is limited by the type of actuators that can produce it. LRA motors can produce *sine wave* and *triangle*, but are costly (Remache-Vinueza et al., 2021). VCA and Piezoelectric are the best for conveying waveforms.

Roughness/Modulation: Roughness is a term that has been used in different ways by authors. Brown et al. (2005) defines it as the modulation of the signal's amplitude by a frequency. This amplitude modulation creates a sense of roughness, with higher frequencies making the vibration smoother and lower frequencies making it rougher. Brown et al. (2005) evaluated 3 levels of modulation, 250Hz (smooth), 50Hz (rough), 30Hz (very rough) and achieved 80% recognition. On the other hand, Rovan and Hayward (2000) suggests that the waveform is the one that influences the perception of roughness since a sinewave, which consists of one partial, is smoother than a square, which consists of many partials. VCA and Piezoelectric actuators can perform this type of vibrotactile feedback, similar to the waveform. Second to those is the LRA, but it has less flexibility and is very expensive.

Duration: Duration is not directly dependent on frequency and amplitude, though they facilitate their perception. They are also used in variations and in comparison to convey information. The suggested durations for vibrations that convey information are no less than 0.1s or longer than 2s, and the duration between two vibrations should not be less than 10ms (Hoggan et al., 2009).

Rhythm/Patterns/Sequences: The combination of different durations and pauses between them creates the Rhythm (Giordano and Wanderley, 2013), also called patterns (Brown, 2007) or Sequences (Matscheko et al., 2010). Rhythm is one of the most important elements when designing vibrotactile feedback to convey concrete information (e.g., symbols and words). However, due to the wide variety of rhythms and combinations that can be made, it is challenging to establish a specific data set of rhythms unless the design starts becoming more systematic (Ternes and MacLean, 2008). Phanomchoeng et al. (2017) showcase the use of rhythm and location and indicated 78% recognizability in 27 spatiotemporal patterns. According to Geldard's guidelines (Hoggan et al., 2009), humans can perceive different speeds if they are at a minimum of 73 beats per second. Hoggan et al. (2009) tested the identification of three tempos 60bpm, 150bpm and 240bpm and baseline duration per stimuli of 500ms. The three tempos express a relaxed to more intense feeling, which indicates the type of information the authors wanted to convey (i.e., confirmation to warning).

Location/Illusions: Location refers to the placement of an individual motor and the arrangement of multiple motors. A wide range of configurations have been explored, particularly in wearable technology, and will be discussed in detail in the next section. The spatial arrangement of motors adds an extra layer of information that can be leveraged in pattern design. It helps facilitate the differentiation and activation of various body areas, enhancing the perception of distinct stimuli. The placement and number of motors on the body should be carefully considered to ensure that the generated patterns effectively convey meaningful messages (Giordano and Wanderley, 2013). Overall, studies highlight two primary roles of location in vibrotactile feedback: directing attention to specific body areas, forming spatiotemporal patterns to convey information -for example forming the letter L on the back of the user by activating the appropriate motors in a 3x3 motor grid (Brown, 2007) or to simulate sensations such as the sense of rain in the head (Kaul et al., 2017). Haptic designers often use location, along with other parameters, to create tactile illusions. These phantom tactile sensations, also known as the *Funnelling illusion*, can create the illusion of a vibration in body locations where there is no motor activity. When motors are placed close to each other and are triggered at a specific amplitude, the user can perceive a single vibration in the middle of the two motors (Salazar et al., 2018; Kaul et al., 2020). Another phantom sensation is the *Cutaneous Rabbit Illusion*,

in which short vibrations are applied across multiple muscles, creating the perception of continuous movement along the body (Giordano and Wanderley, 2013).

The design of a vibrotactile feedback tool depends on various parameters, including frequency, amplitude, rhythm, and location. Those parameters are determined relative to the capabilities of the actuators used. At the same time, human perception and the context of use also impose limitations on how those parameters will be used. Each of the three elements, human perception of vibrotactile feedback, choice of technology and design decisions, has individual parameters and characteristics that contribute to the outline of possibilities for the design process. They are interlinked and inseparable, and all need to be considered in relation to one another to achieve a usable device and feedback design. Having a deep understanding of these relationships is essential to the progress of this research, as it enables informed conversations with participants and suggests the development of solutions that combine appropriate technological choices with an accurate interpretation of participants' needs and suggestions.

2.6 Vibrotactile Feedback Design Methods

The design of vibrotactile feedback directly influences the design of the haptic display that presents it (i.e., the position of the motors, the number, and the type of actuators required). The first step in designing a haptic feedback system is to examine the use case of the intended technology, indicating the type of information to be conveyed. Academic work and industry provide classifications and guidelines for the vibrotactile feedback designs with examples of their use cases. However, the terminology definitions remain unstable and unclear among scholars, although they describe the same content. For example, the descriptions of Haptic Icons and Tactons often overlap. This section aims to provide a comprehensive collection of vibration design definitions and taxonomies as found in the literature, along with equivalent examples of use cases. These categorisations are determined by the purpose of the stimuli (i.e., the kind of tactile sensation they aim to provide), as well as the design methods, based on existing definitions, used to construct them. This understanding of the possible design methods will facilitate a more accurate interpretation of participants' ideas and a more precise mapping of them to feasible vibrotactile feedback solutions.

2.6.1 Definitions and Taxonomies

Literature has provided definitions of vibrotactile feedback based on two conditions: (1) the user's action to receive the feedback and (2) the purpose of the feedback in the context it is used (Brown et al., 2005). For example, Haptic Icons are based on

the user's actions (e.g., feeling the interaction with a key on a touchscreen), whereas Tactons are based on the purpose of the feedback (e.g., getting notification of a message on a smartphone). Both types of vibration stimuli are based on manipulating their parameters in time and space. The term **Haptic Icon** is defined by Brown (2007) as 'brief programmed forces applied to a user through a haptic interface with the role of communicating a simple idea in a manner similar to visual or auditory icons', and 'rendering haptically distinct and meaningful sensation for different functions'. The authors specify that haptic icons are related to, and aim to accompany the user's action, similar to how a visual icon would change shape or colour when pressing a button. Chen et al. (2011) describes them as identifiable signals, meaning the user does not need to train or learn the pattern to understand the meaning. Interestingly, the author denounces the term 'haptic icon' by stating that the click of a key is not a haptic icon, although its description aligns with it. MacLean (2008) approach the haptic feedback through the lens of 'transparency' level. They define it as *'interfaces filled with details yet engage our pre-attentive periphery so we are never surprised'*. According to the authors, Haptic Icons are associated with 'transparency' as they 'allow appropriate background processing with low effort and required level of attention', which allows the user to connect with the action.

Tactons are defined by Brown (2007) as 'structured and abstract messages that can be used to communicate complex concepts to users non-visually'. The intention to convey information non-visually indicates the difference with the Haptic icons, as it shows how they are not connected or rely necessarily on the user's action. They can be part of an action but not related directly to it. An example of understanding the Tactons is the parallelism with the equivalent representations by other modalities. Visually, we perceive information through text and icons; auditorily, we can get information through speech and earcons, and in touch, we obtain information from braille and tactile feedback like Tactons. Ternes and MacLean (2008) and MacLean (2008) produced a taxonomy of vibration patterns as Abstract/Symbolic and Abstract/Representative without being explicit about whether they are talking about Tactons or Haptic Icons, although the description matches Tactons. By *abstract*, both authors referred to an abstract representation of information. Ternes and MacLean (2008) refers to *Symbolic* as patterns that are chosen by the users. MacLean (2008), on the other hand, specifies that representatives are those that depict an object. *Representatives* are those Tactons whose design relies on existing metaphors that help the user understand the message more easily. For example, Hoggan et al. (2009) suggests that a faster tempo indicates a warning sign, whereas smoother and slower vibrations indicate positive information like confirmation. Apple haptic design guidelines suggest an increase in intensity as 'success' and a



Figure 2.9: Example of Apple's 'Notification' haptics designs (Apple Inc., 2024)

decrease as 'warning' (Figure 2.9). Wang et al. (2014) suggests another categorisation of haptic stimuli based on their complexity. Starting from a simple on/off that aims to attract attention to an event, the on/off is combined with the location, which adds a second layer and can indicate a point in the body or directions. Lastly, the complex information includes variations of multiple parameters.

Besides these defined types of vibrotactile feedback, there are also undefined types, which are equally common and meaningful to users. *Vibration sensations* are spatiotemporal patterns that are perceived as cohesive tactile information, mimicking real-world sensations to create a realistic haptic experience for the user. They are primarily used in immersive technology, specifically in virtual environments. One of the definitions that can be used for this type of vibration feedback design is *Tactile Translation*, a term introduced by Giordano et al. (2018). *Audio-driven* vibration design, also part of the Tactile Translation category, is a method that has been used extensively in music-related applications. Designers use sound parameters in direct mapping with vibration parameters, such as frequency and amplitude, to draw a connection between the two stimuli. That results in vibrations amplifying the experience of the sound or substituting it in the case of hearing loss. This method is not used in relation to the user's action, but rather in relation to existing stimuli, such as sound. Despite the direct manipulation of the overlapping parameters, as seen in 2.5.3, the different parameters are perceived in different ranges than those of the sound. Frequency is often interdependent of the amplitude. Even when using motors like voice coils that can perform different frequencies, the information is not always perceived in a meaningful way by the user (Remache-Vinueza et al., 2021). On the contrary, amplitude (i.e., loudness), rhythm, and roughness (i.e., timbre) are most commonly used to convey meaningful information (Birnbaum and Wanderley, 2007; Remache-Vinueza et al., 2021).

Existing taxonomies of vibrotactile feedback facilitate a better understanding of the definitions and purposes of each design method. They provide an initial framework that helps hapticians choose a design based on their intended use case. Vezzoli et al. (2022) provides a Haptic Effect Taxonomy for XR use cases that incorporates the description of the above definitions. First, he refers to the *transient-static effect*, which is used for 'mechanical feeling "click" sensation', which aligns with haptic icons definition. Secondly, *Descriptive Effects* are defined as 'descriptive effect language' like Tactons. Third is the *High-Definition Vibration Effect*, described as 'typical for audio assets and workflows to generate effects like these', highlighting the relationship between this category and audio-driven feedback. Lastly, *Synthesised Vibrations Effect* is explained by the example 'surface texture generated using the contact position on the surface of an object', resembling the description of the tactile sensation like texture (Vezzoli et al., 2022).

Giordano et al. (2018) suggests a taxonomy based on how musical information can be conveyed through haptics by identifying three primary types of vibrotactile feedback design: *Tactile notification, Tactile translation and Tactile language*. This taxonomy serves as a foundational reference for developing a new vibrotactile feedback framework by drawing parallels with and gathering insights from relevant VFT application studies and taxonomies.

Tactile notification serves to convey information regarding the environment and the interaction within it, for example, alarms (Cobus et al., 2018), notifications (Hoggan et al., 2009), and spatial awareness (Schätzle et al., 2019). These types of vibration stimuli can be defined as Tactons. The tactile notification also includes feedback for confirming an interaction, such as the sensation of a button clicked (Park et al., 2020; Tran et al., 2023), and the tactile representation of textures (Strohmeier and Hornbæk, 2017) in digital environments, similarly to Haptic Icons.

Tactile translation directly connects information to its source, aiming to replace or augment the modality from which the information originates (Giordano et al., 2018). This category has two separate clusters: Sensory Substitution and Tactile stimulation. In Sensory Substitution, mainly audio-driven vibrations are often observed as an augmentation of the audio-visual experience (Baijal et al., 2012), and as a means of accessibility for music for deaf and hard-of-hearing individuals (Petry et al., 2016). The aim is to use vibrations to convey information from another modality through haptics. In Tactile Stimulation, Vibrations aim to simulate tactile information of the physical world to the virtual (e.g., sense of touching an object in VR (Kataoka et al., 2019), sense of vibrations in a musical instrument (Marshall and Wanderley, 2011).

Lastly, *Tactile languages* describe the Tactons (Brown, 2007), delivering vibration stimuli

with a specific semiology that users need to learn to identify (Hoggan et al., 2009). Efforts have also been made to use Tactons to convey language, involving the creation of spatiotemporal patterns for individual letters, as seen in studies like Luzhnica and Veas (2019).

Another recent taxonomy focused on Tactons and their mapping to design metaphors has been given by Wittchen et al. (2022) after a workshop evaluation with users. Here, the term 'Tactons' is used in a broader sense, referring to spatiotemporal patterns that convey information but do not necessarily require learning or specialised training. From this evaluation, four categories emerged: *Nominal, Body, Magnitude and Affective*. The authors assigned to the *nominal* vibrations the vibrations designed to convey information linked to specific contexts of use. Subcategories describe the possible ways of designing, such as Tactons, in order to make the information more convincing and immersive. *Naturalistic* mapping indicates a mapping will resemble the information (e.g., zig-zag on the back might mean a thunderstorm), *Logical* is related to mapping the vibration meaning to each literal meaning (e.g., if there are two motors, the top will mean moving up and lower moving down), and visual analogy will be arranging motors in a way to represent a visual icon (e.g., play/pause button). The second category, Body, is location oriented. First, it is the *Spatial* information that the vibration can give, such as direction or directing the attention to a body location, and secondly, the perceptual information, which provides realism of touch in body locations where this is not feasible (e.g., sense of touch when using prosthetics). *Magnitude* refers to the use of vibration for conveying quantitative information, which can be conveyed by using the actual magnitude of the vibration through spatial arrangement and temporal patterns. Finally, the authors refer to Affective mapping, where vibrations are designed to convey emotion (e.g., a smooth vibration will convey a soothing feeling).

Literature presents vibration design in different terms, definitions and descriptions, but often aims to convey the same meaning. The Tables 2.3 and 2.4 summarise how the references descriptions are linked together and express similar notions of haptic experiences.

Authors	Haptic Effects			
Brown et al. (2005),Hoggan et al. (2009)	Haptic Icon	Tactons	Sensations	Audio-Driven
Giordano and Wanderley (2013)	Tactile Notification	Tactile Notification	Tactile Stimulation (Realism)	Sensory Substitution (Replacement)
		Tactile Language		
Vezzoli et al. (2022)	Transient	Descriptive	Synthesized	High Performance

Table 2.3: Taxonomies of Haptic Effects

2.6.2 Review of Vibrotactile feedback Use Cases

The following section reviews the use cases of vibrotactile feedback organised into clusters based on their design methods, led by the existing taxonomies of the literature: (1) Haptic Icons, (2) Tactons, (3) Tactile Stimulation (sensations), and (4) Sensory Substitution (Audio-driven). Within these categories, subcategories emerge from the literature (Table 2.4). For example, in Tactons, vibrations for conveying information, such as language and notification alarms, were included, as well as those that convey directional cues based on the taxonomy in Wittchen et al. (2022), which is grounded in mapping to metaphors: nominal and body. Similarly, for Audio-Driven, there are examples of sensory substitution and tactile stimulation (Giordano et al., 2018). This review will facilitate a deeper understanding of the appropriate application of these design methods, informed by the user's type of interaction. These examples also reinforce the definitions and help establish a consistent and inclusive framework for designing haptic experiences, which is essential for the progress of this research and the appropriate mapping of vibrotactile designs to DAW accessibility needs.

Giordano and Wanderley (2013)	Tactile Language				
Wittchen et al. (2022)	Descriptive	Nominal	Body	Magnitude	Affective
Ternes and MacLean (2008) MacLean (2008)	Abstract	Representative/ Sympolic			

Table 2.4: Taxonomy of Tactons

Haptic Icons

Haptic Icons, being linked to the user's action, are used to simulate the sense of touch in the virtual world, such as interaction with touchscreens, virtual reality and augmented reality. They are transparent, requiring minimal effort to interpret (MacLean, 2008), and don't need training to be learned (Chen et al., 2011). Major mobile companies have established design guidelines for haptic icons on their devices. Apple provides examples of different designs for interaction with various visual elements to enhance realism. They name it *'Impact'* (Apple Inc., 2024) and offer five levels: Light, Medium, Heavy, Regid and Soft (Figure 2.10). Android calls them *Clear haptics* (Google Inc., 2024).

In the literature, haptic icons aim to augment the feeling of pressing a button (e.g., touchscreens, on-body buttons). Park et al. (2020) explored the use of different vibration parameter levels (i.e., amplitude, frequency, and duration), and Shim and Lee (2018) generated virtual textures to augment the sensation of physical buttons. Sadia et al. (2020) suggests designing haptic icons based on studying the tactile sensation of physical buttons and how it can be transferred to touchscreens. Shiraga et al. (2016) examines users' impressions of different patterns for their use in a smartphone context. Chen et al. (2011) also examines haptic icons in mobile phones, specifically focusing on key-click stimulation. Hwang et al. (2015) suggests using smartwatch vibrations to complement the interaction with touchscreens. Altinsoy and Merchel (2009) explores the use of audio-driven design for creating haptic icons for touch screens. Tran et al. (2023) explores a different type of button, an interactive touch surface placed on the skin, and haptic icons produced on the nail of the finger that interact with the digitalised skin area.

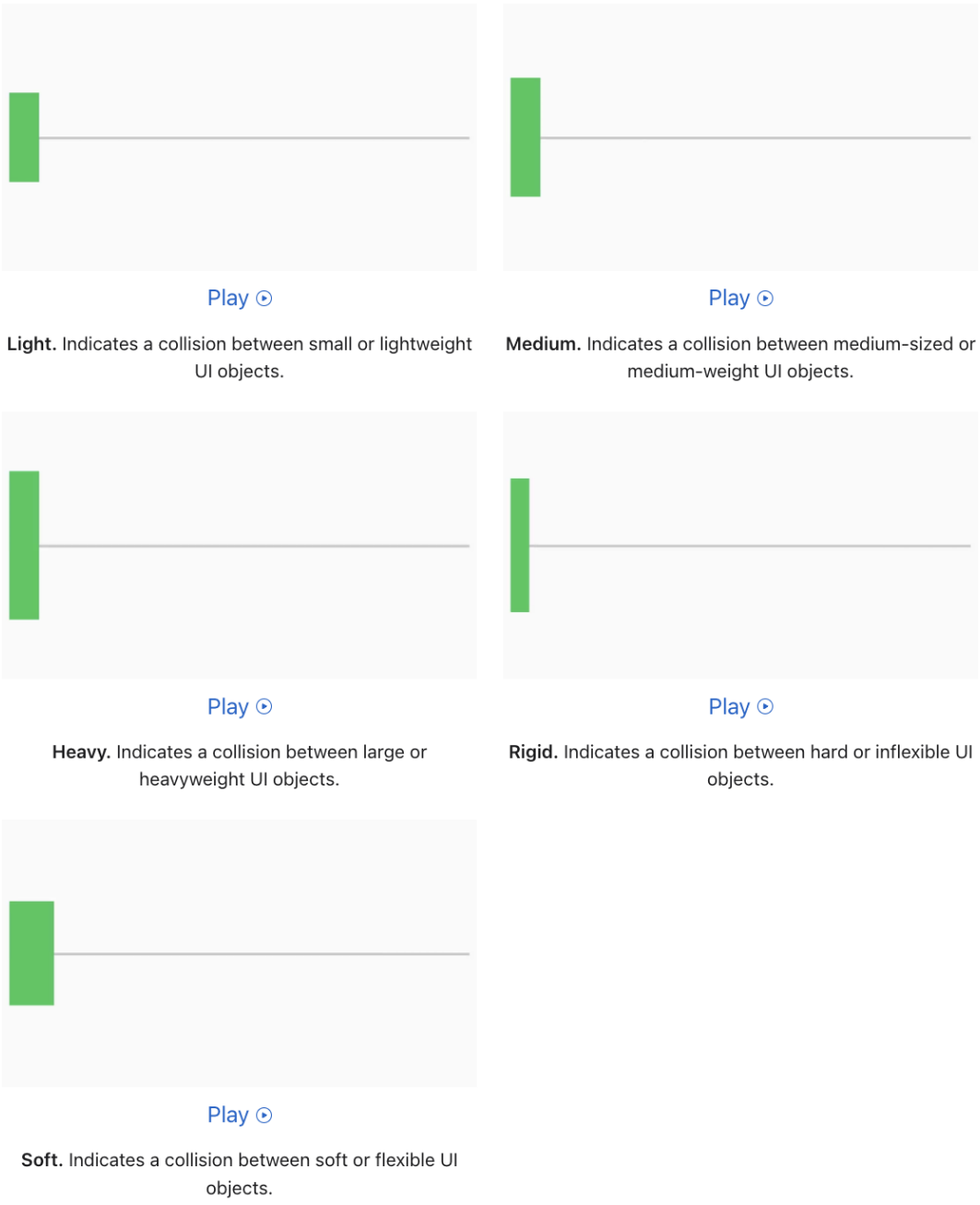


Figure 2.10: Example of Apple's 'Impact' haptics designs (Apple Inc., 2024)

Haptic icons can also be related to interactions with non-tangible surfaces, such as in virtual environments (e.g., VR, AR). This type of haptic feedback also belongs to the 'tactile stimulation' category (Giordano and Wanderley, 2013), as it aims to reproduce a touch sensation that exists in a different structure (i.e., a physical button to a virtual button). Haptic Icons in the VE not only augment the realism of interaction with a digital button but also fill the missing element of interaction with a tangible object (i.e., a touchscreen). For example, where in many cases the sense of tangibility is conveyed by force-feedback haptics, Sziebig et al. (2009) suggests conveying it with vibration patterns. Pezent et al. (2022b) propose a wearable device for conveying the sense of push-pull buttons in VR/AR. Maeda et al. (2022) recommend a finger-worn device for interaction with buttons, switches and textures in VR.

Often, haptic icons might convey textural information to augment the interaction. In Ogawa et al. (2015), the texture provides additional dimensions to the traditional 'click' of the mouse by providing more realistic sensations based on the interaction with the screen in the context of a game. Hlatky et al. (2009) suggests using textural information for interaction with faders in music applications on touchscreens.

Tactons

Tactons, as per definition, are arbitrary designs that aim to convey specific information symbolically. Based on the categorisations by Giordano et al. (2018) and Wittchen et al. (2022), there are several variations on the design approach, which are based on the metaphors used to create the connection between the vibration pattern and the information. The most common Tactons metaphors are the Nominal (naturalistic or logical) and the Body. Logical metaphors are often reflected in spatial-body metaphors, such as providing directions using the body location. For example, when a vibration is triggered on the right side of the body, it will indicate an action to the right. Examples include Tang et al. (2020), Salazar et al. (2018), Schätzle et al. (2019), Wang et al. (2019), Weber et al. (2011), Hong et al. (2017), and Ghiani et al. (2009) and Meier et al. (2015) who use body location in a wearable device for indicating directions and guiding users' movement in various scenarios, such as walking in the physical world or virtual worlds or navigating a digital surface. Similarly, Vries et al. (2009) installed vibration in a chair, and Sucu and Folmer (2014) applied it on a steering device.

Other studies combine body location and the variation of parameters over time to create Tactons that convey more complex information, such as directions with a second level of detail. Brown (2007) defines these designs as *Compound Tactons* and J. Oliveira and Maciel (2014) as *Modifier Tactile Pattern*. Using rhythm or intensity variations is a naturalistic nominal metaphor, as humans can associate slow or fast tempos, low or high

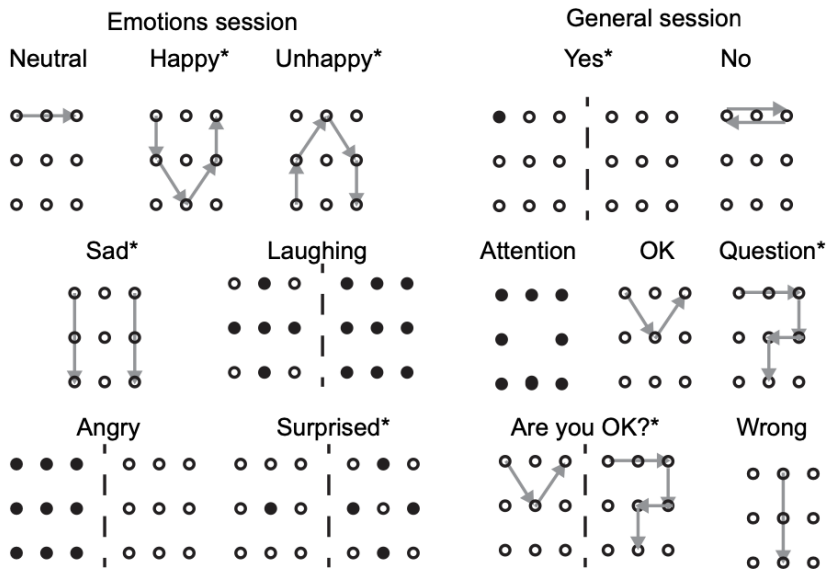


Figure 2.11: Visual Icons translation to spatiotemporal vibration patterns. Image from (Plaisier and Kappers, 2021).

intensities with notions such as non-urgent or urgent or far or near distance. Meng and Spence (2015) use intensity along with body location, and Chun et al. (2013) pulses with location to indicate the level of alertness of the drivers for collision avoidance. Pielot and Boll (2010) used pulses to indicate different waypoint information in navigation tasks; in a second study, Pielot et al. (2010) used rhythm variation to indicate the distance to the next waypoint. Dupont et al. (2020) combined intensity with location to facilitate the target finding in 2D space, and Gay et al. (2020) used duration and location to indicate direction and proximity.

Studies also utilise other vibration parameters to convey information through naturalistic metaphors. For example, Saket et al. (2013) uses duration, Brown et al. (2006a) roughness, and Hoggan et al. (2009) and Barralon et al. (2007) examine various parameters to indicate the urgency of notifications. Visual representation is another nominal metaphor. Plaisier and Kappers (2021) suggest a vibration pattern presented to the back that simulates the visual icons like the 'tick' sign to convey confirmation (Figure 2.11). In the same study, the logical metaphor indicating a motor movement down is represented by a sad face icon. The movement down is also used as a metaphor for a value decreasing, such as in Alirezaee et al. (2020), where this pattern indicates that a patient's vital measurements are decreasing (Figure 2.12). This metaphor can also be referred to as magnitude, as it represents a volume. Similar to the haptic feedback of Brown et al. (2006b), the amplitude directly represents the music's intensity.

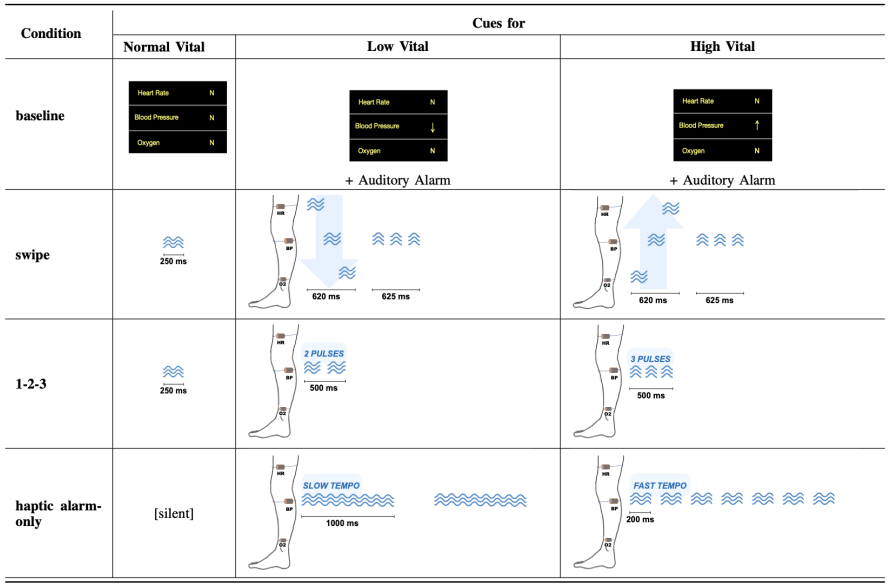


Figure 2.12: Spatial Movement Metaphors. Image from (Alirezaee et al., 2020).

The majority of Tactons do not use metaphors, but they create patterns that need to be learned and trained to be remembered and used by users. Examples of information that the designers of Tactons have tried to convey are colours (Carcedo et al., 2016) and shapes (Israr and Poupyrev, 2011), specific cues during music performances (Schumacher et al., 2013), (Michailidis and Berweck, 2011) musical information as an alternative score (West et al., 2019), assisting in performance-related aspects such as tuning directions (Jack et al., 2016) or music players' posture improvement (Linden et al., 2011). Also, Brown et al. (2005) employed tactons to represent mobile notifications and González-Cañete et al. (2021) mobile icons. In this category, many studies are trying to make tactile languages, such as password messages (Bianchi et al., 2010), English alphabet(Luzhnica et al., 2016), Morse code(Plaisier et al., 2020), Braille(Savindu et al., 2017), time (Töyssy et al., 2008), and new musical notation systems (Giordano et al., 2018) (Figure 2.13). Lastly, Tactons can be made based on an affective metaphor. Singhal and Schneider (2021) and Ferguson et al. (2018) attempt to utilise parameters such as roughness or tempo speed to convey emotional information.

Tactile Stimulation/Sensations Tactile Simulations often aim to provide realism and immersion to the user. Such examples are textures, object manipulation and ambient awareness. Bernard et al. (2022) suggest a dynamic texture change for quantitative touchscreen interaction (also described as Magnitude Tactons by Wittchen et al. (2022)). Maereg et al. (2017), and Normand et al. (2024) both explore texture variations with finger-worn devices in VR environments, while Strohmeier et al. (2020) and Turchet et al. (2010) experiment with foot-worn vibration for ground/ walking-related texture realism

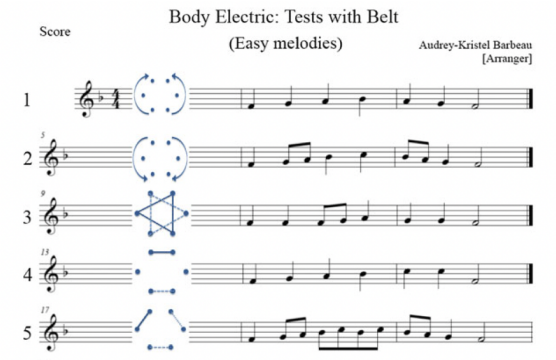


Figure 2.13: Vibration patterns mapped to musical notation system. Image from (Giordano et al., 2018)

in VE. Lin et al. (2024) suggest vibration patterns that simulate forearm deformation for enhancing realism and enjoyment in VR environments. Body correction related effects are also suggested, but Islam et al. (2022) for yoga posture and Rotella et al. (2012) for motor task instructions. Other examples of movement direction provide spatiotemporal vibration feedback and indicate the movement that specialists need to do for needle steering (Rossa et al., 2016; Reinschluessel et al., 2018).

Finally, there is the use of vibration patterns to convey underexplored and undefined types of sensations like those from Turchet and Barthet (2019), Michailidis and Bullock (2011), and Lu et al. (2025a) that are related to dynamic interaction with music performance interactions and Vallgårda et al. (2017), who suggest the Hedonic Haptic Player, an artistic composition using vibration as sensory material.

Sensory Substitution /Audio Driven

Vibrations are often used as a replacement for an unavailable modality, such as auditory. Many studies utilise vibrations to convey sound by driving motors and directly mapping music parameters to corresponding vibration parameters. These audio-driven vibrations are commonly used for accessibility for people with auditory and visual impairments. Baijal et al. (2012), Petry et al. (2016), Branje and Fels (2014), and Russo et al. (2012) are using this technique to convey music-related information to people with hearing impairment. Other accessibility-oriented examples include awareness of surrounding sound (Jain et al., 2020; Perrotta et al., 2021), assistance with lip-reading (Dementyev et al., 2021), and orientation assistance in video games for blind children (Schätzle et al., 2019). Speech-to-vibration is another example that demonstrates the use of the audio-driven technique for sensory substitution, as seen in Kobayashi and Nakamura (2016) and Reed et al. (2019), which aids in learning language punctuation and tactile speech communication.

Music experience and performance enhancement are common examples of audio-driven vibrations, despite their accessibility purpose. Hwang et al. (2013), and Siedenburg et al. (2024) are exploring the enhancement of musical listening experience. Other studies focus on more practical interactions with music, such as for music interval recognition (Egloff et al., 2018), for navigation and recognition of audio loops (Merchel et al., 2012), for understanding different music instruments (Merchel et al., 2010), and for enhancing the feeling of digital musical instruments (Marshall and Wanderley, 2011). Finally, audio-driven vibration has been used for the enhancement of immersiveness in VR (Rosenkranz and Altinsoy, 2019), Gaming experiences (Papetti et al., 2021), (Lim et al., 2013) and multimedia content (Cho et al., 2014).

This section examined the methods of designing vibrotactile feedback based on the existing taxonomies of the literature. The ways of utilising the vibration parameters are related to the specific purposes of use and the types of devices that provide them. The review of existing studies and their categorisation to design methods directly inform the design framework and facilitate the choice of the most appropriate methods for providing an alternative way of receiving information about interactions with DAW software. Tactons are the most flexible design method for vibration patterns. They provide considerable flexibility, enabling the creation of patterns that vary from 'descriptive' (i.e., Nominal, Body) to 'abstract' (i.e., requiring learning). The types of metaphors used in their design often guide device design decisions as well. For example, when actions use a logical/spatial metaphor, vibrations indicate a direction that signifies the importance of placing the motors in a specific arrangement, allowing the user to easily understand the directional cue.

2.7 Conclusion

This chapter lays the foundation for this thesis by helping to understand the research gap in designing accessible tools for music technology with the use of haptic feedback for blind individuals. The respective sections of this chapter outline the background and motivation of this research, as well as the design methods and technical specifications that need to be considered and included in the development and evaluation of a new system in the following chapters. Music production has become increasingly compact and visually oriented on computers, utilising complex software, compared to the previously tactile-interaction-based studios. Although music hardware devices are still available, offering a multimodal interaction alternative, the current practices still disadvantage BVI individuals (Harrison et al., 2023; Saha and Piper, 2020). The primary accessibility of

software is based on voice feedback, providing an added solution rather than an alternative, inclusive design approach. Studies in the accessibility of music making for blind and visually impaired creatives include the exploration and documentation of musicians' challenges in accessing music software like DAWs, and others propose new systems that vary in their design methods, leaving a significant research gap around the design of user-centred solutions.

Using haptic feedback technologies requires a thorough understanding of each layer that influences the design of both the interface and the interaction with it. This literature review examines the classification of haptic feedback based on user interaction with the system and the level of wearability of the suggested hardware device. A deep understanding of the use of vibrotactile feedback will support future design decisions and efficient discussions with participants in the following participatory design sessions. Vibrotactile feedback has been identified as a potentially valuable tool for improving the accessibility of Digital Audio Workstations (DAWs). It offers the opportunity to convey both concrete information through vibration patterns and more abstract tactile sensations. Additionally, very limited work has been done in using this haptic technology for the accessibility of DAWs. The next chapter presents the initial discussion with BVI music producers with the aim of answering the first research question and gaining a better understanding of how they utilise existing tactile feedback devices and which challenges in the accessibility of DAWs can be mitigated with vibrotactile feedback.

Chapter 3

Preliminary Interviews with BVI Music Producers: Exploring Haptic Feedback for Inclusive DAW.

This work has been published in the International Journal of Human Computer Interaction as : "Karpodini, C., Michailidis, T., Creed, C., & Williams, I. (2025). Haptic Feedback to Overcome Barriers for Visually Impaired Users in Digital Audio Workstations. International Journal of Human–Computer Interaction, 1–18. https://doi.org/10.1080/10447318.2025.2464899"

3.1 Introduction

Existing research (Payne et al., 2020; Metatla et al., 2011; Pedrini et al., 2020; Saha and Piper, 2020) has indicated the limitations of current accessibility tools (i.e., screen readers), in terms of DAW usability, but does not delve deeply into the opportunities arising from the use of haptic technologies, revealing a research gap. A wider, comprehensive examination of hardware equipment is necessary to provide a holistic perspective on current accessibility challenges and potential solutions within the music production field for BVI users. Nineteen semi-structured interviews with BVI music producers were conducted to understand how they currently utilise existing hardware devices within their creative workflows and to capture new ideas on how to integrate haptic feedback in DAWs and other music technology tools. The analysis of participants' interviews revealed three themes around BVI music producers' experiences with haptic feedback applications and

how such technology can benefit and support DAWs. The themes specifically highlighted the types of haptic feedback technology currently used (i.e., music hardware), the benefits and limitations of current solutions, and the role of tactile feedback in the participants' workflows.

3.2 Methodology

This study employs a qualitative methods approach. Semi-structured interviews were used to allow flexibility and provide opportunities for in-depth exploration of the subject. This study's interview structure also includes elements of the contextual inquiry technique, which required participants to demonstrate their workflow. This technique is utilised in Part 3 (section 3.2.2) to enable a more accurate understanding of participants' music studio setups through observation (e.g., using DAWs with SR) (Kip et al., 2018).

3.2.1 Procedure

Participants were recruited through an open call published in online forums for BVI users that focus on addressing accessibility challenges for different DAWs. The recruitment criteria for this study required that participants:

1. Are either blind or have low vision,
2. Use accessibility tools (e.g., screen readers and magnification tools),
3. Have knowledge of using DAWs regardless of their level of experience.

This resulted in a specialised and relatively small population, with nineteen participants expressing an interest in joining the study. It is generally considered that a sample of this size can enable a thorough thematic analysis and provide meaningful insights into this underrepresented group (Lazar et al., 2017).

Participants were provided with a questionnaire containing information about the study, demographic questions and a consent form. The demographic questionnaire collected data around age, gender, occupation, country of residence, and main DAW and primary screen reader used. Questionnaires were presented via a Microsoft Form and as plain text versions distributed via email. Upon receiving the consent form, a suitable date and time for the interview were arranged via email communication. To accommodate participants' preferences, two interviews were conducted in-person and 17 online using their preferred method (13 using MS Teams, 3 using Zoom and 1 using FaceTime). Each interview lasted an average of 90 minutes. Institutional ethical commitee approval was obtained to conduct the study.

3.2.2 Interviews

The interview was structured in four key areas: (1) exploring participants' background around music and accessibility, (2) discussing their use of hardware equipment with DAW workflows, (3) participants providing a demonstration of their DAW, and (4) examining their use of haptic technologies within a DAW context. These areas are contributing to answering the first research question of this thesis: 'How do BVI music producers currently use haptic feedback in their DAW workflows, and how do their unmet needs inform the design of new haptic devices?". The interviews employed a semi-structured approach, allowing for flexibility to explore participants' needs and challenges more deeply. In the third part of the interview, contextual inquiry was employed by asking participants to demonstrate their workflow. During this section, it was observed how participants interacted with various areas of the DAW and identified their workarounds to overcome accessibility barriers. The level of detail in the demonstrations varied based on participants' experience, ability to share their screen, and current setup during the interview.

Interview structure

Part 1-Participants' background: Participants were asked about their visual impairment condition and whether they were comfortable discussing it. The level of engagement with music and music production, including prior studies and current practice, was then questioned. Participants were also asked to elaborate further, with examples, on their DAW usage, which DAWs they have previously used and why, and the screen readers they are using and are familiar with. This aspect of the interview served as an opportunity for the interviewer to learn about the participants' backgrounds and allowed interviewees to feel more comfortable and foster trust.

Part 2-Use of hardware equipment: The second part of the interview included questions on how participants use different hardware in their workflow, such as controllers, keyboards, or Braille displays and which aspects of the DAWs they control. This was followed up with two structured questions: 1) What is the role of tactile experience when using the specific hardware, and 2) how has the evolution of hardware technology (i.e., analogue-digital) influenced their practice? The questions in this part expand the latest findings reported by Harrison et al. (2023), with a particular focus on the specific hardware features that enhance efficiency. This part of the interview was designed to remain flexible, as it largely depends on the expertise and insights of the interviewees.

Part 3-Demonstration of DAW: Participants were then asked to demonstrate their workflow within their preferred DAW, particularly the effective and ineffective aspects of the DAW's accessibility. Part 3 served as a bridge between interview segments, helping

the interviewer build a connection with participants' workflows and setups while also prompting participants to recall challenges they may have previously overlooked and to consider potential solutions. The questions were inspired by the work of Harrison et al. (2023), who primarily used contextual inquiry as their main method of data collection. Participants were asked about specific music production activities that have been mentioned in the literature that lack accessibility features (Oltheten, 2018; Saha and Piper, 2020). These elements included EQ, compressor, reverb, automation, recording, editing waveform, midi, and access to actions such as panning and solo/muted. The contextual inquiry approach was limited to Part 3 to maintain focus on the key research questions in Parts 2 and 4, which centred on the use of hardware devices and the future application of haptic technologies in participants' workflows.

Part 4-Haptic technologies in the workflow: Participants were asked about their familiarity with haptic technology and, more specifically, vibrotactile feedback found in smartphones, smartwatches, gaming, or other accessibility tools. Participants were then introduced to the concept of wearable technology with vibrotactile feedback, such as a smartwatch, and asked to envision how this technology could facilitate faster and more convenient DAW workflows. This section was based on the initial stages of participatory design workshops, as seen in the studies of Metatla et al. (2016) and Tanaka and Parkinson (2016). Participants drew on familiar technologies like smartphones and smartwatches to envision how similar devices could be integrated into their DAW workflows.

3.2.3 Analysis

Interviews were conducted in two languages, 16 in English and 3 in Greek. Microsoft Stream was used for transcribing interview recordings conducted in English, whilst interviews conducted in Greek were transcribed and translated manually.

A thematic analysis was performed to analyse the data collected. A comprehensive analysis was conducted by reading the interview transcriptions and listening to the recordings, in alignment with the 'repeated reading' process highlighted by (Braun and Clarke, 2006). An inductive approach via NVivo (Jackson and Bazeley, 2019) was then applied to identify codes and themes were generated from the data (Terry and Hayfield, 2021). After completing the coding procedure, the researcher scrutinised the potential merging of codes into themes. In this step, any codes without significant support from the data were discarded. Finally, the formalised themes have been named, and appropriate examples among the factoids have been selected to support the theme's presentation. After completing the coding procedure, three key themes representing the primary insights of

the participants generated.

3.3 Findings

The analysis of participants' profiles is initially presented, including age group, location, gender, impairment, experience with music production, preferred DAW (e.g., Logic, Reaper), screen reader (e.g., NVDA, VoiceOver), and experiences with haptic feedback, as well as the hardware devices in use (e.g., Komplete Kontrol, Softube), accompanied by an analysis of the companies, models, and specifications. Themes are then presented around the use of hardware devices, limitations of their specifications, interaction with screen readers, and the role of tactile feedback affordances in participants' workflows. A further theme is presented concerning the use of vibrotactile feedback as an assistive tool in everyday life and music creativity. Finally, themes are presented regarding the opportunities, limitations, and design ideas for incorporating haptic feedback into DAWs.

3.3.1 Participants' Information

The participants were aged between 18 and over 65 (Table 3.1). Seventeen users self-identified as male, and two as female. Participants were located in North America (6), the UK (7), and Central and Eastern Europe (5). Seventeen have congenital blindness (CB), one has acquired blindness (LB), and one has lower vision (LV). Participants were categorised into different age groups (Table 3.1).

The main DAWs used by participants include Reaper (9), Logic (6), ProTools (3) and Cubase (1). Twelve participants also self-identified as advanced or experts with DAWs, five as intermediate and two as beginners. All participants use screen readers to interact with DAWs, including VoiceOver (12), NVDA (14), and JAWS (9), with some participants using more than one screen reader depending on the computer's operating system they are working on at the time. 18 out of 19 participants use haptic feedback to enhance accessibility in their everyday lives, such as smartphones: iPhone (15) and Android (3), smartwatches (9), gaming consoles (8) and other tools such as vibrating power bank and Liquid Level Indicator (4). Table 3.1 summarises participant details.

Code	Age Group	Country	VI	Experience	DAW	SR	HFE
P1	39-44	UK	CB	Advanced	Logic	VoiceOver	SP, SW, G
P2	65+	USA	CB	Intermediate	Logic	VoiceOver	SP

Code	Age Group	Country	VI	Experience	DAW	SR	HFE
P3	32-38	UK	CB	Advanced	Reaper	NVDA	SP
P4	32-38	UK	CB	Intermediate	Reaper	NVDA	SP
P5	25-31	USA	CB	Advanced	Logic	VoiceOver	SP, SW, G, O
P6	32-38	UK	CB	Expert	Protools	VoiceOver	SP
P7	55-64	Canada	CB	Beginner	Logic	VoiceOver	SP, SW
P8	39-44	USA	CB	Expert	Sonar	JAWs	SP, SW, G, O
P9	18-24	UK	CB	Advanced	Logic	VoiceOver	SP, SW
P10	18-24	Poland	CB	Intermediate	ProTools	NVDA	SP, SW
P11	25-31	Greece	LV	Advanced	Cubase	NVDA	SP
P12	18-24	Greece	CB	Intermediate	Reaper	NVDA	SP, G
P13	32-38	UK	CB	Advanced	Reaper	NVDA	SP,SW,O
P14	32-38	Hungary	CB	Expert	Reaper	NVDA	SP, SW, G
P15	45-54	USA	CB	Advanced	Reaper	NVDA	SP
P16	32-38	UK	CB	Expert	Reaper	NVDA	SP, SW, G, O
P17	45-54	Germany	CB	Intermediate	Logic	VoiceOver	SP
P18	25-31	Greece	CB-HL	Beginner	Reaper	NVDA	SP, SW, G
P19	65+	USA	AB	Advanced	Reaper	JAWs	na

Table 3.1: **Participants' Information.**
CB = Congenital Blindness, **LV** = Lower Vision, **HL** = Hearing Loss, **AB** = Acquired Blindness, **HFE** = Haptic Feedback Experience, **SP** = smartphone, **SW** = Smartwatch, **G** = Gaming, **O** = other.

3.3.2 Hardware

Sixteen participants indicated that they use some form of hardware device in their workflow. Participants highlighted a combination of 25 different hardware models they utilise, while six models remained unidentified due to insufficient information provided by the participants (Table 3.2 and Appendix B). Among the hardware devices reported, thirteen participants specifically mentioned using a Native Instruments Komplete Kontrol device, with five using this as their sole hardware device, while others used additional hardware devices in their workflow. Sixteen of the identified keyboard devices include controlling surfaces, knobs, faders, buttons, and modulation wheels, while 12 are non-keyboard controllers featuring only knobs, faders, and buttons. Among the remaining hardware models, there is one keyboard with no additional controllers and two audio effects hardware. Table 3.2 summarises the identified hardware devices and presents the type of tactile interaction they offer (keyboard and control surface), the type of technology (digital, analogue or hybrid), the type of individual components (encoders and faders) and finally the number of units identified among the participants.

Model	Type	Technology	Controllers	Units
Akai MPK	Keyboard with Control Surface	Digital	Limited Range Encoders	1
Arturia Keylab MKII	Keyboard with Control Surface	Digital	Motorized Faders, Endless Encoders	1
Avid S1	Control Surface	Digital	Motorised Faders, Endless Encoders	1
Avid S3	Control Surface	Digital	Motorised Faders, Endless Encoders	1
Behringer XTouch	Control Surface	Digital	Motorised Faders	2
Mackie C4	Control Surface	Hybrid	Motorised Faders, Limited Range Encoders	1
Mackie Control Surface	Control Surface	Hybrid	n/a	1
NI Komplete Kontrol S61	Keyboard with Control Surface	Digital	Endless Encoders	4

NI Komplete Kontrol S88	Keyboard with Control Surface	Digital	Endless Encoders	4
NI Komplete Kontrol n/a	Keyboard with Control Surface	Digital	Endless Encoders	3
NI Komplete Kontrol A61	Keyboard with Control Surface	Digital	Endless Encoders	2
NI Komplete Kontrol M32	Keyboard with Control Surface	Digital	Endless Encoders	3
NI Komplete Kontrol S25	Keyboard with Control Surface	Digital	Endless Encoders	1
Korg M3	Keyboard with Control Surface	Digital	n/a	1
Korg mikroKey	Keyboard	Digital	n/a	1
Korg miniLogue	Keyboard with Control Surface	Analogue	Potentiometers	1
Korg nanoKontrol	Control Surface	Digital	Limited Range Encoders	1
Novation Circuit Rhythm	Control Surface	Digital	Endless Encoders	1
Novation SL61-MP3	Keyboard with Control Surface	Digital	Endless Encoders	1
Rolland Jupiter x	Keyboard with Control Surface	Digital	Non-motorised Faders, Limited Range Encoders	1
Rolland Phantom 8	Keyboard with Control Surface	Digital	Non-motorised Faders, Limited Range Encoders	1
Rolland RD-700SX	Keyboard with Control Surface	Digital	Non-motorised Faders, Limited Range Encoders	1
Rolland Drum Machine	Control Surface	Digital	n/a	1

Softube console 1	Control Surface	Digital	Motorised Faders, Endless Encoders	2
Softube console 1 fader	Control Surface	Digital	Motorised Faders, Endless Encoders	1
Bricasti M7	Effect	Digital	Limited Range Encoders	1
Cassio CTS500	Keyboard with Control Surface	Digital	Limited Range Encoders	1
Kurzweil K2661	Keyboard with Control Surface	Digital	n/a	1
NI Machine MK3	Control Surface	Digital	Endless Encoders	1
Nektar Impact LX	Keyboard with Control Surface	Digital	Non-motorised Faders, Limited Range Encoders	1
Pultech EQ	Effect	Analogue	Limited Range Encoders	1

Table 3.2: **Participants' Musical Hardware Devices**
Digital: Digital interfaces and interactive with DAWs, **Analogue**: Operate using traditional electrical signals, not interactive with DAW, **Hybrid**: A combination of software that allows interaction with DAW and analogue features such as motorized faders

3.3.3 Themes

The thematic analysis outlined three main themes: (1) music hardware device usage and technology, (2) tactile feedback experiences, and (3) haptic feedback in the DAW.

Theme 1: Tactile feedback in music hardware devices presents accessibility improvements and challenges

The first theme provides insights into four topics related to the devices used by participants, the role of their technical specifications, the comparison of analogue and digital devices, and the specific use of the device Komplete Kontrol.

Subtheme 1.1.: Hardware usage to make DAW functionalities more accessible
Fourteen participants reported that they mainly control plugin parameters such as filter, EQ (equaliser), pitch modulation, reverb and compression using encoders and faders provided by each hardware device (Figure 3.1). For example, P16 described how using the motorised faders of Behringer Xtouch makes it easy to access the values of the parameters. Five participants also highlighted that they use these features to control panning and volume levels, while five other participants use them to record or recall automation. The most commonly used devices for these functionalities are the Behringer Xtouch, Korg and Mackie devices. P3 emphasised that,

> 'Any kind of pitch manipulation like tuning is easiest just slowly to slide your hand down on the fader and have it corrected that way, rather than going into the parameters and saying at this point you should be that level.' (P3)

Four participants also mentioned using hardware device components to navigate the list of VST plug-ins and their available presets more efficiently. P15 described part of his production process:

> 'I use drums (software instruments) in my recordings, some Native instruments and some other drums. If I am using the Komplete Kontrol keyboard, I can choose the sound that I want and control the levels of the various drums very easily by simply turning a knob.' (P15)

Particularly, eight users of Komplete Kontrol reported that this device helps them access plug-ins that are not accessible in any other way. P10 commented on the usability of Komplete Kontrol that it gives '...the ability to move around the Native Instruments plugging and some other plugging that uses the NKS format'. NKS format allows plug-ins to be compatible with Komplete Kontrol devices (Native Instruments, 2024). P15 raised concerns around accessibility:

> 'There are some plug-ins that are very inaccessible; for example, I've heard of a program that is the favourite of Hans Zimmer, but when I load it in Reaper, I couldn't access the presets. Using it in conjunction with Komplete Kontrol, I have access to all presets and can also make changes to them' (P15).

Finally, some reported using hardware devices, such as Xtouch (Behringer, 2024) and Mackie (Mackie, 2024), to control the transport bar (i.e., play, stop, record, forward, and other essential functions of the app) (P2).

Twelve participants use two or more devices. A comparison of the equipment reveals

that no devices combine all the specifications needed to be fully accessible or to help the workflow effectively. Nine participants have a Komplete Kontrol keyboard and an additional device, which is a controller with a motorised fader (e.g., Mackie (2024), Behringer (2024),Softube (2024), Avid (2024)). For example, P9 has a Komplete Kontrol A61 at their home studio and an m32 that they can carry with them due to their compact size. P17 has an Avid S3 and a Komplete Kontrol device and commented that 'with Avid S3, I can control plug-ins and I got comfortable with that, but the problem is that there is no accessibility, no verbal feedback, so I use it only to do some modifications on my sounds'.

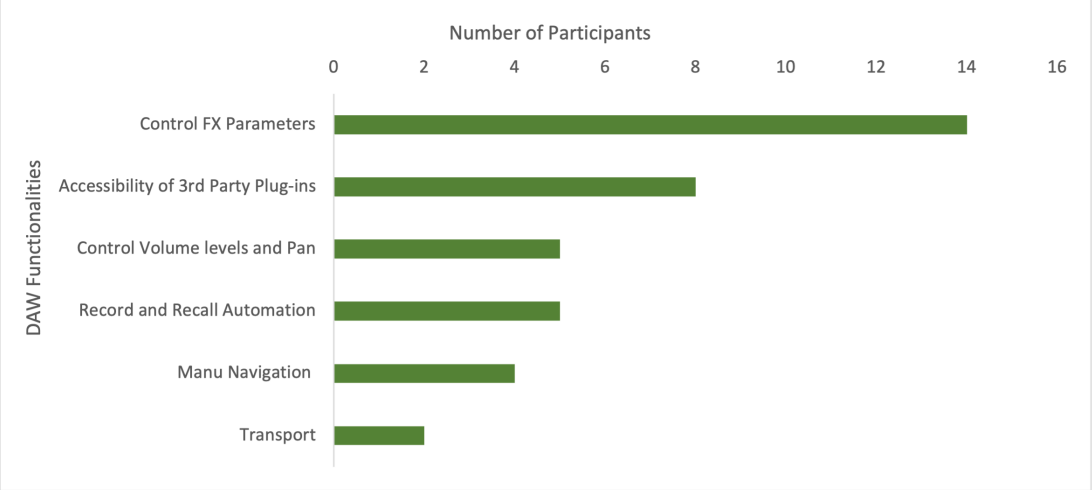


Figure 3.1: The use of Hardware devices in DAW

Subtheme 1.2.: Hardware specifications influence the usability of music hardware. The analysis identified various types of encoder and fader specifications that influence the accessibility and preference of the device for BVI individuals. This includes two types of encoders: limited-range encoders with start and finish points, and endless encoders, which rotate infinitely. There are also two types of faders: motorised and non-motorised (section 2.2). From the devices identified among the participants, thirteen devices have limited-range encoders, 8 have endless encoders, 6 have motorised faders, and four have non-motorised faders (Table 3.2). Each distinct technology affords these devices a unique tactile interaction style and level of tactile feedback.

Participants referred to the advantages and disadvantages of the two types of encoders, highlighting the importance of the balance between tactile and voice feedback in hardware design. Behringer XTouch (Behringer, 2024) has endless encoders, which, for some users, might be an obstacle. P16 mentioned 'the pans are just endless encoders, so again, you kind of need speech feedback for those', pointing out that the need to have

voice feedback when using a knob cancels out the usability of the tactile feedback. P19 adds about Komplete Kontrol that 'all this new feedback that has been put into some of these programs, I just found it to be too much', supporting the need to balance the provided information on the two sensory modalities.

Regarding the overall presence of a fader in a device, its tactile feedback was found to be preferred over its absence. P14, a user of a Korg nanoKontrol (Korg, 2024), expresses how this piece of hardware helps through splitting information up into two modalities, audio and haptic

> 'Very often, when I want to focus on something, it would be really nice if there was a way to split things up and with nanoKontrol to an extent, I can split things. For instance, modulation, panning or setting volume, I don't need to worry about listening to the percentage values being spoken. It's just a lot easier knowing that I use a knob and it works. It also frees up my ear in a way I can focus on the music.' (P14)

However, the only action that can be taken with this device is momentary because of the non-motorised faders, which usually record automation to manually mapped parameters. P14 stated that:

> '...it's absolutely a momentary thing. I would be really happy if they were motorised because that could, I think, improve things. At the moment, I just haven't found an affordable motorised one, and it would be as mappable as another control.' (P14)

Four interviewees highlighted the debate between motorised and non-motorised faders. P16 mentions how the motorised fader of the XTouch (Behringer, 2024) facilitates the editing of the automation, as faders represent the position of the automation line; each time, a small adjustment can be made by moving the fader.

> 'Because they're motorised faders, and they move to represent the position of the parameters and can kind of feel a representation of how the knobs are set that way. And then sometimes I end up just making the adjustments I wanna make on the faders.' (P16)

P8 mentions the use of a motorised fader with Mackie and how, in this case, automation is facilitated: 'I will also write automation. It's got moving. I have motorised faders on the Mackie, so if I wanna fade something out inside the computer, I'll use those faders and draw the automation like that.' Likewise, using motorised and non-motorised faders highlights the existence of a financial barrier that prevents people from purchasing such

devices. Motorised faders tend to raise the cost of control surfaces (P13).

Subtheme 1.3.: Analogue experiences offer accessibility opportunities and shape workflow strategies Music technology started with the use of analogue equipment. Such equipment does not offer voice feedback, but it often represents information in the form of tactile feedback. P8 stated, '...processors are fairly accessible because they're not screen-driven. So there are VU meters or lights and stuff like that that I can't use, but I don't need them because I can hear what needs to happen.' The way the knobs and faders are aligned and mapped in a fixed position on the device helps users feel secure about what they are doing:

> 'At the beginning of the third knob to the left, it always does the same thing. So once you memorise that piece of equipment, you know it works; it works the same way all the time.' (P8)

> 'There was a board in front of me of knobs and faders and switches and buttons, and once you memorise where all of these things are, then at your disposal. You don't have to go through a menu. You don't have to do anything. It's right there ' (P19).

Some participants (P15, P16) have learned music production this way, so when all the tactile feedback is transformed into graphic representations, they look for effective alternatives. P16 describes how he gradually moved from analogue to digital, looking for the ideal combination of DAW and hardware to facilitate his workflow and the corresponding barriers:

> 'I started on like analogue hardware obviously, and then when I first started using a DAW was Pro Tools, and I pretty much had to have a control surface at that point to be productive. So I spent a good few years with a surface there. And then, when I moved over to Sonar for a brief period, I was able to use the same surface, and that kind of made that transition a little bit smoother. And then I arrived in Reaper, and man, their control Surface integration is bad, and it's still bad today. So I kind of just pretty much stopped using a surface at that point. The reason I've picked it up again recently and started exploring it again recently is that there's this open-source project called CSI Control Surface Integrator. Will I ever go back to using a surface full-time? I don't know. It kind of depends on how smoothly this CSI project goes.' (P16)

At the same time, many participants also advocated for digital technology by comparing it with analogue and describing its limitations. Two users (P8, P14) work in a studio environment and highlight barriers caused by the analogue equipment. For instance, P14 stated that interacting with objects like cables and plugging them into the different hardware is difficult for a BVI producer: 'digital is more accessible than analogue – when in the studio, there are a lot of problems to move around, you need help from sighted to interact with objects just as cables'. P8 also mentioned that help is needed (from sighted people) when recording large bands (such as a big band) with multiple inputs in his studio to quickly check the volume levels.

Similarly, P19 describes how the use of analogue devices relies on hearing the sound. Whilst this is occasionally what a producer needs, there are moments, such as the peak of the sound levels, where there is no further indication than a visual light in the console. It may be what you are hearing in your earphones may sound great, but it's way above 0dB and the meters are already going into the red. But you don't know that because your accessibility isn't telling you that.' This can lead to many disruptions in the process of mixing and mastering.

Subtheme 1.4.: Komplete Kontrol widely used by BVI music producers Participants described Komplete Kontrol as the most accessible piece of hardware, with 13 out of 16 users owning one or more models of the Komplete Kontrol series and 4 out of them using only one. These three motivations were highlighted: the easy navigation through long menu lists (P1, P4, P15, P17) due to the quick rotation of the encoder, the access to often inaccessible plug-ins (P1, P9, P14), and voice feedback for each controller (P7, P8, P10, P13, P15). The flexibility of the hardware to tailor the voice feedback according to preference appears to be a significant factor in its popularity: 'Basically for me, it's about the accessibility and the options and the doors it opens to me.' (P1). Similar for the voice feedback on each controller (P1, P7, P8, P10, P13, P15).

> 'I love what native instruments has done because, of course, the hybrid setup. It is the best thing that has happened to us in recent years in the music industry because we can touch the knob and find out what this knob is doing, and it can be turned off, of course, if someone doesn't want to hear that. But you can check what you are doing now.' (P10)
>
> 'Because it gives me confidence that what I'm doing is the right thing. Because if I'm tapping on a screen, I'm not always sure that I'm going to hit the right icon, and then it takes me a few attempts to do so. If I'm

> pressing a button on the keyboard and I know that's the browser button, that's going to work to show me a list of products and presets. I can use the little directional cues of things just to find my way through them. That helps the navigation a lot.' (P13)

Native Instruments launched the integration of accessibility features to its devices in 2016, and at that moment, according to the company's evaluations, 1 in 20 users of Komplete Kontrol were visually impaired (Access, K., 2023). This sustained effort in accessibility created a series of forums and online articles that users can use to help each other. P10 stated that virtual instruments are now widely used within the community and that they think '...it's a great invention, they have done something great, and I wouldn't start making music without it. So I'm very thankful for that'.

Theme 2: Understanding the benefits and limitations of tactile experiences

Subtheme 2.1: The importance of tactile interaction. Seven out of nineteen participants (P3, P9, P12, P13, P14, P15, P19) directly commented on the importance of tactile interaction within their workflow, which makes it faster and more efficient for them to work. P13 commented on improvements in their working process in terms of speech and efficiency, while P14 and P15 both referred to the navigation, 'the more ways we can have access to information in an environment where it's just absolutely chaotic' (P14); 'It is also just the idea that it's right there instead of having to dive into a menu.' (P15). P3 and P14 expressed views around tangible methods for interacting with sound: 'I feel like a hands-on element is needed because you are doing something that you feel at one with that' (P3); 'sometimes it is really good to have a physical representation of how far parameters can go, and there is a tactile feedback, for instance when you press a button'(P14).

Subtheme 2.2.: Tactile feedback should not replace voice feedback but complement. Ten participants mentioned issues arising from using a screen reader in addition to hardware devices. When using hardware, users receive voice feedback, which expresses a parameter's value at each position. Users intentionally exclude this information to avoid cognitive overload as it overlaps with the audio content being processed at the time: 'Obviously, I'm listening to the effect. To me, those numbers never really meant anything. Anyway, it's more about how it sounds.' (P19). P14 also describes, '...it also frees up my ear in a way, it is because I can focus on the music.'

The balance between hardware usage and a screen reader plays a significant role in the workflow and the level of accessibility provided by specific hardware. P10 stated a

preference for using a Mackie control surface that does not provide voice feedback:

> 'If I would like to do some automation, even volume automation, I prefer to do that using a control surface because it's quite hard to do it with voice-over...-Mixing is also easier if you have your faders under your fingers rather than moving around with Voiceover and hearing it basically all the time. So, I think it's better to have the ability to touch it and to do it manually.' (P10)

Newer technologies like the Komplete Kontrol include voice feedback when accessing the hardware devices. Participants commented that although most of the time, hardware is mostly more accessible when providing voice feedback, it can also be problematic when it obstructs listening to the actual sound:

> 'What I do, sometimes, I don't always need to hear the speech, so sometimes I hear roughly the speech, while that makes sense. So I'm actually listening to the music and mixing with my ears as opposed to listening to numbers. Sometimes I have to listen to numbers, for example, when I'm metering and I want to make sure something is not clipping. But generally, it is nice to work with the controllers.' (P6)

Three participants used a Braille display with their DAW to put labels and markers in tracks, split the information into two modalities, and concentrated more on the audio without the voice feedback from the screen reader: 'When I do some sound editing, you don't want to hear the voice, frequency, volumes, etc. So, you turn off the voice, and you have the Braille display showing you the information.' (P18)

Subtheme 2.3.: Challenges and Preferences in Assistive Devices and Equipment. Three participants (P5, P7, P19) highlighted that they believe that the Braille displays will present efficiency challenges, slow down their working practices and that they do not want to have one more device in their workflow (P5, P7, P19). They discussed how they must move around to access information across multiple pieces of equipment and the additional equipment they would potentially need to carry outside the house. Similar to the Braille display, they also comment on the disadvantages of music hardware use: 'Changing environment takes more time, and so it is important to me to be able to stay within the same environment.' (P7). Another argument is about the portability of the equipment. For instance, three participants (P1, P5, P9) felt that it is essential to have their music on the go and accessible anywhere without needing to carry around large keyboards or controllers: 'I like the fact that if I can get the same sound in software, then I can carry my laptop on stage with me' (P1).

Subtheme 2.4.: Affordability barriers in accessibility braille displays and music equipment Hardware devices are often costly compared with low-cost or free software and plugins. The prices of the devices identified in this study ranged from £60 to £4200, with an average price of around £800 (Appendix B). Three out of 19 users highlighted that they do not own any hardware devices due to affordability challenges. For example, P18 emphasised the cost of controllers with motorised faders as a particular issue: 'At the moment, I just haven't found an affordable one that is motorised, and it would be as mappable as another control.'

Braille displays are also often expensive, priced from £1200 to £3000 (Royal National Institute of Blind People (RNIB), 2024), with seven participants highlighting that they do not use a Braille display.

> 'If I had the money, I would give them to a Braille display.' (P12)
>
> 'I just got it from library; they're supposed to be early readers.' (P5)
>
> 'They're interesting because they are expensive for what they are, but they're also very useful.' (P9)

Subtheme 2.5.: Vibrotactile experience shapes BVI producers' perceptions of accessibility benefits Participants described their experiences with smartphones, smartwatches, gaming, and other applications that utilise vibrotactile feedback. Eighteen participants expressed that they have experienced vibrotactile feedback in these devices to some extent, and one not at all. The following theme describes participants' experiences with haptic feedback on the aforementioned devices and in other instances of their lives, whether music-related or not, and how these influences access to different activities.

Regarding vibrotactile feedback in commercial devices, fifteen out of nineteen users use an iPhone, and three use an Android phone. All users have a smartphone and use the haptic feedback to some extent. Most users were not aware of the haptic possibilities of the device beyond the basic vibrating notifications (P10, P2, P3, P4, P8). However, when it is present, vibrotactile feedback positively impacts the phone use experience by providing confirmation on the action and assisting the navigation (P10, P2, P4, P13, P1):

> 'I have an iPhone 10 S. I love the haptic features. One example is the keyboard feedback. I know when I've succeeded in entering a keystroke because I've had feedback.' (P2),
>
> 'I like having the haptic feedback to know if something's gone wrong, but

> just even because it's kind of comforting in hand, you know, it's working.' (P1),
>
> 'When I'm using maps, it will vibrate to tell me that a turn is coming up and that kind of thing.' (P3).

They comment on how Android phones offer more haptic feedback; however, they are not as reliable in accessibility as iPhones' VoiceOver (P18, P7).

> 'I think Apple hardly uses that, except for ringing, but that's pretty much all it does. Android is better in that respect; it gives haptic feedback for a lot of things' (P7), 'Android wasn't as good as the iPhone. iPhone is more accessible. They don't crash. Everything is easy and available. You don't need to download additional applications to make it accessible.' (P18)

Almost half of the participants, 9 out of 19, are using an Apple Watch. The main use of this tool is the Taptic time, which conveys time with various vibrotactile feedback combinations, Digits, Terse, and Morse Code (P1, P14, P7, P8, P9). Participants find the Apple Watch discreet, and it facilitates getting information without the use of a screen reader, which is preferable in situations where they are in public, but also when they are with other people. Some examples are:

> 'You can tell the time in a quiet place or late at night when you don't wanna wake your wife up.'(P1) and 'When I used to attend university classes, presentations were always timed, so I used to have a lot of time defined, and they always vibrated when the time was up or halfway through.' (P14).

Another use of the Apple Watch is for notifications, such as when the phone is out of range (P8), or for reminders to take medication (P5).

Eight participants mentioned that they had some experience with video games that utilise vibrotactile feedback to enhance their gaming experience. This experience was typically dated ten years ago and was primarily informative or brief. None of the participants stated that they were playing video games regularly at the moment.

> 'Vibration is something really important there. Especially because a lot of games do not have much accessibility, but on the other hand, a lot of information is conveyed through vibration. For instance, when you're low on health or sometimes when you bump into something or when you get a notification in the game, there is vibration to convey a sort of more impactful scene or happening. They are very useful there as well.' (P14).

While describing their experience with haptics, participants referred to isolated cases of haptic feedback experiences. Nine different cases have been identified with tools that varied from household appliances to music production assistive tools. The non-music related cases include a Liquid Level Indicator, a household tool that helps blind people with cooking and vibrates when the boiling liquid is near the pot level (P13), a portable charger that vibrates when the battery of the device is full or when the battery of the charger is low (P14), a relaxation app with vibration indicating breaths and other tasks (P10).

Focusing on other music-related haptic feedback cases, there are several research projects and fewer commercial. Participants have tested or are aware of the following research projects: HapticWave (Tanaka and Parkinson, 2016), HapticKnob (De Man et al., 2019), and Haptic Baton (Asakawa and Kawarazaki, 2012) (P8, P1, P5). The commercial products that have been mentioned are the SUBPAC4 (SUBPAC, 2025), Basslet 5 (Lofelt GmbH, 2025) (P5) and a haptic metronome application for Apple Watch (Apple Inc., 2025) (P10).

Beyond mentioning their experience with these tools, participants commented on the effectiveness of this experience. The Haptic wave, although beneficial and well-designed, has a very niche use (P8). The haptic baton lacks inclusive design (P8); most of the haptic information provided is things that sighted people see but are not necessarily valuable for blind people. HapticKnob was a very successful project, but was unfortunately abandoned too soon (P1). From the commercial devices, according to P5, SUBPAC is very effective in its use and may be better than the watch in terms of body location. The Basslet was not a very constructive experience (P5), and the haptic metronome app wasn't reliable (P10).

Participants were asked how comfortable they feel while using tools with haptic feedback in their everyday lives, especially wearables like the Apple Watch and a speculative wearable device. Regarding the Apple Watch, all existing users said that they were comfortable with it except for one who said that it was 'cumbersome' (P8). When they were asked their opinion about future consideration on the design of a wearable tool, they identify the four most important factors for its usability: (1) do not prevent them from doing other things or prevent productivity (P12, P14), (2) to be reliable (P13), (3) to be discreet and 4) portable (P3, P9).

Theme 3: Suggestions for enhancing DAW accessibility and workflow efficiency via haptic feedback

Participants proposed features and functions for DAWs where haptic feedback could be used in conjunction with other assistive technologies, like screen readers, or as a replacement and introduction of a completely new interaction process. They also suggested a wide variety of speculative tools, including various forms of haptic feedback and haptic interaction.

Furthermore, they identified nine possible functionalities in the DAW that would benefit from haptic feedback applications (Figure 3.2). Some ideas were common among the participants, with one idea (peak meter) being mentioned by almost half of the participants.

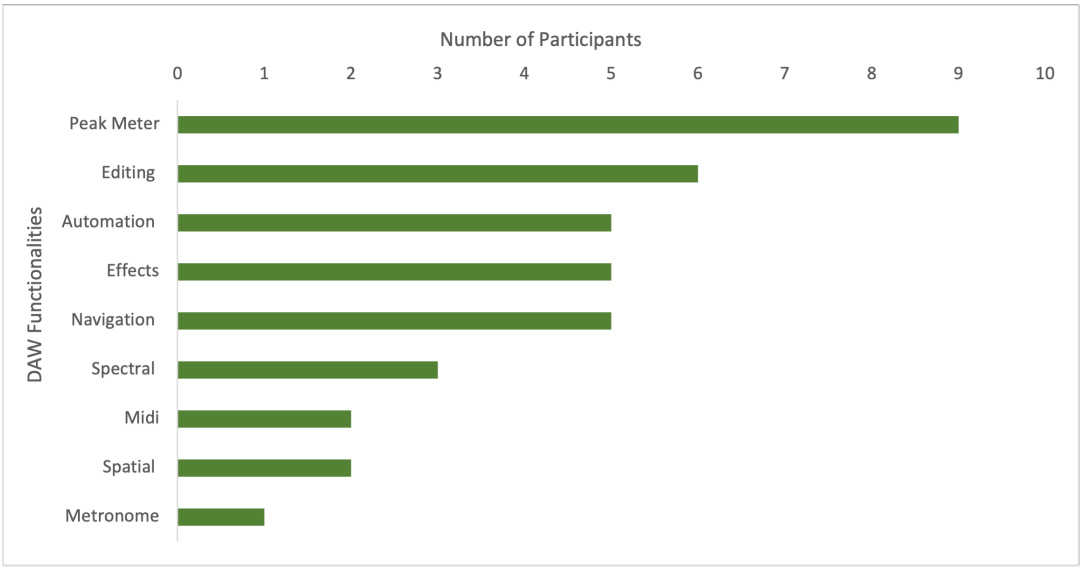


Figure 3.2: DAW Functionalities that need Accessibility enhancement through haptic feedback

Peak Meter: Nine participants suggested that they prefer vibrotactile feedback to inform them about the peaking of the sound. Seven participants suggested vibration to convey information from the peak meter instead of the screen reader (P1, P3, P8, P9, P10, P12, P15).

> 'Sometimes you don't want sound feedback, especially when recording yourself. For example, you set a level, and when you're clipping, you have some feedback on your watch to be able to feel.' (P10).

> 'To have something, when the recording bar (meter) is green or red, to get an indication. It's annoying to hear the voice feedback when you are recording' (P12).

Apart from live recording levels, three participants mentioned the use of feedback for the peak of the sound while mixing, both in the mixing channel and also on the waveform (P2, P14, P15). 'If you have a distortion in music and then you have like a peak watcher or something, I could see that with vibration.' (P14)

Lastly, participants who use analogue equipment in recording studios mentioned the need for a peak watcher on the consoles. The process for identifying the peak here is more complex in comparison to digital software. The participants suggested using a device that can identify the different indications of a volume unit meter (VU) and convey information related to the amplitude of the sound.

> 'You can put a little light sensor over the meter and clamp it down, and then it would vibrate at 0dB, vibrate at 2dB, whatever it is you want. So that would be very helpful for people like myself who are working in big commercial spaces.' (P8).

> 'I think for analogue equipment it could also be very, very useful because a lot of times you know there is no feedback. For a lot of things, like when there is clipping in sound, although you know that it could be heard, but still... Combining a light detector with the vibration, and they would vibrate if the light is on or off, it's an idea' (P14).

Waveform: Editing a waveform is a process that heavily relies on visual feedback. Six participants expressed the desire to have some tactile experience of the waveform to be able to edit it more easily. Most comments are around the access to the waveform itself and the possibility of feeling its form. They describe a variety of ways they would like to experience the waveform by specifying the information of the waveform they seek to perceive, loudness, curve, and peak (P1, P7, P9, P11). P1 suggests using the amplitude of vibration to understand the variations in the sound amplitude while interacting with the waveform. P6, P7 and P15 suggest a tactile representation of a waveform, for example 'Maybe you can have a physical, embossed representation of the waveform. So basically, you can feel and touch what people are seeing' (P6). P6 also suggested a touch-screen-based interaction for navigating and editing the waveform.

> 'Another nice thing we can do is like a touch screen. So, for example, if you feel the waveform, you can actually edit the waveform by moving your finger on the waveforms, shrinking it, making it smaller, pinching to make it smaller, or you know, different types of gestures, different gestures to actually interact and edit the waveform. I think it would be great in real-time.' (P6)

Automation: Automation in DAWs relies on visual interaction by drawing envelopes over the visually represented waveform. This is also represented through the motorised faders. However, when BVI users need to experience the recorded automation, motorised faders require a delicate touch in order not to alter what is recorded, which often creates frustration (P9). When there is no tactile feedback from motorised faders, P15 describes the difficulty of remembering the automation in old projects that want to revisit or reuse 'I guess maybe another interesting thing would be to have it trigger when you go past automation events on a particular track'. P9 suggested a way of expressing automation through vibrations: 'If it was like automation of a parameter and it was, you know, increasing the level or decreasing the level, the haptic could increase or decrease in intensity depending on the positions'.

Effects: Adding haptic feedback to a plug-in is a complex idea since it combines many parameters with different values. Participants suggest two ways of approaching this idea: (1) the one-to-one mapping of vibration and parameter, and (2) the use of vibration as an indication of a threshold. The equaliser is the most common effect that has been discussed. Participants suggested different vibration representations for the changes in the Frequency bands.

> 'So you could have a lower pitch for, say, peak one (frequency band), slightly higher for peak two, peak three, peak four. You can just do like one short for peak one and then two shorts and three shorts and four shorts' (P1)

> 'It only gives feedback; for example, when you reach 100 Hz. So every 50 Hz, it will give you some vibration, and the higher the frequency, the faster the vibration.' (P11)

> 'Different vibration patterns for the band type, for example, so a low shelf could be one beat. The high shelf could be 2, Low Pass 3, and High Pass 4.' (P13)

For other parameters, participants suggested the use of the amplitude (intensity) of the vibrations. For instance, P5 highlighted that '...in Q it would be useful. It could be a sense of density. It is intense, so the Q is too tight. Or the opposite, it's loose, so I don't feel the vibration.'. Furthermore, P13 emphasised that: 'The band gain you could add the intensity feature. So, like the increasing intensities, the slider goes up. It decreases as it goes down.'

While describing frequency bands with certain vibration patterns, P16 and P5 suggest using the vibration as a way to complete a task or reach a specific target.

'...to get the perfect pitch to like guide you into slotting that note into perfect pitch.' (P5)

'If I knew I was aiming roughly for, say, 3 to 4dB of gain reduction, I can twiddle that gain knob while snare drum is playing a part and sort of judging by the feeling on my wrist when I'm roughly in the ballpark and then tune by ear from there. And so again, less speech, more listening, feeling, and then the last little bit is by ear' (P16).

Navigation: Navigation efficiency comes with speed, and the speed of navigation is succeeded by a functional interface design. The participants suggest that using haptic feedback in the DAW will be beneficial for navigation and accessing information, not in the screen reader's focus area. P12 comments that screen readers and Braille displays are not quick enough to convey information, and P9 supports that screen readers cannot inform about events happening in parallel in the software or operating system. For example, during the recording process, screen readers lack the ability to demonstrate that recording is enabled (P9). P13 suggested a way that vibrotactile feedback can express the state of a button in the screen: 'three beeps could mean it's armed, four beeps could mean that it's not, or you could have the beeps in different patterns.' (P13). P1 suggests 'So on the tracks header, it's gonna do mute solos in short bursts'.

Vibrotactile feedback has also been suggested for navigating through tracks and receiving information quickly without getting distracted by audio processing. P3 highlighted that when processing, and you feel a vibration for the peak of the sound, you want easy access to which track was peaking. This is where another vibration could be useful in symbolically representing the number of the track. In parallel with feeling the track number with haptic feedback, P11 suggests the use of haptic interaction to navigate tracks more effectively: 'so to have a way to change the sound levels and navigate across the channels, and maybe it's with some taps - three taps is channel three and so on.'P8 provide a similar idea but in more detail about the use of vibration to represent the number of tracks.

'Let's say it vibrated twice to tell you that you're on track two. It vibrated three times to tell you you're on track three, or maybe because if you have 80 tracks, you don't want the fader vibrating 80 times, so maybe you could have different vibration levels, like a weak vibration is a single digit. A strong vibration is a double-digit' (P8).

Spectral: More experienced participants mentioned the lack of accessibility in the spectral analysis plug-ins (P2, P6, P15). Their ideas focus on the haptic representation of

frequencies that are peaking or the noise in a sound file.

> 'The noise detection mode. There it could search for signal strength. In or amplitude whatever in the low noise area. It gives some sort of degree of intensity' (P2)

> 'I also think something to do with spectral displays. You know, people are able to look at a spectral display and see that there is a lot of energy in one area of the frequency spectrum, and I think that it would be useful to know some features to be built into this peak watcher so that we can watch certain areas of the frequency spectrum. And you know, low frequencies are notorious. Taking up a lot of spectral space. And so if instead of just giving me a peak, you know. If it could say that frequencies below 100Hz are at 0 dB, but everything else is fine. I don't know exactly how it would do it, but we have a way to perceive the peaks or the spectral information' (P15).

MIDI: Participants highlighted a wider challenge in understanding haptic feedback from MIDI signals. These interactive approaches are narrowed into two main areas, navigation across the edit field (event list or piano roll) and velocity of the notes. P4 and P14 suggested mapping the vibration density to the velocity, whilst P8 suggested the use of vibrotactile feedback to identify switches between edit fields.

Spatial: Two participants suggested different ideas for interacting with spatial information through haptic feedback. P2 suggests the use of two vibration motors, representing left and right, to assist in understanding the panning of a track. This participant also suggested using a touchscreen device for better interaction in the surround field 'It would be kind of neat though if there was a... like on the iPhone, let's say the iPhone represented the round field. It would be great if I could move my finger on the screen to where I want that sound and then have the haptic feedback'. P8 is also interested in accessing multichannel mixing and described the need for accessibility in specific tasks as industry standards are moving more and more toward multichannel mixing. In particular, P8 suggested the use of a joystick with integrated vibrations to facilitate navigation and interaction in the aural space.

> 'I think some kind of joystick would be great. If you didn't wanna integrate vibrations into a control surface, you know you could use the joystick. You could say all the way left is one vibration, and all the way right is one vibration. You kind of know which way you are, but if you're in the middle, say you're 50% left, you might get two vibrations or whatever you can get. You know you could get a lot of interesting information that way'(P8).

Subtheme 3.1.: Considerations and concerns about vibrotactile feedback in DAW

Two participants expressed the need to tailor vibrotactile feedback according to their needs, 'Which probably would have to be defined in a user-configurable area' (P1). They highlight the need for intensity adjustment as different people have different levels of perception of vibrations: '...there's no unisex approach, so to speak, each user is different' (P7).

Furthermore, the designs need to be easy to understand and have fast responses (P7), so they do not create further cognitive overload 'It seems conducive to have something immersive with the sound. But then, having said that, a more practical language that your brain interprets' (P3). Haptic feedback should not hinder them from doing anything else with their hands. The application supporting the haptic feedback should also be accessible and easy to install.

> 'I think the only caveat is, as you said, can you tailor it to give you what you want and turn it on and off when you use your hands. Blind practitioners have to use their hands a lot because they use so many keyboard commands. So you wanna make sure that things are not just coming on and off all the time.' (P8).

Participants' experience with screen readers also influences their approach to haptic feedback design. The way information is provided via voice feedback is time-consuming, as it relies on presenting the information in descriptive language (e.g., track 36 piano, arm enabled, zero point 45 dB). P1 suggests that vibrotactile feedback can be combined with a screen reader to create a better experience and enable faster information communication.

> 'This is very long to get the information across. Why don't we do parallel streams? So, the speech would have fewer words to say, but, in part, the necessary information [...] If you have a long track name, "track 36 piano, violins and oboe mute solo". I want the vibrotactile to tell me "mute solo". But I know the track number by listening to the speech and what the track is. So, by the time I've heard the name of what's spoken, I already know the thing is muted and solo.' (P1)

P6 supports the idea that screen readers are efficient at what they are doing, and haptic feedback should not replace them but accompany them. On the contrary, P9 highlighted that, at times, haptic feedback would be preferable to voice feedback. P2 proposes that this alternative feedback should work like the screen readers; while navigating to different areas of the software, you can access haptic feedback where available.

Seven participants expressed concerns about possible disadvantages or barriers while developing the tool. Three indicated that the existing technology meet their needs (i.e., a screen reader and other hardware), and expressed little concern regarding potential changes (P2, P10, P16). Two participants highlight the importance of the low latency between the interaction and the feedback and how the existence of any delay will make the device dysfunctional (P15, P1). P10 and P13 mentioned the process of learning how to use the application and the semantics of the different vibrotactile feedback patterns. P10 supported that 'the more signals you have, the more time it takes to learn it for different users, so it shouldn't be more complicated.'. Other concerns concentrate on the feasibility of adding a new haptic tool to their workflow. P10 questioned how easy it would be to set it up or how easy it would be to make such a device. P4 suggested that vibrotactile feedback might not be usable in representing a small number of changes. 'It could be difficult; I mean, how, for example, do you represent fractional values using haptics? If you say minus 13.47, how on Earth are you going to know the difference between .47 and .46?' (P4).

On the other hand, participants identified many benefits that haptic feedback could offer in the usability of DAWs. Vibrotactile feedback can convey information faster than voice feedback (P12, P9), and it can be similar to the visual cues that sighted people have at their disposal (P15). It can be helpful to people who need more time to complete a task due to cognitive or physical impairment (P13). Finally, haptic feedback can help audio processing functions that require concentration on the audio and cannot be completed with voice feedback.

3.4 Discussion

Interviews with 19 BVI music producers were conducted to understand their practices and how they use music hardware equipment in their workflow. Results revealed some of the challenges that arise with these tools and how tactile interaction is crucial in making them more accessible and user-friendly for BVI users.

This chapter also expands previous work by providing new insights into the plethora of software and hardware tools BVI producers combine to create the most accessible workflow for themselves. Harrison et al. (2023) initiated the discussion on how music hardware devices facilitate a better workflow for BVI users, providing insights into the use of hardware within DAW, their limitations, and the role of voice feedback in making these tools accessible. This chapter's findings identify the rationale behind users' choice of tools, which is influenced by specific technical specifications and the level of software-hardware compatibility.

The use of vibrotactile feedback in commercial devices, such as smartphones, smartwatches, gaming devices, and other tools, was also explored, along with the level of assistance they provide. Through these interviews, emerging guidelines were presented for designing vibrotactile feedback in the context of DAW accessibility, including concrete vibration pattern ideas and considerations about the proposed system design. This work contributes to understanding the needs of BVI users from a vibrotactile feedback system and the importance of using co-design techniques when designing assistive tools.

The discussion is divided into the following categories: (1) the advantages and disadvantages of music hardware devices as those emerged from participants' lived experiences, and (2) the way the findings inform future research and design, expressed by concrete design recommendations. These insights led us to propose ways to improve the inclusivity of music hardware devices and design guidelines for the use of vibrotactile feedback in the DAW.

3.4.1 Current practices in music hardware use and emerging opportunities

Participants provided valuable insights on how music hardware devices enhance their workflow. These insights helped identify the technical specifications of devices such as faders and knobs, enabling participants to have inclusive workflows. Four main design affordances were identified related to *precision*, *speed*, *tactile feedback*, and *portability*, showcasing the rationale of BVI music producers in using hardware devices.

Faders are a pivotal specification in music hardware, allowing *precise* interaction with sound within the DAW. They also provide an alternative to voice feedback, which is essential for users during various sound manipulation tasks (e.g. volume level). Knobs, on the other hand, facilitate *speed*. Participants have frequently mentioned in the literature that screen readers hinder their ability to interact efficiently with software due to the linearity of information presentation and the speed of speech propagation (Saha and Piper, 2020), and have pointed out the importance of splitting information between touch and hearing to provide equal opportunities for perceiving information in a shorter time. Knobs lower this barrier by providing an alternative way for navigating within the DAW or accessing parameter values. Music hardware *tactile* affordances improve accessibility to tools that are not accessible through screen readers. Currently, all visual information must be translated into audio through voice feedback. Translating the information into different types of tactile feedback would allow BVI users to access it more efficiently, especially in cases of screen reader inaccessibility. Lastly, depending on the size of the device, they offer *portability* to a more efficient workstation. Small-sized

hardware devices such as the Komplete Kontrol M32 and nanoKorg (Appendix B) can fit in a backpack, which gives users the confidence to bring their workstations outside of the house and effectively participate in the broader community of musicians and music producers.

3.4.2 Benefits of multimodal interaction

Multimodal interaction allows users to choose the most suitable way of engaging with a system based on their needs. This flexibility is especially beneficial for BVI users, as there are instances where voice feedback from a screen reader is not the most effective method for interacting with a DAW. For example, users often prefer using motorised faders to write automation in tracks, as these provide a more expressive and tactile way of performing the task. Additionally, when voice feedback delivers information such as numbers that may not be contextually meaningful, interacting through hardware helps reduce the cognitive load imposed by continuous audio feedback. A well-designed multimodal system creates synergies between different modalities, enhancing the overall experience. Participants noted that dividing information between modalities allows them to focus on listening to the audio while receiving complementary data through haptic feedback. In some cases, users may partially listen to the screen reader and complete the missing details through tactile input. - this interdependence between voice and haptic feedback showcases their synergistic effect. Furthermore, according to participants' insights, the modalities complement each other, thereby increasing speed and efficiency. This two-way complementary approach is evident as knobs can help navigate lists more quickly with voice feedback while voice cues confirm the information accessed via endless encoders.In scenarios where voice feedback is particularly helpful, haptics provide additional information that is challenging to convey through text alone, such as indicating the range of a parameter.

3.4.3 Music hardware devices limitations and participants' unmet needs

Based on participants' adverse feedback on music hardware devices, the design of *software-hardware compatibility* is the primary factor preventing existing technology from providing an optimal solution for DAW accessibility.

Faders and knobs, which provide beneficial tactile feedback, are also limited in their usefulness if they cannot synchronise with digital information. For example, the nanoKorg controller (P14) offers only real-time control; its knobs and faders are not motorised or endless encoders and cannot recall any values from the DAWs. Motorised faders can

address the gap between software and hardware by effectively recalling information, but their high cost poses a barrier for many potential BVI users. Endless encoders can address this issue by not requiring motorisation to access and represent software values. However, users report that not all DAW functions can be effectively represented by endless encoders. For instance, panning is a function that demands limited-range encoders, which clearly represent left and right positions with their tactile affordance.

3.5 Design Recommendations

The interviews with 19 BVI music producers provided valuable insights into users' experiences and current needs, helping to define key design requirements. This section presents recommendations for the development of inclusive music hardware, emphasising the core features that an effective new device should incorporate. The following two sections discuss the specific areas of the DAW where vibrotactile feedback can provide further accessibility. Finally, based on existing methods of designing vibrotactile feedback, emerging guidelines are proposed to support the creation of intuitive and user-centred haptic interactions.

3.5.1 Designing Inclusive Music Hardware

Each of the 19 participants contributed their unique approaches to DAW accessibility, shaping an overview of the advantages and limitations of using music hardware technology in their workflows. These results focus on the technological aspects of hardware devices. Three main areas are highlighted as most important by most of the participants. However, it is crucial to consider the individuality of each user and provide flexibility by creating tools that can be easily tailored to their needs. The main areas identified are: (1) *Cost-Efficiency*, (2) *Voice-in-Design*, and (3) *Haptic Feedback*. Although these areas are equally important, it is acknowledged that they have different time frames for implementation. Cost-efficiency represents a long-term solution, relying not only on technological and design decisions but also on socio-economic and socio-political progress. For instance, the development of awareness about available and accessible technology, as well as the state's provision of accessibility technology to individuals who require it. In contrast, incorporating voice feedback into the design is considered an intermediate-level solution. While it currently exists, improvements are needed, along with frequent re-evaluation of user needs. Finally, the use of haptic feedback in design is an immediate solution. New technologies can be effectively implemented in new designs, providing an advanced accessibility method for new devices, but also with the opportunity to retrofit in non-haptic-enabled devices (Moon et al., 2019). Haptic feedback, in particular, will

be reviewed in more detail in section 3.5.2.

Cost-Efficiency: Financial barriers are a crucial factor to consider when designing a new accessibility tool. Data shows that the relationship between participants' age and environmental context influences the choice of DAW and hardware devices (Table 3.1). More specifically, factors, including age, profession, location, educational background, gender, and ethnicity, collectively contribute to shaping this ongoing challenge (Borg et al., 2011; Longoria et al., 2022; Cote, 2021). Utilising the possibilities of cheap yet robust haptic technology or commercial devices can suggest a more cost-effective solution, though. However, using existing commercial devices designed for different purposes will lead to other limitations. An example of this is *TouchEq* by Pesek and De Man (2021), which utilises textual information generated by vibrotactile feedback on a tablet to provide an alternative non-visual interaction with EQ. Research by De Pra et al. (2021) (HapticKnob) demonstrates the incorporation of haptic feedback that can imitate the sensation of the limited-range encoder by using resistive force feedback technology to create four different haptic feedback effects. Vibrotactile feedback is also integrated within hardware such as smartphones and computer trackpads to imitate the sense of a 'click' (Boréas Technologies, 2022). Similar technology could be used alongside DAWs specifically for knobs and faders in the future. At the same time, new devices can utilise affordable actuators, such as ERMs, and suggest adaptable configurations that will allow the device to be adaptable and usable in other use cases with minor alterations.

Voice-in-Design: Informed by participants' needs, design decisions can render voice feedback an indispensable and valuable element of hardware devices and users' workflows. Utilising voice feedback to indicate the functionality of encoders or sliders and hardware capabilities can be expanded, resulting in cost reduction as the same equipment can be mapped to multiple parameters. Apart from the functionality, voice feedback becomes crucial in situations when there is no tactile indication about the level of a specific parameter being accessed. In such cases, it serves as a vital means for users to gain essential information and interact with the hardware effectively. However, while voice feedback can be beneficial for providing initial indications, caution should be exercised when using it within scenarios that lack meaningful interpretation, as numerical representations may not hold significance for the user. Voice feedback should be easily tailored to the user's preference or dynamically and intelligently adapt to their specific needs. Optimising its utility, voice feedback should emulate the role of a sighted human assistant and intervene in the users' workflow only when necessary (e.g., providing alerts when sound peaks or other thresholds are exceeded).

3.5.2 Haptic Feedback: Integrating Vibrotactile feedback to DAW

According to the findings of the interviews with 19 BVI music producers, haptic feedback could be beneficial in nine areas of the DAW interface. These areas include *peak meter, editing, automation, effects, navigation, spectral, MIDI, spatial, and metronome* manipulations (Figure 3.2). Observing the participants' examples of design haptic feedback for DAW accessibility revealed three types of information that apply to different DAW functionalities: (1) *event notifications*, such as sound peaks or button states; (2) *graphical information*, such as waveforms or MIDI data; and (3) *ranges of numerical values*, such as automation lines or effect parameters. This understanding enables one to comprehend how barriers to accessibility for BVI music producers were created. DAWs adopted the graphical interfaces that visually represent faders and knobs found on analogue consoles in recording studios (Macchiusi, 2017). This is similar to how a computer's interface visually represents folders, files, and trash bins that exist in an actual office environment. BVI users are relying on music hardware technology, such as surface controllers, to replace the functions that were previously utilised in early music production processes within an analogue studio (e.g., audio effects, menu navigation, and automation). However, elements such as editing waveforms and MIDI arrangements were never physical. Thus, new opportunities were presented to create novel ways of conveying these graphical elements effectively to BVI users using haptic feedback. Moreover, the design of DAW interfaces should be reconsidered to provide alternative representations and interaction methods that do not rely solely on visual interaction.

Participants' insights provide clear guidance for shaping the system's functionality and seamless integration in their workflow. The essential considerations in this regard emphasise that the system should be (1) easy to integrate into the DAW and (2) flexible for customisation based on users' needs, perception levels and preferences. Furthermore, (3) the patterns should be easy to learn and should not introduce extra cognitive overload. Importantly, (4) the system should be conceived as a complementary component that works in parallel with voice feedback from screen readers rather than aiming to replace it. This approach acknowledges the potential synergy between the two systems, enhancing overall usability without compromising existing assistive technologies.

	Button States	**Alert and Notifications**	**Navigation/ Information/ Numbers**	**Continuous Values**
Haptic Icons	Buttons like solo/muted, armed/unarmed			
Tactons (any)		Sound peak, FX parameter thresholds, Button States	Buttons like solo/muted, armed/unarmed	
Rhythms			Numbers (e.g., navigation (track number), MIDI, FX parameters (Values)	Metronome
Spatial			Spatial, Editing, navigation	Automation
Compound Tactons (Spatiotemporal)			Numbers, complex info (spectral and editing, MIDI)	Spatial, parameters
Sensory Substitution (Audio-driven)		Sound peak	Editing, spectral	Automation
Tactile Stimulation				
Amplitude				Automation, parameters, spatial
Spatial				Automation, parameters, spatial

Table 3.3: Haptic Feedback Categories and Their Applications

3.5.3 Emerging Design Guidelines

DAWs are complex software with numerous, often inaccessible features, each demanding a unique strategy of mapping with vibrotactile feedback to convey their meaning. For example, in typical user interfaces, the state of buttons like armed/unarmed or solo/-muted buttons, are recognised by sighted users through skeuomorphic representations that incorporate visual cues, like button shapes and colours. The existing design methods presented in Chapter 2, section 2.6, can be used to facilitate an accurate representation of information with vibrotactile feedback. This section presents the emerging design mapping of participants' suggestions and the existing vibration design methods (Table 3.3) generated by utilising the interviews' analysis findings (Section 3.3.3 Theme 3 'Participants' suggestions on haptic feedback for enhancing DAW functions accessibility and workflow efficiency'.) *Haptic Icons* (Hoggan et al., 2009; Giordano et al., 2018) can convey the tactile sensation of a button pressed down (i.e., enabling an action) and pressed up (i.e., disabling the action) (Koskinen et al., 2008), which can be used in the interaction with buttons such as solo/unsolo, muted/unmuted. *Tactons*, using more abstractive combinations, can convey additional information about buttons, for example, using rhythm and location to represent the state of the button and the functionality; for example, a rhythm on the right of two quick vibrations can be linked to a solo and one long vibration un-solo, but the same rhythm in the left can be a different button like mute.

The exploration of translating numbers, such as those found in navigating audio tracks and FX parameters, to haptic feedback has received considerable attention in the literature. Various approaches have been proposed, all falling under the umbrella of Tactons or Haptic Language, mainly utilising a combination of rhythmic patterns and spatial allocation. One noteworthy case involves using Morse code in the form of vibration and applying it to letter recognition (Plaisier et al., 2020).

Continuous values, such as automation lines or value changes during interaction, can be represented using variations of vibration amplitude or location. A common method for mapping sound parameters to vibration frequency, amplitude, or timbre is to use audio-driven vibrations (Birnbaum and Wanderley, 2007; Remache-Vinueza et al., 2021). For example, Egloff et al. (2018) maps the frequency of the sound to the frequency of the vibration to convey a musical interval. Merchel et al. (2012) mapped both spectral information and rhythm to convey information about the type of audio material (e.g., percussive).

An alternative way is to map the numerical values directly to vibration properties that surpass the audio information. This method is expressed as Tactile Stimulation, the

design of complex spatiotemporal vibrations, similar to Magnitude Tactons (Wittchen et al., 2022), which do not need to be memorised but can still provide meaningful information. This method aims to transfer the information as it is perceived in the physical world, like the movement of a motorised fan, to the digital world. An example of this is presented in Michailidis and Bullock (2011), where haptic feedback is used to enhance music performers' gestures that control live electronic effects. While these can convey nuanced information, further research is required to determine the optimal method for presenting this information to individuals with visual impairments using DAWs.

3.6 Limitations

The main method of data collection was through an online interview process. While online interviews offer the advantage of reaching a broader range of participants across diverse locations, extending the scope of findings beyond local boundaries, they also present technical challenges. Achieving equally deep engagement with participant as with in person interviews proved to be a challenge in this format. Technical limitations posed the main challenges; for example, gathering demonstration data was restricted due to difficulties in sharing screens to demonstrate music content. Nevertheless, new insights were collected from participants despite the technical challenges.

3.7 Conclusion

Findings from interviews with 19 participants who were blind and low-vision users of DAW at various levels of experience in music production helped answer the first research question by contributing to the investigation of the BVI people's requirements for building a tool that enhances the DAW accessibility with vibrotactile feedback. Their insights were centred around their DAW workflow while utilising external hardware devices such as Native Instruments Komplete Kontrol, Behringer X Touch, and Softube Consol 1. Through rigorous thematic analysis of the interviews, three main thematic groups were identified that express the key elements affecting the use of hardware technology and the future design of haptic technology to support DAW accessibility. The first thematic group is related to the technical specifications, encompassing aspects such as the design of the current hardware devices and a comparison between newer offerings, such as Komplete Kontrol, and older analogue equipment, all examined through the lens of their tactile affordances and usability in the workflows. The second group revolves around usability issues, including the configuration of hardware with other systems and the economic affordability of these devices. The third thematic group addresses the participants'

needs but also presents ideas for future tools and alternatives to voice feedback within the DAW environment. This included the use of vibrotactile feedback for receiving notifications (e.g., peak meter), accessing graphical information (e.g., automation lines), and enhancing interaction with numerical ranges (e.g., FX parameters).

Interviewing BVI music producers during this research phase enriched the list of requirements for the new accessibility system for music production. The chapter's findings recommend four ways in which hardware devices can benefit the efficiency of workflow for BVI people: (1) precision, (2) speed, (3) tactile accessibility, and (4) portability. Participants specifically suggested three key points that should be considered for future development of accessible music technology: (1) cost efficiency, (2) voice-in-design, and (3) haptic feedback. Although tools like control surfaces, grounded haptic devices, are offering clearly perceivable affordances regarding their tactile interaction possibilities, they are costly and hard to move to different places. Thus, a wearable, adaptable and robust device would be the most suitable for interacting with DAW through computer keyboard interaction (SR) in any possible environment (i.e., music studio or public space). Participants specifically highlight how vibrotactile feedback benefits their everyday lives and how it can be applied in DAWs as well. Combined with the literature review (Chapter 2, section 2.6), specific design guidelines emerged that map participants' ideas with design methods. The following Chapter 4 explores existing wearable vibrotactile feedback devices, focusing on body locations, motor arrangements, and their affordances. The aim is to identify the optimal design paradigm or a possible underexplored design that would be suitable for this research based on the requirements that emerged from these interviews.

Chapter 4

The Affordances of Body Locations for Wearable Vibrotactile Feedback: A Literature Review

4.1 Introduction

Previous chapters have indicated that wearable vibrotactile feedback devices have potential for enhancing the accessibility of DAWs, offering precise and rapid feedback, being compact and portable, and being non-intrusive. The review of literature and the insights from the interviews led to the emergence of two new sub-research questions with the purpose of revealing the most suitable design requirements for the device that will be used in this research:

1. What are the existing guidelines for designing a wearable device and vibrotactile feedback?
2. How do the affordances of body locations of wearable vibrotactile feedback devices influence their use cases and their designers' decisions, and
3. how can they inform the optimal wearable placement for keyboard interaction with computer and musical hardware devices for BVI users?

This literature review explores the research questions by identifying existing design guidelines (section 4.2.2) in the literature and examining current wearable vibrotactile feedback devices (both commercial and academic), focusing on the various body locations and

device designs, as well as the use cases to which they are linked. This analysis led to the identification and understanding of design trends in wearable devices and how design decisions balance the use cases of these devices based on the embedded affordances of each body location where they can be used. Additionally, this analysis identifies wearables suitable for use with other tactile interactions (e.g., computer keyboards or musical instruments). It determines the most suitable ones for conveying information about music and providing opportunities for more inclusive musical interactions.

4.2 Related work

4.2.1 Understanding Affordances

Interaction with technology relies on the affordance that the respective mechanism offers. Norman (2013)'s affordance definition focuses on the potential action of an object as the user perceives it. This affordance is expanded by Benbunan-Fich (2017), including the role of the user, technology, and object in the process of designing affordances. This approach will help readers understand the design guidelines for wearable devices examined in this chapter and how designers can utilise this knowledge to create inclusive, usable devices. On the other hand, this chapter also utilises Hartson (2003) definitions of affordance, which break down into four complementary types: cognitive, physical, sensory and functional affordances. This approach facilitates understanding of the affordances available at each body location where a device is worn. This separation helps designers make better choices about the number and arrangement of motors based on the haptic feedback each body location affords. Therefore, different definitions of affordance are applied to cover both stages of designing a wearable device with vibrotactile feedback: the choice of the appropriate body location for the device and the design of the motor arrangement to provide the required feedback.

Hartson (2003) provides the following definitions: 'a cognitive affordance is a design feature that helps, aid, supports, facilitate, or enables thinking and/or knowing about something', 'a physical affordance is a design feature that helps, aids, supports, facilitate, or enables physically doing something', 'a sensory affordance is a design feature that helps, aids, supports, facilitates, or enables the use in sensing (e.g., seeing, hearing, feeling something', and 'a functional affordance is a design feature that helps users accomplish work (i.e., the usefulness of a system function)'. For wearable vibrotactile feedback devices, sensory affordance is central to the design process. The affordance here indicates that the body location where the wearable device is worn receives information, rather than the device's action opportunities. That informs the way the technology is

going to be used in the wearable, for example, the way vibration motors will be arranged and the information they will provide based on the arrangements. The different body locations of wearables provide devices with distinct affordances for users, utilising the physical and cognitive affordance so users understand what they are meant to do with the system (i.e., wear it to receive information) or what they are meant to understand (i.e., what a vibration stimulus means based on where it is felt on the body). This level of affordance also influences the choice of use case for each wearable device. Finally, functional affordance links body location directly to use-case suitability (i.e., the relationship between skin surface size and the complexity of the information displayed).

Benbunan-Fich (2017) examines the dynamics among the *Person* (i.e., user), the *Technology*, and the *Object* (i.e., device), providing useful suggestions on how to design a device given the constraints of wearability and the passive feedback information it provides through vibrations. The *Person-Technology* relation forms the *'handling affordance'*, which is based on the technology's capabilities and how designers can use them to serve the user's needs. At the same time, it shapes how the device is worn, perceived, and incorporated into users' interactions with the world. The *Technology* with the *Object* also forms the affordance of *'effector'*, which relies on the possibilities the technology gives to the object. How technology can enhance and repurpose the use of objects like sensors or motors in wearable devices, such as jackets and wristbands. In the case of wearables, the embodiment of technology unifies technology and object, creating the self-effector affordance, which is driven by the motivational needs of the user (Benbunan-Fich, 2017). This paradigm showcases designing for users' needs, creating tools that can become an extension of the self and enhance their role of agency. This form of affordance entangles the roles of technology, the object, and the user, enabling a personalised form of engagement, something which is required in inclusive design (Figure 4.1).

4.2.2 Design Guidelines and their Affordances

Wearable devices are the most suitable haptic devices for tasks that include interaction with the physical world (e.g., computer keyboard interaction or playing a musical instrument) (Bermejo and Hui, 2021). Haptic feedback embedded in wearable devices benefits the user by reducing the need for visual cues to perceive information, especially in cutaneous feedback (e.g., vibrations) (Vlam et al., 2023). Additionally, they can be socially acceptable (Bermejo and Hui, 2021; Zeagler, 2017) in resembling garments and fashion accessories. Many commercial devices showcase how wearable technology is inclusive by providing assistive applications and enabling social inclusion to people with disabilities without being specifically labelled as assistive technology (Moon et al., 2019)

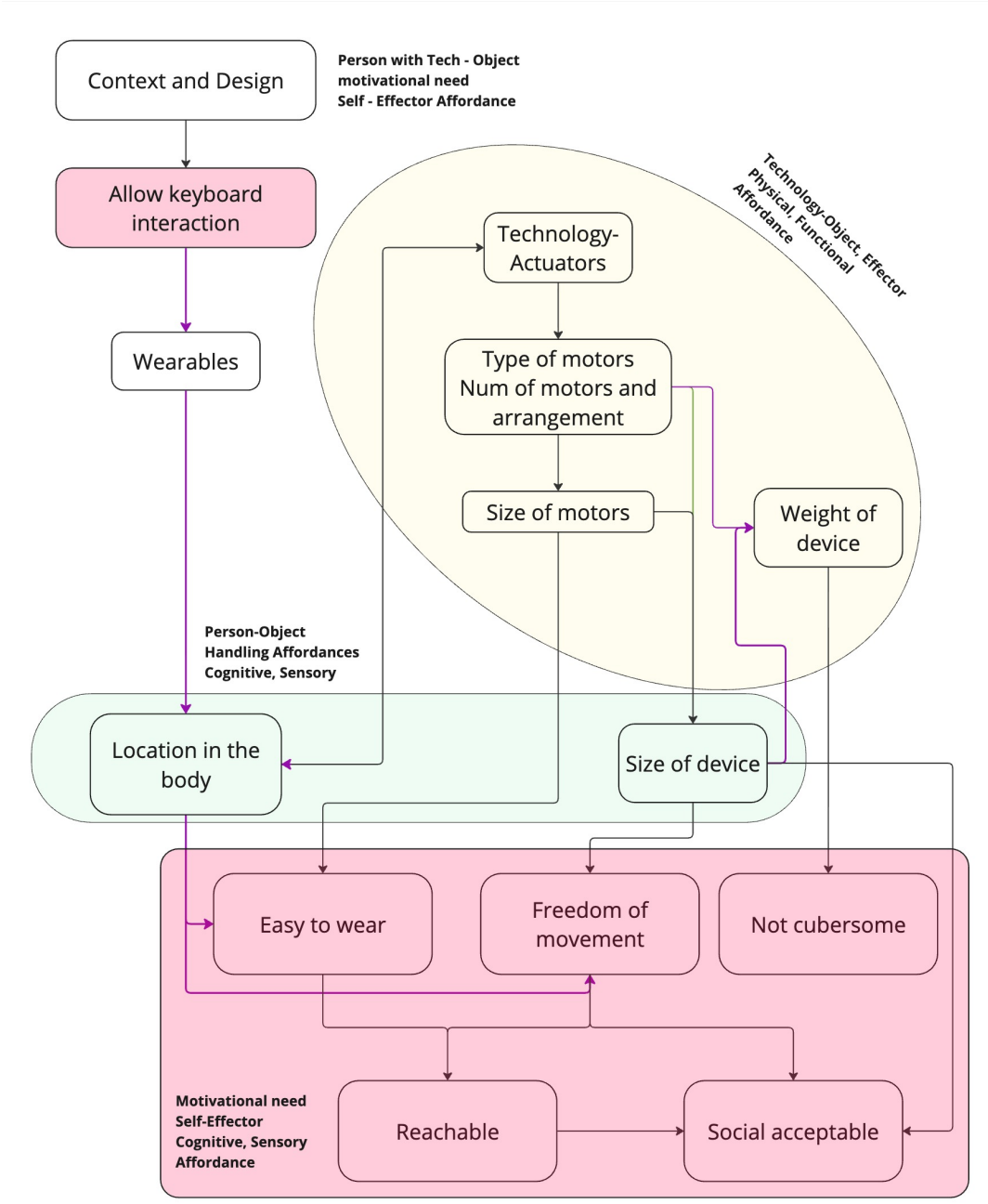


Figure 4.1: Diagram of Affordances

(e.g., smartwatches vs. braille displays).

Studies from Pacchierotti et al. (2017), Bermejo and Hui (2021), and Zeagler (2017) provide guidelines for designing a device that fits the above description. These guidelines are concentrated into three interdependent categories: (1) the technology used, (2) the location worn, and (3) the design based on the use case. Regarding the technology, the choice of actuators significantly influences the wearability and usability of the device. There is a great variety of actuators that are small, lightweight, and compact (section 2.5.2). The weight of the device, which depends on the actuator and other overall design elements, must be suitable for the location where the device is placed to avoid discomfort. While humans have a specific perception of their body size to navigate and avoid obstacles successfully, according to Zeagler (2017), the device size should not exceed the user's perceived size of themselves. Thus, the size of a device should be considered in relation to the self-perception of the size of the different parts of the body. Such characteristics facilitate the usability of a device, making it easy to wear, not cumbersome, allowing freedom of movement, and often cost-efficient (Vlam et al., 2023; Bermejo and Hui, 2021).

The choice of the location of the wearable device also depends on the skin's mechanoreceptors, which are responsible for the perception of vibrotactile feedback but also rely on the age of the user, frequency of vibrations, and the underlying tissue where the motor is positioned (e.g., fat, bone, muscle, temperature) (Sziebig et al., 2009; Dementyev et al., 2021) (section 2.5.1). Further studies confirm the role of the different body parts' sensitivity in the frequency of the vibration (Sonza et al., 2015) and the magnitude (Quick et al., 2022), highlighting the interlink between human body limits and needs, and the technology capabilities and limitations. Consequently, it is crucial to consider the explicit positioning of the actuators in the specific body part. When more than one motor is used, the just-noticeable difference regarding the distance of the motors, as well as the vibration propagation in the skin, needs to be considered to assess the arrangement of the motors (Shah et al., 2019). Matscheko et al. (2010) suggests that, ultimately, the placement depends on the 'skin surface' that is available and appropriate to use.

Considering the social acceptance of the device and the aesthetic of the design, Dementyev et al. (2021) and Zeagler (2017) suggest upper body locations such as the head, hands, waist and chest as the most accessible and acceptable locations for wearable technology. Social acceptance is linked to the device's use case. For example, the *Hampti-met* (Lordianto et al., 2024) presents the integration of vibrotactile feedback in a hamlet for the safety of roadway workers and is tested in a VR scenario. The *'Keep your Distance'* vest (Gay et al., 2020) presents a garment which provides directional

information through vibrotactile feedback in the waist and shoulders, improving navigation and social presence of people with deafblindness. The *MHWA* (Musical Haptic Wearable for the Audience) (Turchet and Barthet, 2019) is an arm-worn band that aims to convey musicians' gestures to the audience via haptic feedback. Those examples, although diverse in design and purpose, showcase a considerable design and the link between the design and the intended affordances. According to Benbunan-Fich (2017), the affordances of wearable technology depend on the user's level of embodiment of the device. Therefore, the affordance of the device is influenced by both the user's body and the device's impact on it (i.e., sensory affordance). This leads to the *self-effector* affordance, which is based on the user's motivational needs. These motivational needs are expressed in the social acceptance guidelines, which aim to cover the psychological, social, cognitive, and emotional needs of the user.

4.2.3 Existing Reviews

Existing reviews have explored haptic feedback devices by focusing on various characteristics, such as their wearability, the technology used, and the context of use. Adilkhanov et al. (2022) provided a review of haptic devices focusing on their level of wearability. The review includes a taxonomy of devices based on the type of haptic feedback, including both kinesthetic and cutaneous feedback, and the location where they are worn, such as fingers, hands, and the waist. Similar to this review, Culbertson et al. (2018) also presents devices based on whether they are grounded, graspable or wearable. This review, unlike Adilkhanov et al. (2022), focuses more on the type of feedback and the kind of haptic sensation that can be provided to the user. Pacchierotti et al. (2017) focuses the review on finger and hand-worn devices only. The taxonomy is based on the design's challenges and considerations, including tactile interaction, technology, and location. The end of this review provides a series of suggested guidelines for consideration in designing wearable devices. Other studies are more targeted in one specific type of wearable design, such as those in Wang et al. (2019) and Perret and Vander Poorten (2018). Both reviews are focused on gloves, particularly their use in virtual environments. Remache-Vinueza et al. (2021) examines a specific topic of devices for musical expression. Both grounded devices and surface displays are included, but there is also an extensive review of wearable devices named 'haptic music player-wearable devices'.

This chapter reviews wearable devices with vibrotactile feedback from the perspective of the affordances of the different body parts. These affordances explain the rationale of the design choices of wearable technology, such as the number of motors and their arrangement, and the respective use cases. Identifying design patterns will facilitate informed design decisions for a wearable device that enhances accessibility to music

production software.

4.3 Methodology

To conduct this review, publications were compiled by searching various databases, including Google Scholar, IEEE Xplore, ACM Digital Library, Springer, and ScienceDirect. The keywords used for this search were 'wearable haptic devices', 'vibrotactile feedback devices', 'wearable vibration feedback', and 'vibrotactile feedback display'. These words were searched for in the title, abstract, and beginning of the document. The inclusion and exclusion criteria are presented in the following lists. Accepted papers fulfil at least one inclusion criterion and are rejected if they follow any exclusion criteria.

Inclusion criteria

1. Devices that examine design and usability testing of wearable vibrotactile feedback devices.
2. Devices that are only designed to offer cutaneous feedback.
3. Devices that are suitable to be used with other tactile interactions, such as keyboard interaction.

Exclusion criteria

1. Devices that combine multiple haptic feedback, for example, vibration and pneumatic.
2. Multimodal devices, for example, include wearable sensors that control the interaction and feedback.
3. Devices that offer kinaesthetic feedback.

While this review aims to identify the most suitable location for the wearable device with vibrotactile feedback for the accessibility of DAWs, the guidelines from Adilkhanov et al. (2022), Pacchierotti et al. (2017) and Bermejo and Hui (2021), as summarised in 4.2.2, contributed to the selection of exclusion criteria by defining key design factors that influence the usability and practicality of wearable haptic devices. Therefore, the review includes wearable devices that (1) enable interaction with the physical world, (2) are socially acceptable and consequently are easy to wear, are not cumbersome (lightweight and small), and allow freedom of movement. Devices that offer kinesthetic feedback typically rely on force feedback technologies and require the use of servo motors, which are larger in size and weight. This type of technology is characterised as exoskeletons

or grounded to the body, and they do not comply with the goals of wearable technology (Adilkhanov et al., 2022). Some examples of these devices aim to control the movement of the fingers, preventing them from interacting freely with the physical world (Choi et al., 2016). Other studies suggest that haptic feedback and other sensors can be used for stand-alone applications. Although these devices serve a different concept, adding these sensors increases the weight and size of the device; for example, Horvath et al. (2014) features a mounted camera on the device. Lastly, devices that combine many types of haptic feedback technologies were excluded, such as pneumatic and vibrotactile (Zhu et al., 2020), force feedback and vibrotactile (Huang et al., 2017), and thermal and vibration feedback (Gabardi et al., 2018). Although these studies have promising results and valuable contributions, they do not align with the purpose of this research; thus, they were excluded from this review.

4.4 Results

Although the human body offers a wide range of potential placements for a wearable device with vibrotactile feedback, not all locations provide usability and comfort to the user, depending on the context in which they are used. This review explores the location placement based on the use case and how this enables the best user experience. The devices identified in the literature will be reviewed by location and their intended use. The categories that emerged were: (1) Torso, (2) Head and Neck, (3) Legs and Feet, (4) Multiple Locations, (5) Hands, and (6) Arms. Arm-based devices will be presented with an extensive review, as they have already been identified as having more potential for usability and alignment for this research context.

4.4.1 Torso

The torso, which consists of the main body of a human, includes locations such as the waist, chest, back and abdomen that are suitable for applying vibrotactile feedback (Figure 4.2). These locations enable freedom of movement, and they are sensitive to vibration feedback. Designers can take advantage of the larger space provided in this body part and suggest devices that enable high-resolution haptic displays to convey concrete and detailed information. Many commercial applications utilise this area of the body to create devices that convey haptic feedback for virtual environments (VEs), gaming experiences, or augmenting music experiences. Such examples are: the bHaptics (2025), Actronika (2025), OWO (2025), Woojer (2025), Feelbelt (2025), SUBPAC (2025), Not Impossible Labs (2025), Feelspace (2025), Strap Tech (2025). These devices demonstrate the variety of locations in the Torso and the application of vibration

motors, including the number and arrangement of them. The purpose of their use and the resolution of the information they can provide are based on the affordances of their design. For example, the bHaptic vest consists of 40 motors that can be controlled by location, frequency and amplitude. Due to their extended skin coverage, this device can convey a variety of information, from tactile sensations, such as the feel of rain or air, to concrete information, such as spatiotemporal patterns and sound, through audio-driven vibrations. Other devices, such as the Woojer belt or the SubPac, which features only one tactile transducer, are more limited in conveying more generic information through audio-driven vibrations.

Studies focused on music experiences use designs where the motor's placement varied from one specific area to the whole torso. For example, Yamazaki et al. (2017) uses two motors to produce stronger vibrations, acting as one in a belt-like device to enhance the listening experience of music and low-frequency sounds. Richards et al. (2022) utilise nine voice coil actuators distributed across bone-conductive locations to expand the possibilities for perceiving vibration information, similar to the hearing-timpani, for individuals with hearing loss. Studies that aim to convey concrete information using spatiotemporal patterns utilise different arrangements and more vibration motors. The most common location in this case is the waist. For instance, Barralon et al. (2007) suggests a belt-like device with eight actuators placed around the waist to provide medical professionals with information about patients and their medical state. Hoggan and Brewster (2007a) used three actuators placed in the waist in a belt-like wearable to convey mobile device messages (type of message, urgency, and sender), and Mortimer et al. (2020) used 16 motors in two arrays of 8 around the waist to convey haptic cues for movement training. Theil et al. (2020) proposed 16 motors in a 4x4 grid in the back in the form of a vest for conveying text and speech via tactile signs to deafblind people. Schumacher et al. (2013) utilised two motors located at the back (one on the right and one on the left) to convey information to musicians about their performance using interactive electronic systems. Directional cues also fall into the category of concrete information, but they utilise, especially, the spatial arrangement of a greater number of motors to convey the coordinates. For example, Gay et al. (2020) suggests the use of a belt under the chest with five motors in the front part of the body, and Pielot and Boll (2010) suggests the use of a 12-motor belt around the waist to convey information related to navigation tasks. Boer et al. (2017), Vallgårda et al. (2017) highlight the flexibility of the torso design through an artistic endeavour that presents a haptic composition. The placement of the three vibration actuators is in the form of three different belts that accommodate cylindrical cases for the actuators, and they are worn across the body in various locations (e.g., under the shoulder, chest, and lower in the abdomen). Finally,

among the designs, there are examples of the use of the waist as a location to facilitate direction specifically for blind and visually impaired users (Cosgun et al., 2014; Gay et al., 2020).

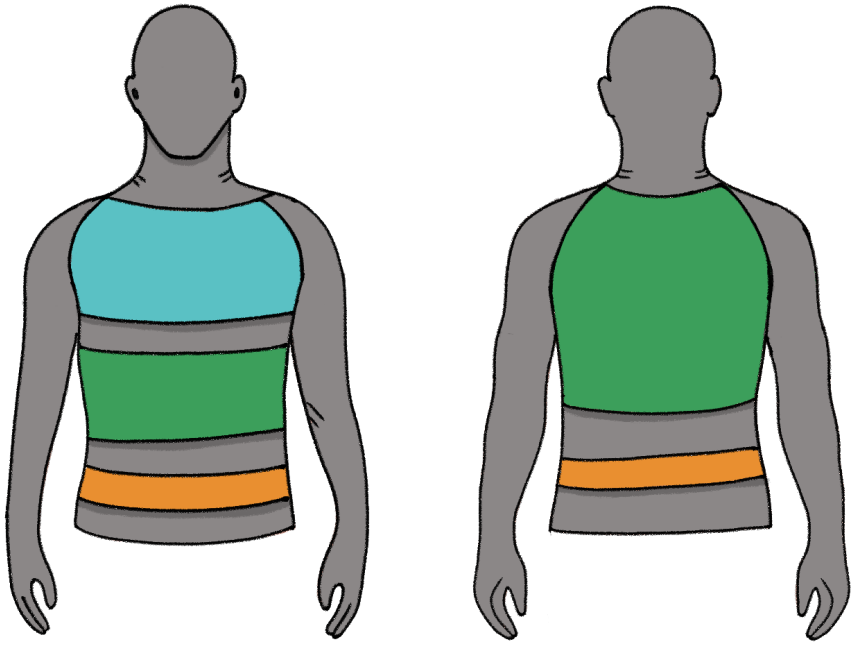


Figure 4.2: Areas of the Torso where vibration feedback has been applied. Blue: chest, Orange: waist, Green: back and abdomen

Device	Location/Num of Motors	Use case
Barralon et al. (2007)	Around waist/8	Information/ Medical
Hoggan and Brewster (2007a)	Front waist/3	Information /Mobile device /Communication
Pielot and Boll (2010)	around waist/12	direction
Schumacher et al. (2013)	Back /2	Music performance information
Vallgårda et al. (2017)	Chest and abdomen/3	Artistic experience
Yamazaki et al. (2016)	Chest/2	Music experience

Yamazaki et al. (2017)	Chest/2	Music experience
Gay et al. (2020)	Abdomen/5	Direction/ Accessibility (BVI)
Cosgun et al. (2014)	Around waist/8	Direction/ Accessibility (BVI)
Mortimer et al. (2020)	Around the waist/16	Information/ Teleoperation
Richards et al. (2022)	Front of torso/9	Music experience/ Accessibility (DHH)
Theil et al. (2020)	Back/16	Communication/ Accessibility (Deafblind)

Table 4.1: Torso devices

Summary/Analysis

The most common areas for placing vibrotactile feedback on the Torso are around the waist (7), the back (1), and the front under the chest or lower in the abdomen (3). The wearable designs that host these placements are belts and vests. The large skin surface available enables the secure and clear transmission of information, which is tied to sensory affordance (Hartson, 2003). The arrangement of motors around the waist facilitates the clear indication of directions. This enables this location to be suitable for accessibility applications. The waist is the most popular among the identified studies, because it is easy to wear and does not hinder other activities with the body providing a clear physical affordance (Hartson, 2003). The waist, being the centre of the body, is also a secure and less tiresome location in which to carry the weight of the device. This is because it provides a stable balance point, reduces strain on other body parts, and allows better weight distribution (Zeagler, 2017).

Location: Waist, Back, Front under the chest

Type of wearable: Belt, Vest

Context of Use: Information, Directions, Accessibility

4.4.2 Head and Neck

The head is one of the least common locations for haptic feedback. Any hat-like device can become heavy and inconvenient for users over time. Commercial applications suggest using vibrotactile feedback in the form of a face cushion under the VR headset, as seen in the *TactVisor* by bHaptics and in the study by Valkov and Linsen (2019). This special case already hinders comfort as the user wears the often heavy and tiresome VR headset. However, some cases that suggest the use of vibration in hats (e.g., hamlets) are appropriate based on the context in which they are used. For example, Lordianto et al. (2024) utilised five motors, four positioned around the head and one on top, to convey alert notifications to roadway workers using spatiotemporal patterns. Kerdegari et al. (2016) suggests using an array of 12 motors inside the hamlet to assist navigation in low-vision environments, such as for firefighters in smoke-filled spaces. Kaul and Rohs (2017) used 24 motors placed in three concentric ellipses around the head for non-visual navigation in an indoor environment. Other studies suggest more minimalistic designs, such as headbands with vibration actuators to convey less complex information, such as direction in a 1D context (Kangas et al., 2017) or convey information in a VE environment (Yu et al., 2023).

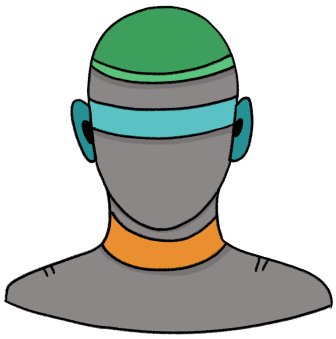


Figure 4.3: Locations in the head where vibration feedback has been applied. Green: Scalp, Blue: Face and Ears, Orange: Neck

Another commercial device introduces vibrations through the headphones. Razer Inc. (2025) with embedded haptic drivers in the earcups, aiming to enhance the sound experience in gaming, particularly by conveying location (left-right), improving spatial awareness, and providing accessibility to users with hearing loss. Although not part of the Head, studies also suggest using the neck as a placement for VTF. Schaack et al. (2019) and Matsuda et al. (2020) both suggest the use of this location for navigation tasks.

Device	Location/Motors	Use case
Kangas et al. (2017)	Forehead/6	Directions
Kaul and Rohs (2017)	Whole head/24	Directions/ VE/ Object avoidance /Non-visual interaction
Lordianto et al. (2024)	Whole head/5	Information/ Work safety
Valkov and Linsen (2019)	Face /8	Information VE/ Object avoidance
Yu et al. (2023)	Around the head/8-16	Information/ Sensations/ VE driving
Schaack et al. (2019)	Neck/4-6-8	Directions/ Eye-free navigation
Matsuda et al. (2020)	Neck/16	Directions/ Remote collaboration task
Kerdegari et al. (2016)	Whole head/12	Directions/ Navigation/ Non-visual interaction

Table 4.2: Head-worn devices

Summary/Analysis

The limited use of the head as a location for vibrotactile feedback display indicates the inconvenience and dysfunctionality of the location. The physical affordance of this location indicates that anything put in the head can be heavy and socially unacceptable (Hartson, 2003). The entire head, including the scalp, is used for directional tasks, primarily in VEs. Hats and motors placed around the head or on the entire scalp provide an opportunity for vibrotactile feedback to be utilised in cases outside of VE. Hat-like devices are suitable for alert-type feedback, which ensures easy and secure perception by the user, as well as for outdoor navigation. Face placement motors are tied to the use of a VR headset, so they do not apply to the established usability prerequisites. The neck provides a good location for navigation information; however, it can be inconvenient to the user. In the form of a collar or necklace, they can also be unstable in their skin attachment, which prevents the secure transmission of vibration patterns, highlighting a sensory affordance limitation.

Location: Scalp, Face, Neck

Type of wearable: Hat, Cushion, Neckless

Context of Use: Navigation, Virtual Environment

4.4.3 Leg and Feet

Although legs and feet are of very limited use in the context of wearable haptic technology, they present a variety of applications. In commercial applications, *Tactosy for Feet* by bHaptics (2025), featuring three motors on the top of the feet, offers a simulation of environmental interaction in VEs. Similar studies aim to convey information such as the texture of the walking surface (Turchet et al., 2010) or other virtual materials (e.g., elasticity or friction) (Strohmeier et al., 2020) using positioning actuators insoles. For directional cues, Meier et al. (2015) suggests placing the motor insole under the feet and in different prototypes around the feet on the wall of the shoe. Velázquez et al. (2009) also suggested the use of a motor insole under the foot, and Schirmer et al. (2015) used two motors on the sides of the right foot, both for a navigation use case.



Figure 4.4: Locations in the Legs and Feet where vibration feedback has been applied. Red: around and under the feet, Orange: ankle, Green: below the knee,

Using the rest of the space of the legs is more commonly used. In the navigation tasks, Magana and Zang (2024) proposed the use of an ankle; this design specifically aims not to hinder the use of a white cane by blind and visually impaired users. Studies also suggest the use of legs for conveying information related to language, notifications and alerts, especially when hands are occupied and the operations involve body movement. Alirezaee et al. (2020) suggested the placement of 3 motors on the ankle, knee, and hip for conveying information to physicians about a patient's vital status. Michailidis

and Berweck (2011) used two motors in the ankle and shin to assist musicians while performing by conveying the status of foot pedals.

Summary

The extensive and diverse skin surfaces of the legs provide multiple opportunities for the placement of feedback. Direction-type feedback is mostly used in shoes, either in the insole or around the foot, near the ankle. Insole location is also used to convey textural information, such as the ground texture in VE, enhancing realism. Locations higher than the ankle are used for conveying information, especially when users use their hands for other interactions, such as physicians. Despite the practicality of the hands-free character, feet do not provide enough skin surface for multiple motors. Indicated by physical affordance, adding more motors to the feet or legs might create a heavier device or one that hinders comfortable movement and walking. For this reason, not many devices are used for conveying complex information (i.e., language), but are limited to textural information or simple alerts.

Location: Under the feet, Around the feet, Ankle, Below the knee and combinations.

Type of wearable: Embedded in shoes, Sleeves

Context of Use: Texture, Directions

Device	Location/Motors	Use case
Trivedi et al. (2019)	Between knee and ankle.	Music experience/ Accessibility
Alirezaee et al. (2020)	Ankle, knee and hip/3	Information/ Medical
Magana and Zang (2024)	Ankle	Direction/ Assistive technology
Michailidis and Berweck (2011)	Ankle and shin/2	Information/ Music performance
Turchet et al. (2010)	Under foot, Insole/2	Texture
Strohmeier et al. (2020)	Under foot, Insole/1	Texture
Meier et al. (2015)	Under foot, Insole and around foot/12	Directions
Velázquez et al. (2009)	Under the foot, insole/	Directions
Schirmer et al. (2015)	Side of foot /2	Directions

Table 4.3: Leg-worn devices

4.4.4 Multiple Locations

Many studies suggest the use of multiple body locations for vibrotactile feedback placement. That means using 2 or 3 garments that complete a full-body haptic experience. This is common in commercial devices where the user is fully immersed in the virtual world. For example, a combination of haptic devices enables realism and immersion in the virtual world by combining multiple devices to build a full-body suit. That includes a vest, sleeves, and devices for the feet and face.

Existing literature has explored different combinations of body parts based on the context and the type of feedback. The most common combinations are (1) Torso and Hand, (2) Torso and Arms, (3) Torso and Legs, (4) Arms and Hands, (5) Arms, Hands and Legs, (6) Arms and Legs, and (7) Free to the user. The combination that includes the hands (e.g., fingers or palm) is most commonly used to convey coded information. For example, Egloff et al. (2018) combined the waist and fingers to convey information about melodic intervals. Another combination is the hand with arms - for instance, Luzhnica et al. (2016) suggests the use of fingers and across the forearm for language communication, Terenti and Vatavu (2024) utilises fingers, wrist and forearm for conveying tactile sensation when interacting with touchscreens, and Elvitigala et al. (2019) uses fingers and wrist to convey information that enhances non-visual interactions. Finally, Vo et al. (2023) combines hand, wrist and thigh to provide vibration information to pilots in the context of plane turbulence (i.e., the presence of mechanical vibrations).

When arms are combined with the torso, it is mainly used to convey body posture or directional cues. Rotella et al. (2012) uses the waist and arms, Islam et al. (2022) the waist, arms and legs, and Linden et al. (2011) the waist, upper arm and wrist for posture improvement in various contexts (i.e., movement training, yoga, music learning). Bayat et al. (2023) arrange motors around the waist and across the hand in the form of a belt and a glove to suggest a system that assists the visually impaired with object avoidance and navigation.

Finally, arms and legs showcase a practical use case for audience involvement in art installations (Hattwick et al., 2015) and for music performance interactions (Giordano et al., 2018). Music experiences have utilised devices on the torso, arms and legs (West et al., 2019) and Torso and arm alone (Hashizume et al., 2018).

Studies also suggest giving the user a free choice of the location of the motors; these

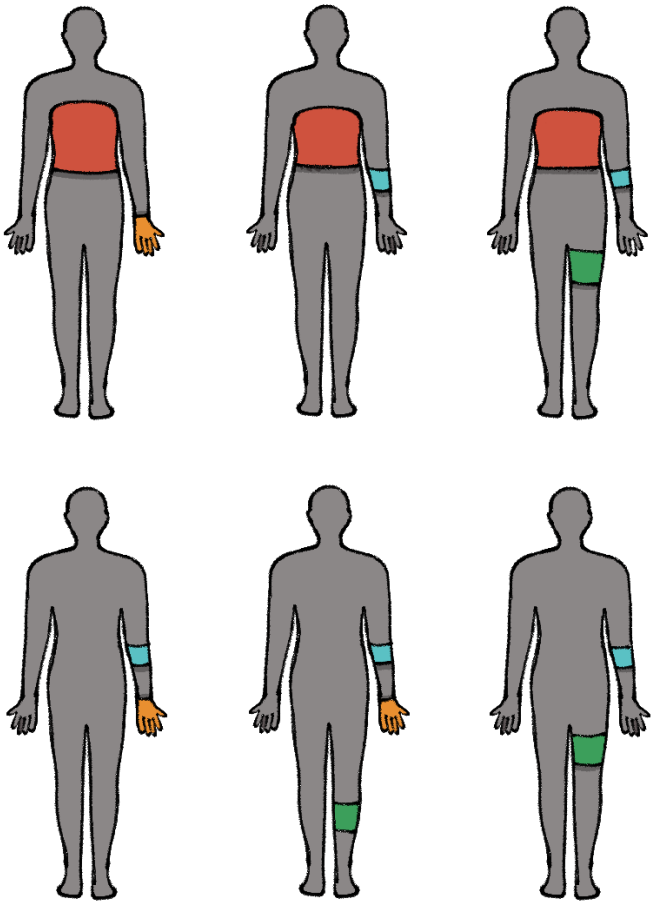


Figure 4.5: Multiple Location combinations where vibration feedback has been applied

cases are related to music experience (Hattwick et al., 2017), music experience and accessibility (Petry et al., 2016), and enhancing the XR experience (Najm et al., 2024).

Device	Location	Use Case
Egloff et al. (2018)	Torso and Hand (Waist and Finger)	Music Performance
Giordano et al. (2018)	Arms and Legs (free)	Music Performance
Hattwick et al. (2015), Hattwick et al. (2017)	Arms and Legs (free)	Arts/ Social Presence

Rotella et al. (2012)	Arms and Torso (waist and arm)	Posture
Bayat et al. (2023)	Arms and Torso (waist and arm)	Object avoidance
Linden et al. (2011)	Arms and Torso (waist, upper arm and wrist)	Posture/ music learning
Hashizume et al. (2018)	Arms and Torso (forearm, upper arm, front and back of torso)	Music experience
Islam et al. (2022)	Torso, arms and Legs	Posture (yoga)
West et al. (2019)	Torso, arms and Legs	Music Experience
Luzhnica et al. (2016)	Arms and Hands (finger and across forearm)	Information/ Language communication
Terenti and Vatavu (2024)	Arms and Hands (finger, wrist, forearm)	Touchscreen interaction
Elvitigala et al. (2019)	Arms and Hands (finger and wrist)	Information
Vo et al. (2023)	Arms, Hands and Legs (hand, wrist and thigh)	Information
Najm et al. (2024)	Free	Sensations/ Information/ XR
Petry et al. (2016)	Free	Music experience in XR

Table 4.4: Multiple location devices

Summary/Analysis

Combining multiple locations increases the skin surface available for motor placement and, consequently, the amount of information that can be transmitted as well as its complexity. Arms, in combination with legs or hands, are used for conveying information and are typically employed in artistic contexts, such as music performance or experience. They can be easily worn, coming in the form of straps and bands, and they are also not tiresome, which makes them particularly suitable for artistic settings. When one of the multiple locations is the torso, the information is relevant to movement guidance

for posture improvement. In this case, the devices are also minimalistic, like bands and belts. Unlike this, whole-body suits and jackets aim to convey more abstract information and sensations that augment the music or VR experience.

Location: Torso and Arm, Torso, Arms and Legs, Torso and Hand, Arms and Hands, Arms and Legs.

Type of wearable: Straps, body suits.

Context of Use: Information, Movement Guidance, Directions, Music, Immersive Experiences.

4.4.5 Hand-worn Devices

The hand is a common and effective area for placing haptic feedback. It can be divided into three distinct regions: the fingers, the palm, and the dorsum (back) of the hand. Finger-worn haptic devices, also known as 'Thimbles', are commonly used for interaction with the virtual world. A clear sensory affordance is presented in the high resolution of the fingers that enable detailed rendering of tactile feedback (Tran et al., 2023)(Hartson, 2003). The main affordance of such devices is to enable interaction with the virtual world by conveying sensations such as texture, interactions with user interface elements (e.g., pressing buttons), or simulating the sensation of touch to enhance the experience of interacting with objects.

The usability of these devices depends on their context of use. When they are used in virtual environments where there is no need to interact with the physical world, gloves that cover the entire hand are the most popular design. Among these devices, there is a significant variety in how the motors are arranged to deliver haptic feedback. For example, Jonatandsiuclmes et al. (2014) suggests a glove with two motors in each of the fingers and two in the palm, conveying the sense of physical touch of objects in the VEs, and Pabon et al. (2007) uses three motors in each finger for teleoperations and virtual social presence. Within the context of VR interaction, there are also more minimalist designs that aim to make the experience of the wearable device more pleasant and less cumbersome. Maereg et al. (2017) proposes placing motors in each of the five fingers, but in the form of five ring-like devices to convey stiffness. Lehtinen et al. (2012) suggests a glove with two motors in the palm and 2 in the dorsum that covers only that part of the hand and leaves the fingers exposed. This design is proposed for touchscreen interaction. Focused on virtual environment (VE) interactions, Preechayasomboon and Rombokas (2021) places motors on all five fingernails, while Maeda et al. (2022) and Normand et al. (2024) propose using a single motor on the index finger.

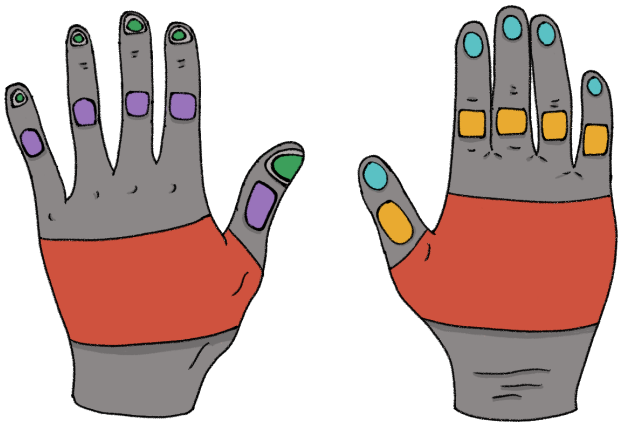


Figure 4.6: Hand locations where vibration feedback has been applied. Red: Dorsal, Palm, Blue: Fingerpads, Yellow and Purple: Finger Phalanx, Green: Finger Nails

Beyond the interaction in VEs, studies explore the location of the hand for conveying information to enhance music perception, especially in relation to accessibility. Sharp et al. (2019), Mazzoni (2018) examine the way to convey emotions of music through vibrotactile feedback. Specifically, Mazzoni (2018), Lucía et al. (2020), and Enriquez et al. (2020) are utilising vibrotactile feedback to enhance the accessibility of music for individuals who are deafblind. Other accessibility-centred studies are the 32 motors in the finger and palm by Gollner et al. (2012) for conveying information to DHH and a grid arrangement of 9 motors in the dorsal by Uchiyama et al. (2008) for giving directions to wheelchair users.

Studies such as Chauvette et al. (2024), Luzhnica and Veas (2019), and Park et al. (2018) demonstrate, regardless of motor placement, the potential of the hand in understanding haptic patterns that convey concrete information. Each of these examples places the motors on the middle phalanx of the dorsal side of the hand, unlike the previous example for VE interactions, where the motors were located in the fingerpad, suggesting a different approach where the fingers are free for other interactions with the physical world.

Device	Location/Motors	Use Case
Jonatandsiuclmes et al. (2014)	Fingerpads and palms (full-finger glove)/2	Phsycical Interaction in VE
Pabon et al. (2007)	Fingers (full-finger glove)/3	Telerobotics, rehabilitation, virtual social interaction
Maereg et al. (2017)	Fingers (rings)/5	Texture in VE
Lehtinen et al. (2012)	Dorsum and palm (fingerless glove)/4	Direction in touchscreen
Preechayasomboon and Rombokas (2021)	Fingernails (Epidermal device)/5	VE interactions
Maeda et al. (2022)	Index finger (ring)/1	VE interactions
Normand et al. (2024)	Index finger (ring)/1	AR texture
Sharp et al. (2019)	Fingers and palm (full-finger glove)/6	Music experience
Mazzoni (2018)	Dorsum and palm (fingerless glove)/8	Music experience/ Deaf accessibility
Lucía et al. (2020)	Fingers and palm (full-finger glove)/2	Music experience/ Accessibility (DHH)
Enriquez et al. (2020)	Fingers (full-finger glove)/5	Music experience/ Accessibility (DHH)
Gollner et al. (2012)	Finger and palm (full-finger glove)/32	Accessibility (DHH)
Uchiyama et al. (2008)	Dorsal (full-finger glove)/9	Directions for wheelchair users
Chauvette et al. (2024)	Finger (middle phalanx on the dorsal side - full-finger gloves)/5	Information
Luzhnica and Veas (2019)	Finger (middle phalanx on the dorsal side -fingerless glove)/5	Information

Park et al. (2018)	Finger (middle phalanx on the dorsal side - rings)/4	Information

Table 4.5: Hand-worn devices

Summary/Analysis

The hand is used predominantly for enhancing tactile interactions with the virtual world, such as conveying tactile sensations, touching an object in a VE or feeling texture in a touchscreen. Depending on the context, cases were distinguished between full-finger and fingerless gloves. Touchscreen interaction demands a fingerless glove design or ring-like device, allowing the fingerpads to interact with the screen. In this case, the motors are placed mostly in the dorsal part of the finger (phalanx). On the other hand, when using VR scenarios, haptics are employed to simulate the sense of touching an object or understanding texture, making motor placement in fingerpads necessary. Fingerpads are highly sensitive locations; thus, they can perceive complicated information and have a dense arrangement of motors. Gloves, regardless of the motor placement (fingers, dorsal, palms), are easy to wear and not cumbersome; in combination with their high resolution of information, they can support a better music experience, especially for people who are Deaf or Hard of Hearing (DHH).

Location: Dorsal, Palm, Fingerpads, Finger Phalanx, Finger Nails, Fingerpads and Palm, Finger Phalanx and Palms, Dorsal and Palm.

Type of wearable: Full-finger Gloves, Fingerless Gloves, Rings

Context of Use: Sensations, Texture, Music, VEs, Accessibility, Digital Surface interaction

4.4.6 Arm

Arm-worn devices are known for their usability. They are hands-free, allowing for flexible interaction with both the physical and virtual worlds (Adilkhanov et al., 2022). Although the resolution of the haptic perception is not as high as in the hands (fingers, palm, dorsal) (Meier et al., 2015), the practicality of the location that provides social acceptance through its wearability level, which is not bulky and heavy, ensures convenience and comfort to the user and makes this location popular for commercial applications (Pezent et al., 2022a). Various smartwatches and smart bracelets are available on the market, providing users with meaningful information through spatiotemporal patterns. Some

examples include the Apple Watch (Apple Inc., 2025), Samsung Galaxy Fit (Samsung Electronics, 2025), Garmin Vivosmart (Garmin Ltd., 2025), Xiaomi Mi Band (Xiaomi Inc., 2025), and Fitbit Charge (Fitbit, 2025), which are used as wearable devices for smartphone notifications and tracking fitness activities. Other devices, such as the Embrace Plus (Empatica Inc., 2025), focus solely on measuring physiological data and assist users by sending notifications and alerts, as seen with the Whoop Strap WHOOP Inc. (2025) and Touchpoints (The TouchPoint Solution, 2025). Other applications of such devices enable remote communication and social presence, like the Bond Touch (Bond Touch, 2025). Lastly, Lofelt Basslet (Lofelt GmbH, 2025) suggests a wearable subwoofer for enhancing the music experience. These examples primarily utilise wrist devices to convey notifications and alerts. However, commercial products also showcase the potential to convey more advanced types of information. An example is the bHaptics TactSleeve (bHaptics, 2025), which is worn on the forearm and features two motors, used in gaming experiences to enhance realism.

Academic studies showcase how the different locations of the arms can accommodate various arrangements and a number of motors, and consequently different types of information. These three elements are interlinked and influence the design. Among those locations are the wrist, forearm, and upper arm. The larger the skin area available under the device, the more possibilities there are for motor arrangement.

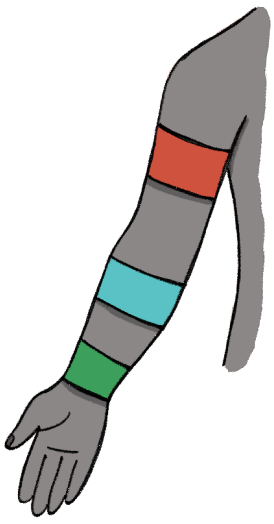


Figure 4.7: Arm locations where vibration feedback has been applied. Green: wrist, Blue: Forearm, Red: Upper Arm

For example, **wristbands** are most popular for containing only one motor, such as commercial devices. The most popular use cases are to convey information, enhance the music experience, and provide accessibility. Jain et al. (2020) and Goodman et al. (2020) suggest the use of one motor wristband for conveying environmental sounds and La Versa et al. (2014) music intensity information to people who are DHH. Melder and Savery (2024) aims to enhance the music experience by conveying information in a way that matches the tempo of the music. Choi and Ishii (2020) utilise rhythmic vibrations to help users regulate their heartbeat rate. Schneider and MacLean (2016) and Wang et al. (2016) explore the mapping of vibrations to information such as visual icons and mobile applications (also represented by icons).

When more motors are present, a greater variety of use cases is observed. Devices with three motors around the wrist primarily convey concrete information with more complex spatiotemporal patterns, utilising the properties of the individual motors and the opportunities afforded by their spatial arrangement. For example, the following studies are using three motors around the wrist. Cœugnet et al. (2017) aims to assist elderly people crossing the road by providing relative haptic alerts that help them avoid car collisions. Scheggi et al. (2014) presents a robot-assisted navigation system and vibrotactile feedback that conveys the robot's navigation guidance. Carcedo et al. (2016) explored the translation of colour to vibration patterns for people with colour blindness.

Devices with four motors are most commonly used for navigation tasks. The four motors positioned around the hand correspond to the four cardinal directions, improving both the device's functionality and user intuitiveness, such as in Dobbelstein et al. (2016), Dupont et al. (2020), Bahrin et al. (2023), and Hong et al. (2017). Other applications utilised the number of motors for their endless pattern compositions to convey complex messages. Matscheko et al. (2010) and Wang et al. (2019) use four motors, and Chase et al. (2021) and Pezent et al. (2022b) use six motors around the wrist to explore the learnability and understanding of vibrotactile information. Also, while using six motors around the wrist Luces et al. (2019) and Salazar et al. (2018) examine the directional guidance of the hand in digital space, and Schätzle et al. (2019) explores the opportunities of directional guidance in physical space for BVI users.

Motors around the **forearm** are less commonly explored but offer valuable insights. Examples include Bimbo et al. (2017), which utilises four motors to guide movement during teleoperation tasks, Perrotta et al. (2021) for conveying sound properties to DHH, and Reinschluessel et al. (2018) and Rossa et al. (2016), which both employ eight motors to guide physicians in needle-based procedures. While forearms provide a larger surface area, alternative arrangements, such as motor grids, unlock new possibilities.

Studies by Zhao et al. (2020) and Vlam et al. (2023) investigate 2x2 grid configurations, focusing specifically on the perception of vibration localisation within this setup. In Ma et al. (2019), a 2x3 grid is placed on the forearm, supporting navigation tasks for automated vehicle drivers, Lee and In (2023) for blind and visually impaired users, and Tang et al. (2020) a 2x4 grid for general navigation tasks. Hong et al. (2024) suggests a sleeve with eight motors placed in a grid of 2x4 and another four around the top of the forearm to convey the sensation of tactile stroke illusion in spacecraft robotic arm teleoperation. Examples of more motors include Lin et al. (2024) (16-motors), Sabry and El-Atabany (2024) (18-motors), Reed et al. (2019) (24-motors), with grids that cover the entire forearm, demonstrating numerous opportunities for haptic feedback in the hand, mainly focused on conveying haptic sensations and more abstract feedback. Lastly, some studies suggest an array of motors, as in Brown et al. (2006a), with three motors for investigating the spatiotemporal pattern perception limits, and Savindu et al. (2017), which uses six motors in the form of two arrays of three to convey braille patterns through haptic feedback for BVI users.

The **upper arm** is utilised as a location in combination with other locations in the body (as seen in the previous section) or as a combination of the two arms with a limited number of motors. That derives from the unpredictable level of perception, which is based on the physiology of the arm under the skin (fat or muscle) (Sziebig et al., 2009) as well as the size of the circumference of the arm (Carcedo et al., 2016). Turchet and Barthet (2019), turchet2021musical use two motors in each upper arm to convey information about music performance. Stratmann et al. (2018) uses three vibration motors in each arm to convey directional cues for navigation tasks. Cobus et al. (2018) suggests the use of three motors in an array in the upper arm for conveying information about the vital state of the patient to the medical professionals. Other studies include the combination of the upper arm with the forearm, as seen in Michailidis and Bullock (2011), which utilises three motors across the entire arm to convey information for music performance gestures.

Summary/Analysis

The arm is separated into three locations: wrist, forearm, and upper arm, with an ascending circumference, which provides a larger skin surface. However, the skin surface is not the only variable that determines the number of motors and their placement, while the underlying tissues (i.e., fat, muscle, bone) also influence the perception of vibrations. For that reason, the Upper Arm is not the most popular location as it is the place with the most variety in physicality. For example, one can have a large circumference in the upper arm, which is ideal for placing more motors around it; however, if there is fat or

muscle under the skin, that will influence the level of perception. Most studies in the upper arm use a small number of motors in an array arrangement, ensuring the accurate transmission of information. Wristbands are the easiest to wear, comfortable and allow freedom of movement. However, due to the small skin surface, it cannot rely on the number of motors for the information it provides unless expensive motors are used. Four motors help with navigation tasks and respond to coordinates. This location is ideal for communicating notifications and information, enhancing accessibility, music, and other digital interactions. The forearm, on the other hand, has a similar level of usability as wristbands but offers a slightly bigger circumference, which allows for the placement of more motors in more diverse arrangements. Studies have used up to 24 motors around the forearm. The more motors present, the more abstract the haptic patterns become, which are primarily used to convey sensations, guide movement, and convey complex information.

Location: Wrist, Forearm, Upper Arm.

Type of wearable: Arm-bands

Context of Use: Information, Directions, Movement Guidance, Music, Accessibility, Alerts.

Body Area	1	2	3	4	6	8	>10
Wrist							
around	Jain et al. (2020)(A)		Cœugnet et al. (2017)(A+I)	Dobbelstein et al. (2016) (D)	Chase et al. (2021) (I)		
	Goodman et al. (2020) (A)		Scheggi et al. (2014) (D)	Dupont et al. (2020) (D)	Pezent et al. (2022a) (I)		
	Melder and Savery (2024) (M)		Carcedo et al. (2016) (I+A)	Bahrin et al. (2023) (D)	Luces et al. (2019) (D)		
	Choi and Ishii (2020) (T)			Hoggan and Brewster (2007a) (D)	Salazar et al. (2018) (D)		
	Schneider and MacLean (2016) (I)				Schätzle et al. (2019) (D+A)		
	Wang et al. (2016) (I)						
	La Versa et al. (2014) (M)						
grid				Matscheko et al. (2010)			
			Wang et al. (2019) (I)				
Forearm							
around				Bimbo et al. (2017) (D)		Reinschluessel et al. (2018) (S)	
grid				Zhao et al. (2020) (D)	Ma et al. (2019) (D)	Rossa et al. (2016)	Lin et al. (2024) (S)
				Vlam et al. (2023) (D)	Savindu et al. (2017) (A)	Hong et al. (2024) (S)	Sabry and El-Atabany (2024) (S)
						Tang et al. (2020) (S)	Reed et al. (2019) (S)
array			Brown et al. (2006a) (I)				
Upper Arm							
around		Turchet et al. (2010) (I)					
		Weber et al. (2011) (D)					
array		Cobus et al. (2018) (I)					
Wrist, Forearm, Upper Arm		Michailidis and Bullock (2011) (I)					

4.5 Discussion

This literature review examined wearable devices equipped with vibrotactile feedback that enable interaction with the physical world. The analysis focused on the body location where the device is worn, with the aim of identifying the affordance of the different body parts when used for wearable technology and their typical use cases. The individual positioning and arrangement of motors in each location, particularly in the armbands, was examined. Information about the type of wearable device, the number of motors, the kind of information, and the context of use was extracted. Consequently, arms were determined as the location that would be most suitable for conveying information about music to people with visual impairments (section 4.5.2).

4.5.1 Affordances Overview

Human body parts offer diverse opportunities for wearable device designs, with each location providing unique affordances for delivering haptic feedback. Understanding these location-specific affordances is essential when designing a device for a particular use case. Affordances can indicate that certain locations are better suited to convey specific information. For example, the cognitive affordances of arms, head, and hands indicate that they are used effectively to provide alerts and notifications in a discrete way, torso, legs, and arms are practical for directional cues due to the spatial distribution of the motors, hand and feet are conveying textual information resembling physical tactile experiences and arms, hands and multi-locations are efficient for more abstract sensations such as object manipulation or sensory substitution. Technological constraints influence these affordances, such as the number and arrangement of motors, as well as the surface area available, skin sensitivity, and physiological characteristics (e.g.,fat, muscle).

'Handling affordances' by Benbunan-Fich (2017) and physical and functional affordances by Hartson (2003) describe what the body can physically do with the technology and how it embodies the device capabilities. A clear example is the belt-like device, based on the traditionally worn accessory. The nature of the belts being around the waist suggests the placement of motors around it, too. This arrangement is naturally linked to directions (i.e., left, right, front, back) and for that reason this location can be used to provide effective directional information (Pielot and Boll, 2010). Another example is insole haptics, which simulates ground textures to provide realistic tactile feedback (Strohmeier et al., 2020) and the gloves that provide the sense of touching an object in a VR environment (Jonatandsiuclmes et al., 2014; Normand et al., 2024). In such examples, both the device's affordances are very clear, and the information it conveys is often expected by the user, which enhances the system's usability.

In a user-centric design approach, designers must consider self-effector affordances, which refer to the motivations or needs that drive individuals to use a device. These affordances emerge from the user's lived experiences rather than solely from the designer's intentions. In the case of accessibility-focused design, these motivations can vary significantly across users with different sensory abilities. For example, navigation tasks are the most frequently used case (Figure 4.8). Yet, different disabilities (e.g., visual, auditory) require a different approach to device design. Wristbands offer the affordances for providing information related to the user's environment or in relation to other digital devices. Wristbands are easy-to-wear devices that inherit the affordances of long-term wear from their relative ascendant devices (i.e., watches). Goodman et al. (2020) proposes the use of a one-motor wristband device for sound awareness of deaf people, while Cœugnet et al. (2017) suggests conveying the alert type of information for safe road crossing for elderly people. However, the limited feedback resolution of single-motor devices may necessitate the use of complementary visual cues. A slightly different design with six motors, as proposed by Schätzle et al. (2019), provides directional information to blind users. Six motors, in contrast to one, can provide clear indications of directions, especially in the case of blind people, where visual cues are absent. Thus, with minor adjustments, the affordances are tailored to the user's needs.

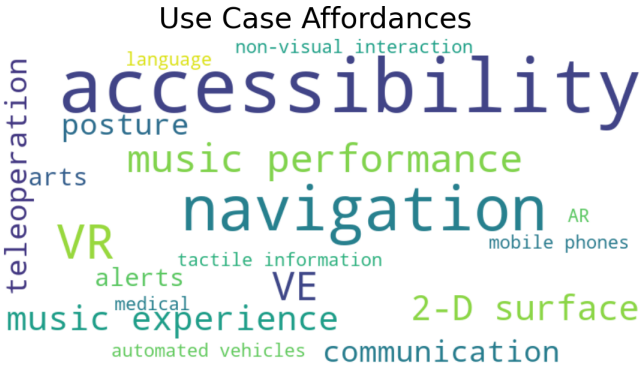


Figure 4.8: Use-Case affordances

4.5.2 Determine the best location based on identified affordances

This review facilitated the understanding of the affordances of each body part and how it can be utilised for wearable technology. Both functional affordances and handling affordances of each location in the body can be found in the frequency of the use case and type of information that each location has been used for, and what is most suitable for. The effector, self-effector and physical affordances determine the optimal location for the specific use case of this research based on the technology opportunities and

users' motivational needs. In parallel, participants in Chapter 3 highlighted the need for something portable, which implies a device that is easy to wear, allows freedom of movement, and is comfortable while worn. Especially for BVI users, reachability and social acceptance enhance the usability of a device and suggest a potential for more prolonged use (Zeagler, 2017). The forearm and upper arm are the optimal locations, according to the above review. They do not restrict the hand movement and interaction with the keyboard and music hardware. At the same time, given their sensory affordances, they have sufficient skin surface area for multiple motor arrangements and consequently provide a high-resolution display. Due to their appearance and inherent physical affordances from watches and jewellery, armbands are socially acceptable and can be used outside the music studio to offer discreet feedback. Wristbands could also be considered; however, they are limited to a smaller number of motors around the wrist, which limits the complexity of the information that can be provided. Hands and fingers are likely to interfere with the use of other physical devices, such as keyboards; for this reason, it is considered unsuitable. The same applies to the torso, legs, and head. These types of devices are usually larger, heavier and socially awkward. Apart from being cumbersome in long-term usage, they are not suitable for portability outside the music studio. Thus, the following chapters will focus on the design of an arm band that can be worn on the forearm and upper arm, examining the most suitable location of the two and the possible arrangement of motors, as well as the optimal number of them.



Figure 4.9: Type of Information that body locations afford

4.6 Conclusion

This chapter presents a comprehensive literature review of existing vibrotactile feedback wearable devices, exploring emerging design trends, use cases, and the types of feedback they can provide. The primary aim is to identify and understand the embedded affordances in each body part used for a wearable device and how these influence the use case of the device. Consequently, the review facilitated the identification of the optimal

location for a wearable accessibility tool for music production software (DAW) for BVI people, which allows interaction with a computer keyboard, music hardware and can be used in music studios and public spaces. Three types of affordances formed the scope of this review: (1) the handling affordance (i.e., what the user can do with the specific technology), (2) the effector (i.e., the technology possibilities) and (3) the self-effector (i.e., the user's motivational needs).

The identified devices are categorised per body part: (1) Torso, (2) Head and Neck, (3) Legs, (4) Multiple Locations, (5) Hands and (6) Arms. The torso provides a large skin surface, making it suitable for providing detailed sensations and directions. The head and neck are also used for outdoor and specific context navigation and brief alerts. Legs and, particularly, feet have been used to convey textual information in VEs, as well as directional cues. Multiple locations are used for flexibility in feedback and motor placement arrangements, making it suitable for conveying abstract information, tactile sensations, and movement guidance. Hands are strongly linked with their natural affordances to feel textures and interact with physical worlds (object manipulation simulation); thus, they are primarily used for these purposes, especially in virtual environments. Arms are used extensively for providing coded information, alarms, notifications, and directions.

Moving forward in this research, the findings from Chapters 2, 3, and 4 will be utilised to guide the design decisions for the work implemented in the following chapters. Specifically, these first chapters examined the research gap through literature review and qualitative data from BVI participants' interviews and suggested the need for a device that produces vibrotactile feedback for the accessibility of DAWs. Additionally, a collection of participants' ideas on the DAW elements that could benefit from vibrotactile feedback, mapped to vibration pattern design methods existing in the literature. The second part of this thesis aims to develop and evaluate a new haptic device (Chapter 5) and examine the potential of vibrotactile feedback usage in the context of music production (i.e., DAW) (Chapter 6). Additionally, to explore the most suitable vibration patterns to convey information (Chapter 7) through the use of real-world music production scenarios.

After the vibrotactile feedback device (an armband with three vibration motors encircling the arm) was developed (Chapter 5), specific examples were chosen from participant ideas, and evaluation techniques were investigated. Two important factors influenced the evaluation approach for the subsequent chapters: the selection of the DAW feature (scenario) and the nature of the interaction with it. The choice of DAW features is derived from both users' insights in Chapter 3 and the established importance and popularity of the music production process, as referenced in the literature (Izhaki, 2017). The type of interaction with the DAW is informed by the stages of human-computer interaction,

which are (1)forming the intention, (2) selecting an action, (3) executing the action, and (4) evaluating the outcome (Norman, 1984). The music production workflow involves a similar sequence of ongoing engagement. Users continuously perceive information from the sound material (music) or about the sound material (screen reader feedback), interact with the system (keyboard or external hardware), and evaluate the outcome (music or information from the SR). Norman's framework allows a rigorous and theory-grounded evaluation of the suggested new system designed to improve accessibility of DAW with the use of vibrotactile feedback. This section will be utilised to structure the evaluation of vibrotactile feedback in the following Chapters. Specifically, Chapter 6 focuses on the stages of forming the intention and selecting the action and in Chapter 7, participants will execute the action using vibrotactile feedback and evaluate the outcome of their action based on that. The following Chapters of the thesis aim to answer the second research question through these multifaceted evaluation methods and to contribute to the use of vibrotactile feedback for accessibility, particularly in conveying information from a DAW in a non-visual way to BVI music producers.

Chapter 5

Design and Development of a Wearable Vibrotactile Feedback Display

This work has been published in the proceedings of the 7th International Conference on Human-Computer Interaction as: Karpodini, C., Michailidis, T. (2025). Less is More: Designing Wearable Vibrotactile Wristbands for Blind and Visual Impaired Creatives. In: Wei, J., Margetis, G. (eds) Human-Centered Design, Operation and Evaluation of Mobile Communications. HCII 2025. Lecture Notes in Computer Science, vol 15823. Springer, Cham. https://doi.org/10.1007/978-3-031-93061-4_17

5.1 Introduction

Based on the findings, which emerged from the literature (Chapters 2 and 4) and the interviews with BVI individuals (Chapter 3), this Chapter proposes a new vibrotactile wearable armband. Although the previous part of the thesis has narrowed to the initial design approach, new sub-research questions emerged regarding some design elements that remained uncertain, such as the number of motors on the device and the optimal location in the hand that needs to be worn. These RQs are: 'What is (1) the optimal number of motors and (2) the most suitable placement on the arm to enable accurate identification of vibrotactile stimulus locations, and (3) what additional factors may influence the perception of these stimuli?'.

The first part of this chapter outlines the development process, including the selection of technologies for a wearable, wireless, vibrotactile feedback armband device. The

second part presents the evaluation of the device's usability. It was examined whether participants can identify the location of the vibration motors around the arm, regardless of the location where the device is worn, in order to determine the optimal location for wearing the device on the arm. Other factors that might influence the perception of the stimuli were also investigated. The first prototype consisted of five motors around the arm (Figure 5.1 Left); the findings of its evaluation helped narrow the design specification and arrive at the final device with three motors (Figure 5.1 Right). This device will later support the design and use of spatiotemporal patterns for conveying information in the DAW, as will be examined in Chapters 6 and 7.



Figure 5.1: **Armband Prototype Devices: Left three motor device, Right five motor device**

5.2 Development of Apparatus

Arms have been the optimal location for wearable technology that enables interaction with the physical world (e.g., computer keyboards and musical interfaces) and in desk-based environments (e.g., music studios) (Zeagler, 2017). This approach allows for freedom of movement and remains socially acceptable for both indoor and outdoor use (Zeagler, 2017; Profita, 2016). These considerations led to the design of an armband that is easy to wear and inclusive. By 'inclusive' in this case, participants, regardless of their physical characteristics related to age, body mass, or dominant hand, will be able to identify the stimuli. The device consists of two iterations that aim to examine the optimal number of motors around the arm. Starting with five motors and concluding with three

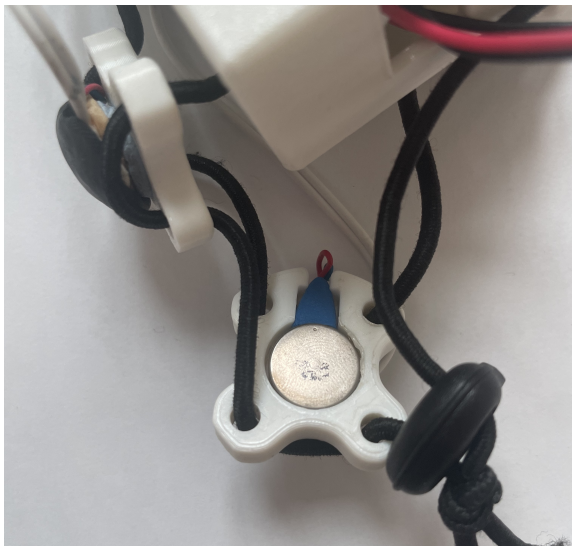


Figure 5.2: ERM motor on the device

motors, both equally placed around the arm, allowing for flexible wear on the forearm and upper arm. The motors used are small and lightweight, ensuring the comfort of the device during extensive use. The number of motors determines the resolution of the haptic display. This research aims to convey clearly perceived spatiotemporal patterns. Thus, evaluating the ability to recognise the location of each motor around the arm clearly is essential and determines the optimal number of motors that such a device can afford to improve accessibility in DAWs through vibration patterns effectively. The following sections present the specifications of the hardware technology and the design of the device (case and assembly) and software.

5.2.1 Hardware Device

Figure 5.1 illustrates the design differences between the two devices, which, despite their distinct appearances, share the exact hardware implementation. The second device, featuring three motors, represents an iterative and informed design improvement based on the evaluation results of the first device (Section 5.3), which utilised five motors.

Vibration motors: Both devices employ 11mm diameter, 3mm height eccentric rotating mass (ERM) coin motors (Precision Microdrives 310-113.009) (Figure 5.2), which offer several advantages, making them popular in vibrotactile feedback research (Hong et al., 2017; Tran et al., 2023). These benefits include affordability, availability in various shapes and sizes (coin or cylindrical), ease of programming, and robust tactile feedback, which is particularly useful during prototyping (Hong et al., 2017; Remache-Vinueza et al., 2021).

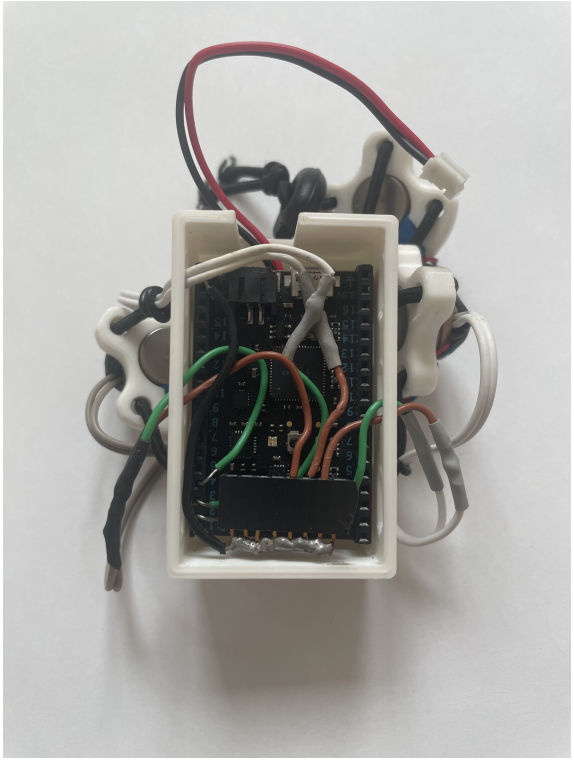


Figure 5.3: Electronics assembly using x-OSC device

I/O board: To control the motors, the *x-OSC I/O* board was utilised (https://x-io.co.uk/x-osc/), a compact and easy-to-use solution that requires no additional libraries or complex wiring (Madgwick and Mitchell, 2013). x-OSC enables wireless control of the motors using PWM (Pulse Width Modulation) at a maximum frequency of 250 Hz (Figure 5.3).

Assemble and 3D printed Case: The first device (5 Motors, Figure 5.1 Left) features a thick elastic band with small Velcro sections spaced evenly to attach the motors. These motors are wrapped in thinner elastic fabric to ensure effective vibration transmission to the skin and limit the unwanted propagation of vibration further from the focus area. A 3D-printed plastic case (7.5cm x 4.5cm x 3cm) at the centre of the band houses the electronic board and a 1200mAh rechargeable battery. Initially, the motors are spaced approximately 8cm apart, but can be adjusted based on arm size (Figure 5.4). The second iteration (3 Motors, Figure 5.5) consists of a smaller 3D-printed case (5.5cm x 3.5cm x 2.5 cm) for the electronics and 3D-printed cases for the motors that cover one side of the coin and the periphery of each motor, leaving the other side exposed for direct skin contact. The use of 3D printed cases for the individual motors also helps reduce the vibration propagation to the skin (Jones and Tan, 2012). Both electronics cases and motor cases are mounted on a thin elastic cord. Documentation for the 3D-printed cases can be found on the GitHub page (Karpodini, 2025a).

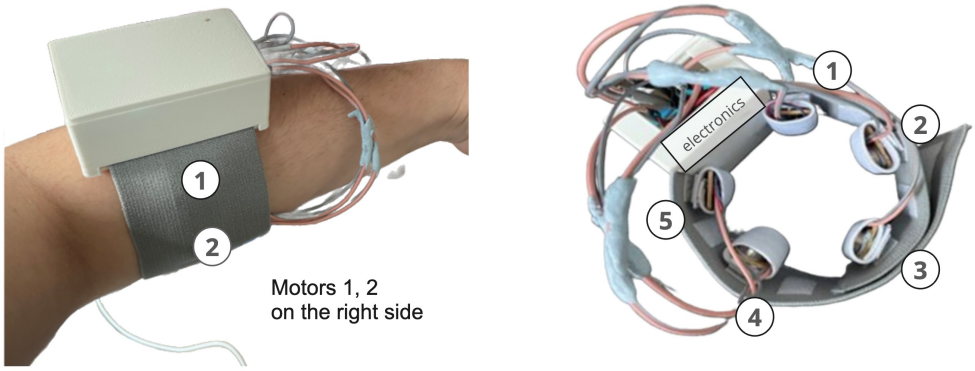


Figure 5.4: Prototype 5 motors, motor arrangement

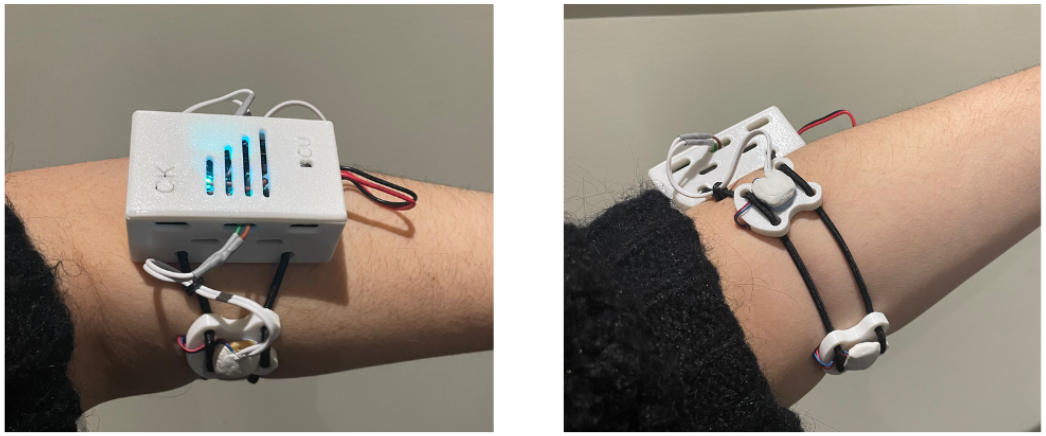


Figure 5.5: Prototype 3 motors, motor arrangement

The first device's (5-motor) number of motors was selected based on the findings of Chapter 4, which showcased a lack of exploration of armbands with five motors. The literature mostly explored 4 and 6-motor devices focused on presenting directional cues, and three or fewer motors for Tactons that present symbolic information. The suggestion of using 5 motors will allow investigating this gap in the literature and exploring the possibilities of a bigger resolution armband haptic feedback device.

Software

Vibration Design program in Max 8 The vibration design was developed in the visual programming environment MAX ('74, 2025) and utilises OSC communication to activate motors wirelessly. All source code is openly published on GitHub for the wider community (Karpodini, 2025b) and in the Appendix C.

ERM motors have inherent properties where amplitude and frequency are interdependent, increasing linearly together. The rotation frequency was set to 250Hz using PWM, which is the peak frequency for vibration perception (Remache-Vinueza et al., 2021). Based on the motor's datasheet (Microdrives, 2025), the envelope's attack and release times were configured to match the motor's rise and stop times: 91 ms for the attack and 112 ms for the release. The duration of motor activation (sustain) is set to 200 ms.

5.3 Evaluation of 5 Motor Armband

After the prototype design was finalised, the optimal location on the arm (forearm, upper arm, left or right hand) and the optimal number of motors were examined. The device aims to support BVI creatives in music production, which requires the design of precise and clear patterns (e.g., use of Tactons). For this reason, the evaluation focuses on identifying the location of vibration around the arm to ensure the device design allows the production of clear, distinct vibration stimuli.

5.3.1 Methodology

A mixed-methods within-subject study was conducted to evaluate the prototype. Quantitative data has been collected by testing the absolute identification of the stimulus location on the device with five motors. The results aim to indicate if five motors allow for the distinct recognition of stimuli. Demographic information was collected, including age and hand circumference, which were also used as part of the quantitative analysis to investigate additional factors that may influence the perception of the stimuli. Qualitative data were collected through a post-test open feedback form. Combining quantitative data (task accuracy and task completion time) with qualitative data (participant feedback) will provide evidence of the optimal location for wearing the device.

5.3.2 Participants

Twenty-four (24) participants were recruited, with an age range of 21 to 37 (M = 29 years, SD = 4.4) (15 male, 8 female), 3 of them were visually impaired. Sighted participants for this study were recruited from Birmingham City University via an open email invitation. Visually impaired participants were recruited through advertisements in online forums for accessibility of music production software. Prior experience with vibrotactile feedback was not required to participate in the study. The recruitment criteria for this study were that participants had no medical conditions that might be triggered by the vibration stimuli (e.g., epilepsy) and no allergies or skin sensitivities to

materials such as metal and synthetic fabrics. All participants were provided with an information sheet detailing the study's purpose and procedures, along with a consent form to ensure their informed and voluntary participation.

5.3.3 Procedure

Ethical approval was obtained from Birmingham City University's ethical committee. On the day of the study, it was verified that the consent form had been received, which also included demographic information. In cases where the form had not been completed in advance, participants were asked to complete it before the test began. The study was conducted in person in the university facilities. Participants were instructed to sit in front of a laptop computer placed on a desk. The researcher measured the participant's forearm and upper arm to ensure the device was properly fitted and logged the information for future analysis. Based on these measurements, the device's vibration motors were placed in equally distributed positions on the armband.

Before the test began, the facilitator provided an example of the test stimuli to ensure that the intensity of the vibrations was comfortable and perceivable for each participant. This step was essential to ensure participants' comfort and willingness to proceed with the test. Additionally, a brief explanation was provided to participants, indicating which vibration motor corresponds to specific responses displayed on the interface (Figure 5.6) and how they will interact with it by clicking on the corresponding visual representation of the motor position or keyboard number. Participants then engage in a short training session to familiarise themselves with the setup and the process.

Participants were asked to complete four tests, one for each arm location (Right Forearm (RF), Right Upper Arm (RU), Left Forearm (LF), Left Upper Arm (LU)), each consisting of 50 trials. Each trial involved a random motor excitation; each of the five motors around the arm was triggered 10 times in a random order, creating a total of 50 vibration excitations. Participants were required to identify the location each time they felt the vibration and provide their answer by selecting the corresponding visual or keyboard representation of the motor. The graphical user interface (Figure 5.6) depicted the 5 locations of the motors as small circles positioned around a bigger circle that represented the arm circumference (section 5.3.4).

This series of trials was repeated in all four arm locations. The order of these locations was counterbalanced, using the Balanced Latin Square, and the device was adjusted accordingly to ensure the motors were equally distributed around the arm and that the participants were comfortable.

During the test, participants wore headphones with no sound but acting as noise cancellation, minimising the influence of potential sounds from the vibration motor. After each set of trials, participants took a 5-minute break, during which they engaged in conversation and provided feedback on their experience. The study session lasted approximately 30 minutes.

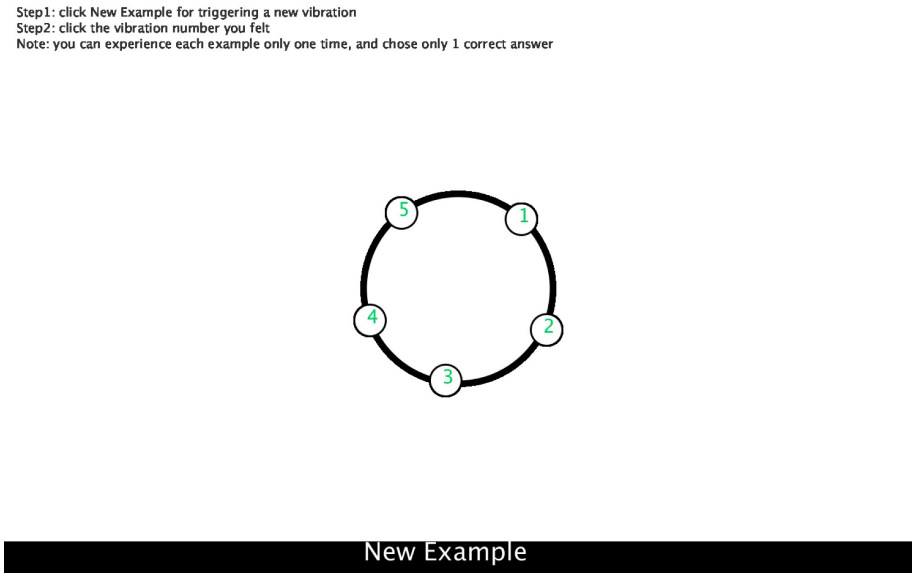


Figure 5.6: **Experimental Interface**

5.3.4 Experimental Interface

For the evaluation process, an experimental interface was developed using the Processing (Java) library (*Processing: A Programming Environment for Artists, Designers, and Educators* 2025). This program visually represents the armband as a circle with five motors equally distributed around its periphery, inspired by related work (Wang et al., 2018). Participants can log their responses by clicking inside the circle, and the space bar triggers the next test question. To enhance accessibility, participants can select their answer using the keyboard, with numbers one to five corresponding to the five motors, aided by a screen reader. The program connects to Max via local OSC communication to trigger the next vibration and saves participants' answers in a CSV file. To confirm accuracy in the data collection, the Max patch was cross-verified to ensure its output matched manually collected data over multiple trials, ensuring reliable and consistent performance. (Figure ??, 5.7)

5.3.5 Measures and Analysis

Participants chose their answers by clicking the circle representing the motor location that corresponded to the stimuli they felt. Answers are saved in a .txt file along with

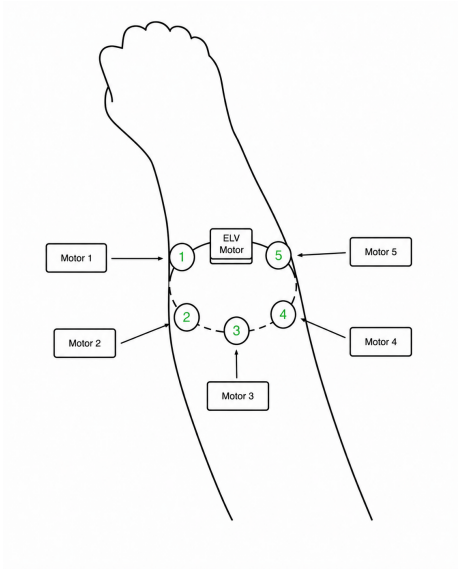


Figure 5.7: **Anatomical positioning of five motors around the arm**

the timestamp of each answer submission.

The **Task Accuracy** was calculated by comparing the submitted answers with the actuator number that had been activated in the test. As **Task Completion Time** represented by the duration between each activation of the 'next example' button was recorded. As the participants performed the task without interruptions, the average time taken to complete the task was calculated.

Demographic information was collected, including the age and gender of the participants and whether they had prior experience with vibrotactile feedback devices. Before testing, the circumference of the participant's forearm and upper arm was measured at the location where the device was worn for the test. Similarly, the distance between the motors was measured after participants wore the device to ensure the motors were equally placed. Finally, at the end of the test, participants were asked to state their preferred location for wearing the device and share any comments about their experience with the device on a post-test open feedback form. Both inferential and descriptive statistics were used to analyse and present the quantitative data. The Shapiro-Wilk Test was used to assess the normality of the data distribution. Following that, One-way repeated measures ANOVA for normally distributed data and the Friedman test for non-normally distributed data were used to compare the results among the four hand locations.

Hand Location	N	Av. Score	St Dev
Left Forearm	3	88.67%	11.02%
Left Upperarm	3	89.33%	7.57%
Right Forearm	7	76.29%	8.01%
Right Upperarm	10	81.6%	10.36%

Table 5.1: Hand Location Statistics

5.3.6 Results

Performance per hand location

The Shapiro-Wilks test assessed whether normality had been violated in the data related to the accuracy rate and average time. All data on the accuracy rate are normally distributed in all four locations tested. The time average data were not normally distributed in all three hand locations.

Accuracy Rate

One-way repeated-measures ANOVA showed no significant difference between the four conditions: Left Forearm (LF) (M = 70.43%, SD = 2.95%), Left Upper arm (LU) (M = 67.13%, SD = 3.08%), Right Forearm (RF) (M = 74.26%, SD = 2.26%), Right Upper arm (RU) (M = 73.13%, SD = 3.04%). Wilk's Lamda = .734, F (2, 20) = 2.417, p =.096, which indicates a large effect size. No significant difference was observed in the pairwise comparison.

Average Time Friedman Test indicated that there is a significant difference in the average time of participants' performance between the four hand locations: LF (M = 2351.61ms, SD = 216.17ms), LU (M = 1993.36ms, SD = 111.04ms), RF (M = 2207.65ms, SD = 138.77ms), RU (M = 1950.9ms, SD = 71.81ms). x^2(3,23) = 13.847, p =.003. Post-hoc Test with Wilcoxon Signed Ranks showed a significant difference after Bonferroni corrections (p =.0125) between LU and LF (p = .002), RU and LF (p = .005), but not between RF-LF, RF-LU, RU-LU or RU-RF.

Although there is no statistical difference in hand location accuracy, there is always one hand that performs better for each participant. The hand with the highest score was selected for each participant, and the frequency of each location among the best-performing hands was calculated. Table 5.1 shows the frequency of each location and the average accuracy score. Overall, 17 participants performed best in the Right hand and 6 in the Left hand.

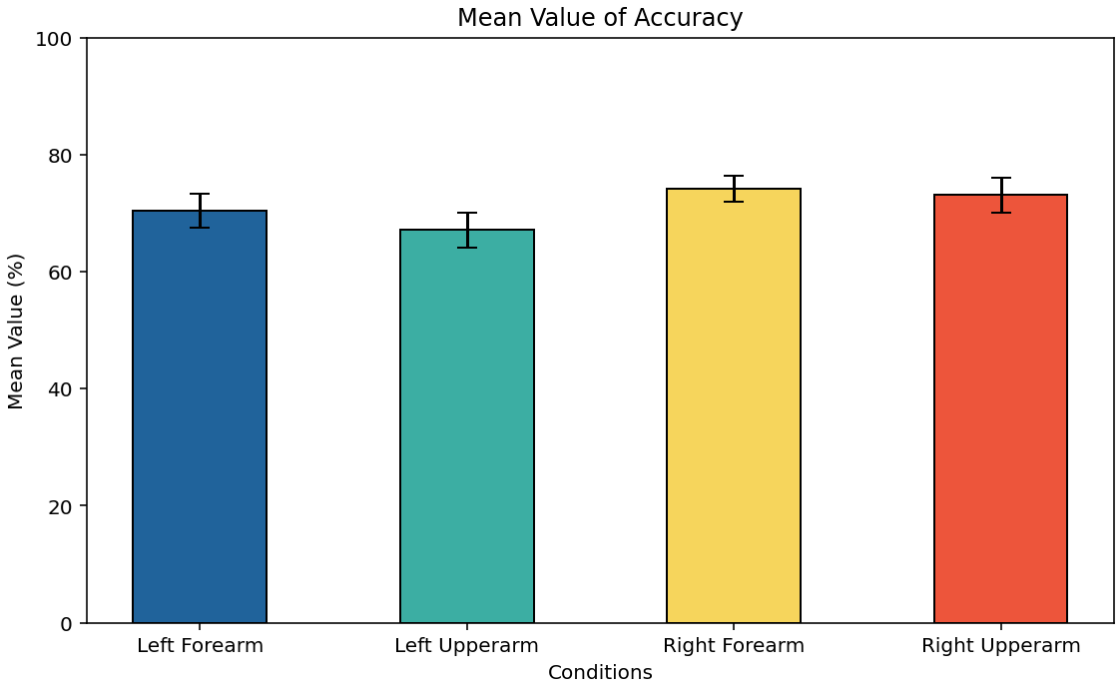


Figure 5.8: Accuracy Mean per Arm Location

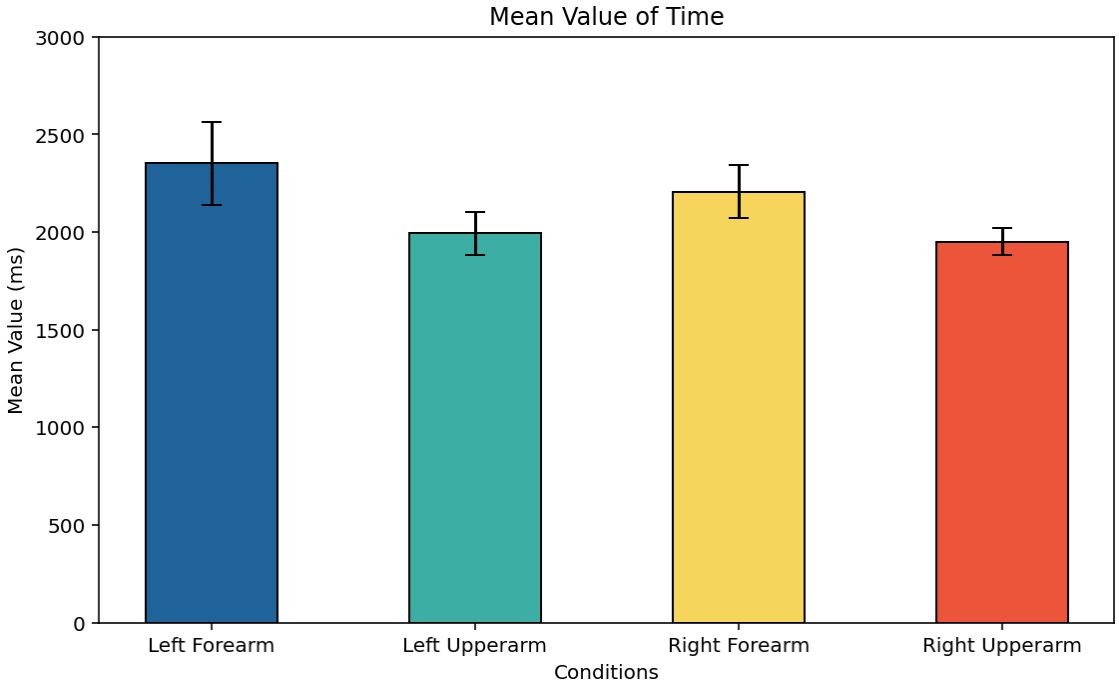


Figure 5.9: Time Mean per Arm Location

Age Group	N	Av. Score (%)	St Dev(%)
21-25	5	78.5%	9.39%
26-30	9	71.11%	10.48%
31-35	6	65.33%	7.85%
36-40	3	71.33%	16.75%

Table 5.2: Age Statistics

At the end of the test, participants were asked which location they felt most comfortable in, and they would prefer wearing the device when using it in a computer interaction setup. Five participants said 'Left Forearm', another five said 'Left Upperarm', one participant said 'Right Forearm', and twelve participants said 'Right Upperarm', which indicates a strong preference for the Right Upper arm. Among the participants, 9 out of 23 (39%) preferred the location where they performed best. Finally, 7 out of 9 belong to the majority that replied to the Right upper arm location.

Individuals' Characteristics

While testing the prototype, demographic information that might influence the perception of the stimuli was collected. The section presents the analysis of the accuracy rate in comparison to participants' age and hand size.

Visual Ability Among the participants were three BVI people. The findings showed a very small difference in the average accuracy performance between the three BVI participants (M = 74.1%, SD = 10.8%) and the remaining 20 sighted participants (M = 70.8%, SD = 11%).

Age Participants were divided into five-year age groups: 21-25, 26-30, 31-35, 36-40, and the average score was calculated for each age group. The findings are concentrated in Table 5.2. The best-performing age group was the youngest.

Hand size Hand size influences the distance between the motors. The hand sizes were grouped based on the distance between the motors when participants wore the device, and four distances were concluded for each location on the forearm and upper arm. (Table 5.3)

The data indicated the best performances, which are in Forearm circumference 24-26 (LF: M = 71.2%, SD = 18.41%, RF: M = 78%, SD = 11.01%) and 27-28 (LF: M = 75.25%, SD = 13.6%, RF: M = 78.5%, SD = 11.02%) and Upper arm Circumference 26-27 (LU: M = 77%, SD = 15.99%, RU: M = 73.66%, SD = 18.21%) and 32-37 (RU: M = 77.15% SD = 13.61%) (Table 5.4)

Forearm Motor distance/ hand circ.	Upper Arm Motor distance/ hand circ.
4cm for sizes 21-22	5cm for sizes 23-24
5cm for sizes 24-26	6cm for sizes 26-27
6cm for sizes 27-28	7cm for sizes 28-31
7cm for sizes 29-31	8cm for sizes 32-37

Table 5.3: Distance between motors and circumference of the forearm and upper arm

Motor distance/ hand circ.	**Left Forearm**	**Right Forearm**
4cm for sizes 21-22	66 (SD=10)	73.33% (SD=7.02%)
5cm for sizes 24-26	71.2% (SD=18.42%)	78% (SD=10.49%)
6cm for sizes 27-28	75.25% (SD= 13.6%)	78.5% (SD=11.01%)
7cm for sizes 29-31	60% (SD=5.29%	67.14% (SD=10.25%)
	Left Upper Arm	**Right Upper Arm**
5cm for sizes 23-24	64% (SD=2.83%)	66% (SD=16.97%)
6cm for sizes 26-27	77% (SD=15.99%)	73.66% (SD=18.21%)
7cm for sizes 28-31	67.25% (SD=12.69%)	71% (SD= 13.98%)
8cm for sizes 32-37	59.43% (SD=15.04%)	77.14% (SD=13.61%)

Table 5.4: Mean accuracy per distance between motors and circumference across location

Performance per motor

Since no significant difference was observed between the four hand locations, the results of all conditions were combined for the next analysis. This analysis aims to explore any significant differences between the accuracy rates of the five motor locations in all conditions (40 tasks per motor). A Shapiro-Wilk test showed that the data were not normally distributed in all five motor locations. Motor 1 (p = .008) , Motor 2 (p = .040), Motor 3 (p = .074), Motor 4 (p = .184), Motor 5 (p = .067).

The results from the Friedman Test indicated that there is a significant difference between the five motors. Motor1 (M = 84.13%, SD = 2.88%), Motor2 (M = 69.57%, SD = 3.75%), Motor3 (M = 70.87%, SD = 4.17%), Motor4 (M = 63.37%, SD = 3%), Motor5 (M = 68.26%, SD = 3.8%).x^2(4,23)=23.87, =<.001. The Post-hoc Wilcoxon Signed Ranks Test showed specifically significant difference and after Bonferroni corrections between Motor 1 and 2 (z = -3.124, p = .002, with a large effect size .46), Motors 1 and 4 (z = -3.866, p < .001, with a large effect size .57), and Motors 1 and 5 (z = -3.673, p < .001, with a large effect size .54).

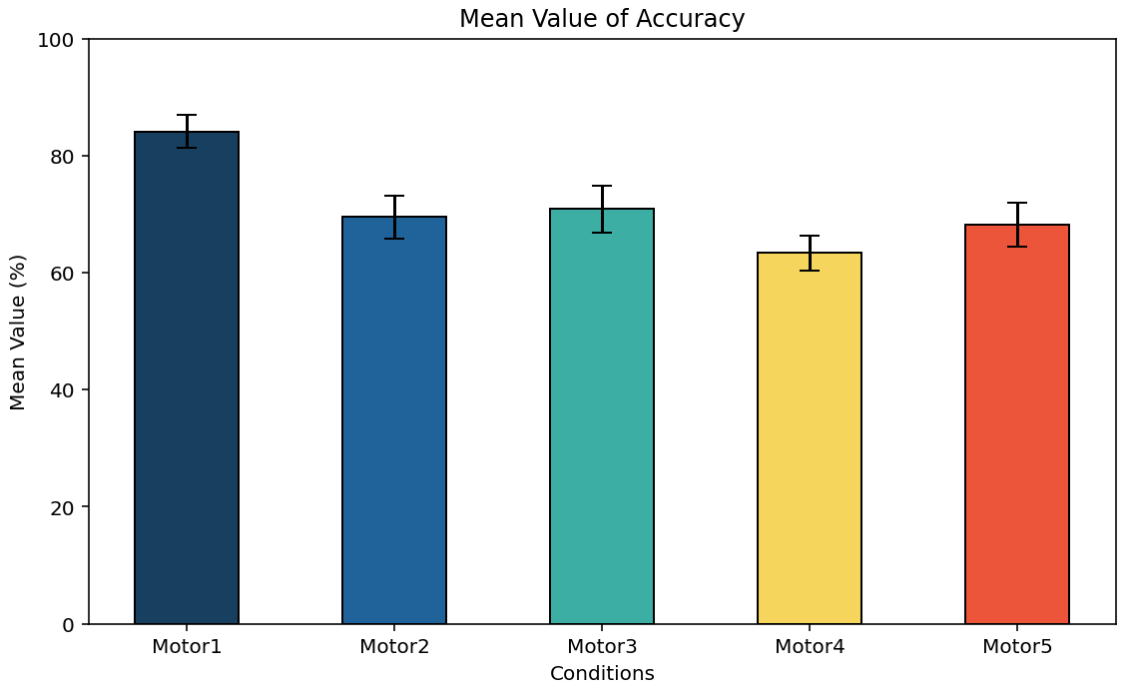


Figure 5.10: Accuracy Mean for each motor in all four arm locations

	Mean Accuracy	Mean Error	Previous Motor	Next Motor	Across Motor
Motor1	84.13%	15.87%	12.39%	2.28%	0.87%
St Dev	13.81%	13.81%	12.87%	4.19%	1.79%
Motor2	69.57%	30.44%	20.65%	9.02%	0.76%
St Dev	17.97%	17.97%	13.00%	8.78%	1.59%
Motor3	70.87%	29.13%	14.78%	13.48%	0.76%
St Dev	19.98%	19.98%	17.17%	15.31%	2.76%
Motor4	63.37%	36.63%	6.09%	29.02%	0.00%
St Dev	14.43%	14.43%	6.48%	15.48%	0.00%
Motor5	68.26%	31.74%	2.61%	27.07%	2.17%
St Dev	18.27%	18.27%	4.30%	16.18%	4.79%

Table 5.5: Motor Performance Mean Accuracy, Mean Error, Mean Error Type (Previous, Next, Across Motor)

Observing the Error Rates

Some motor locations were perceived more accurately by the participants than others. The errors in the accuracy data were analysed to determine which motor locations were commonly confused, whether between previous motors, the next in sequence, or crosswise positions. Participants tended to confuse motors 4 and 5 with their previous ones. That means motor four was confused with 3 (M = 12.39% out of 15.87% of the total errors) and motor 5 with 4 (M = 20.65% out of 30.44% of total Errors). Motors 1 and 2 are getting confused with the next motor, motor 1 with motor 2 (M = 29.02% out of 36.63% of total Errors) and motor 2 with motor 3 (M = 27.07% out of 31.74% of total Errors). Motor 3 is equally confused with the next and previous (M next = 14.78% and previous M = 17.17% out of 29.13% of the total errors). In very few cases, the motors were confused with motors that were two places away (Across Motors) (Table 5.5).

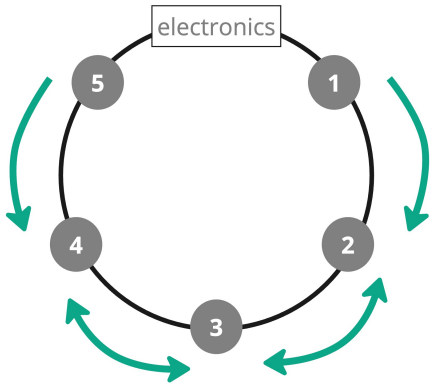


Figure 5.11: Observed error trends in the identification of motor locations.

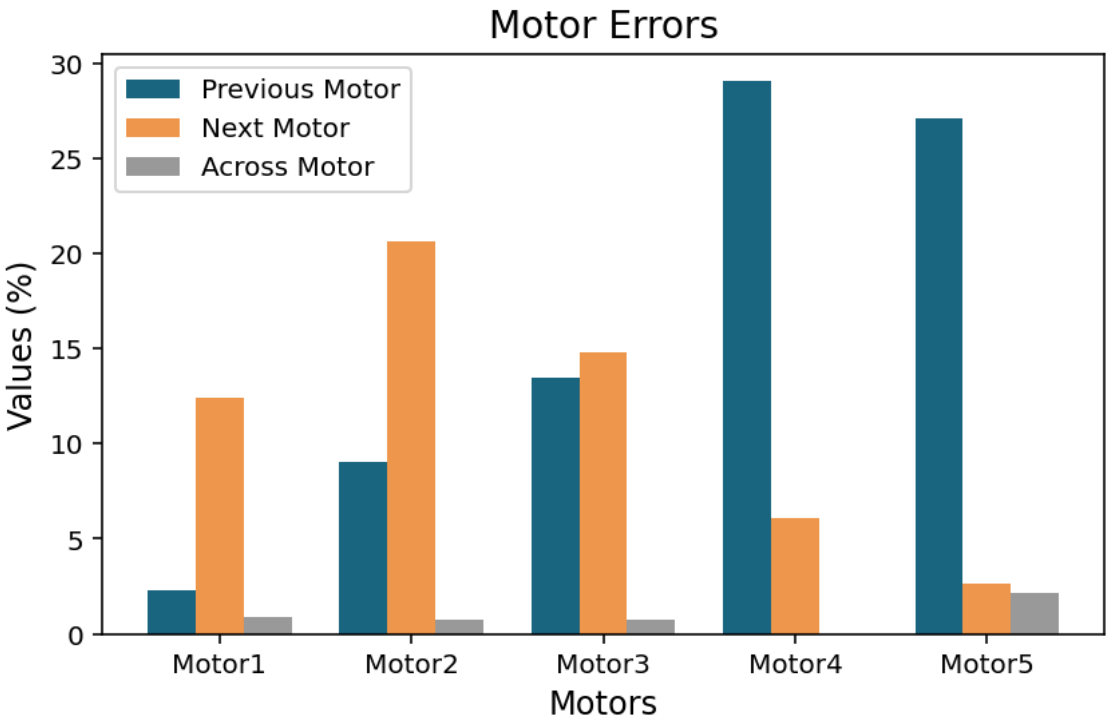


Figure 5.12: Error rates by misidentified motor location

Participants' Feedback

Participants provided feedback about the usability of the device at the end of the test. The comments were focused on the perception of the five vibration locations. For example, participants (P7, P8, P9, P10, P12) commented that it was difficult to distinguish between the motors 2 to 3, and 3 to 4. 'couldn't understand which one it was, mostly between 2-3 or 3-4' (P10). P9 highlighted that it was the distance between the motors that got him confused, 'Hard to understand those close to each other, especially when you come back from the other side'. Similarly, P13 supports that it was hard to understand unless the motors were across to each other (e.g., 1-3 or 3-5) 'Unless it was across to each other, it was confusing.' Another comment had to do with the way participants approached the task completion, which showed the cognitive challenge of finding the location: 'I took my previous response as a reference' (P13) and 'If I do one wrong at the first time, I will probably continue recognising it wrong'.

5.3.7 Results Discussion

Four locations on the arm were examined to identify the optimal location for using a wearable hand-based haptic display, answering the respective research question. The different locations, the forearm and upper arm of the right and left hands, have small

differences in relation to the accuracy rate and larger differences in relation to the average time for task completion. The results of the one-way ANOVA test and the Friedman Test indicate that the location of the arm does not significantly affect the accuracy of vibration identification, but it may influence the time required for stimulus identification.

However, participants performed differently on each hand. The best hand performance comparison demonstrates that the right hand (17) performed better than the left (6). This performance difference between the Left Upper arm and the Left Forearm, but not between the Right Upper arm and the Right Forearm, might occur due to the fact that participants are all right-handed. Therefore, no conclusion can be drawn about whether the dominant hand influenced this result. When participants were asked which location they preferred to use the device, more than half (14) answered a different location from the one where they performed best, which shows that best performance and accuracy in stimulus recognition do not necessarily align with usability, a crucial aspect of the device.

Accuracy rate results, analysed in combination with the demographic information collected, including age and the size of the arm (forearm, upper arm) circumference. Descriptive analysis revealed that the youngest individuals in the 21-25 age group performed better than the rest of the age groups. The effect of age on the perception of vibrotactile feedback stimuli has been observed in the literature before by (Sziebig et al., 2009). The arm size, which influenced the distance between the motors, was the most interesting as it showed that people in the middle of the range, 24-26cm and 27-28cm of both right and left forearms, performed better than those with a smaller or larger circumference. On the upper arm, the best results were observed in the middle, 26-27 cm for the left and the right hand, and the large size of 32-37 on the right. Although the results are limited by the number of participants and the equal distribution of participants in the size groups, they support the existing literature that suggests that people with a bigger circumference in their arm perform better (Carcedo et al., 2016), but at the same time, the underlying tissue composition (i.e., fat or muscles) also influences the perception (Sziebig et al., 2009). This effect was most evident in the performance of the upper arm, where the accuracy data varied and presented a large standard deviation. deviation. The literature suggests no difference in the perception abilities based on gender (Matscheko et al., 2010), which led to the exclusion of this demographic information from this analysis.

5.4 Re-evaluating the design

Results from the evaluation of the 5-motor device showed that individuals' uniqueness influences the perception of vibrotactile feedback. Location in this use case indicates that it is up to the user's preference and needs. For this reason, the design needs to ensure the vibrations are distinguishable and perceivable by all users. The use of stronger intensity might lead to an unpleasant experience for more sensitive individuals to vibrations; thus, the number of motors around the arm needs to be reconsidered to achieve maximum perceivability.

The individual error rate of each motor in all locations demonstrated some useful patterns informing the prototype iteration. Although participants' overall scores varied between 67% and 75% across the four hand locations, differences in the performance of the individual motor's accuracy rates varied from 63% (Motor4) to 84% (Motor1). When errors occurred in motor stimulus identification, participants consistently tended to confuse a given motor with a specific other motor. Specifically, motors 1 and 2, as well as 4 and 5, are being confused with motors toward the centre back of the device, gravitating towards motor 3. On the contrary, motor three was equally confused with motors 2 and 4. Additionally, motors 1 and 5 were rarely confused with each other because of the clear separation, thanks to the plastic case that hosts the device's electronics.

Finally, the qualitative data supported the quantitative data, with most comments confirming the confusion between motors 2-3-4 and the difficulty in distinguishing their locations.

Summary of findings for the next iteration:

- Motors 2-3-4 can be replaced by one motor
- The plastic case hosting the electronics between motors 1 and 5 might enable better distinction of vibration location.
- Fewer motors will enable secure perception of the stimuli and be more inclusive to age and hand size.

5.5 Evaluation of 3 Motor Wearable Haptic Display

The insights from the evaluation of the prototype device with 5 motors helped refine the device design and make it more inclusive. The improvement in the design aims to ensure a clear understanding of the stimuli. Additionally, this iteration aims for a more aesthetically pleasing design and an easier-to-wear solution, which is very important to participants as it minimises the stigma associated with wearable assistive technologies (Moon et al., 2019), (Jain et al., 2020). Therefore, a new device with the following changes was developed:

- Reduction of motors to 3, based on the indications that motors 2, 3, and 4 were difficult to distinguish. The 3 motors are equally spaced and positioned around the arm.
- Make the electronic case smaller (5.5cm x 3.5cm x 2.5 cm), both for aesthetic reasons, to make the device more comfortable to wear, and to minimise the effect of the bigger case in the identification of motors 1 and 5.
- Change the type of elastic band that puts everything together to a more easy-to-wear one and potentially an aesthetically pleasing design (Moon et al., 2019).

5.5.1 Methodology

This study follows a quantitative research methodology. The data was collected through testing of absolute identification of stimulus location, repeated across four different arm locations, similar to the first evaluation. This evaluation aims to identify if there is a performance improvement in relation to the previous prototype.

5.5.2 Participants

For this evaluation, 12 participants were recruited, aged 21 to 35 (M = 27 years, SD=4.1, six male, six female, all sighted). The recruitment method and criteria were the same as in the previous study.

5.5.3 Procedure

Ethical approval was obtained from Birmingham City University's ethical committee to conduct this study. The participants proceeded to the test room and took their seats in front of the computer. The same procedure as the previous test was applied to ensure

appropriate application of the device on the participants' arms. The introduction session, which presents the stimuli and device functionality to participants, has been refined into an automated process. A sequence of three vibrations was triggered, one for each motor location around the hand. The vibrations had a 2-second time interval between them to allow for participants' receptor recovery and avoid cognitive load. The pattern will be presented twice for each location where participants wear the device during the test to ensure familiarisation. Participants were asked if they felt comfortable with the vibrations and if they could distinguish the different locations before the test began. The experimental interface has been adjusted to represent the three motors (Figure 5.1, Left). Participants were presented with the interface, received a demonstration of the interface's relation to vibrations, and were given the opportunity to practice with it.

Participants were tested in 30 vibration excitations, including 10 of each motor location in a random order. During the test, participants identified the location of the vibration excitation around the arm and submitted their answer via the on-screen interface. Participants repeated the test at 4 locations, counterbalanced and following the same procedure as the previous test. After each arm location, participants had a 2-minute break to rest. This round of tests lasted around 15 minutes.

5.5.4 Experimental Interface

The same experimental interface as the previous evaluation, with small adjustments, was used. The iteration is based on the number of motors displayed on the screen and available for participants to select. This is in response to the test needs and the new iteration of the device. Thus, this experimental interface visualised three motor locations (Figure 5.13,5.14)

5.5.5 Measures & Analysis

The same variables as the previous evaluation were measured (i.e., accuracy and time). Data analysis is based on the Shapiro-Wilk Test to assess the normality of the data distribution and the One-Way ANOVA or Friedman Test for normally and non-normally distributed data, respectively.

5.5.6 Results

Performance per Location

The results of the Shapiro-Wilks Test indicated that the data related to accuracy are not normally distributed in any of the four locations: Left Forearm ($p = .002$), Left

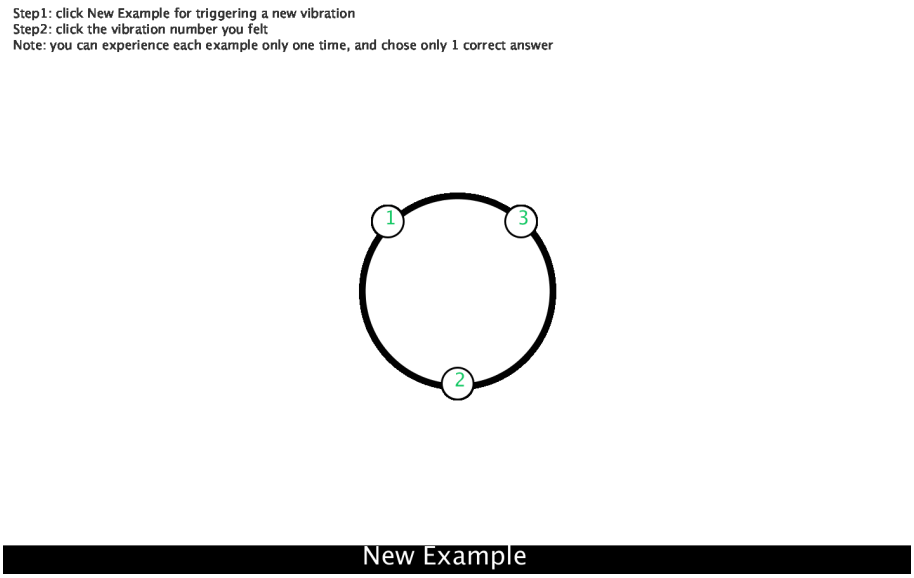


Figure 5.13: Experimental Interface

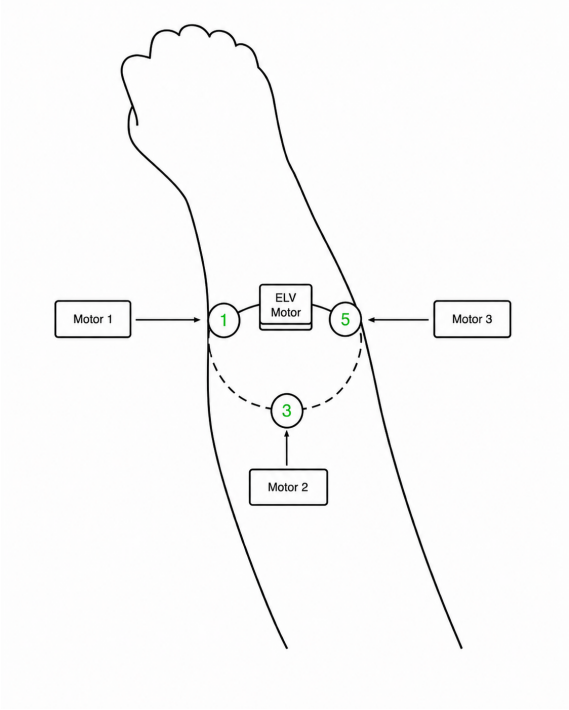


Figure 5.14: Anatomical positioning of three motors around the arm

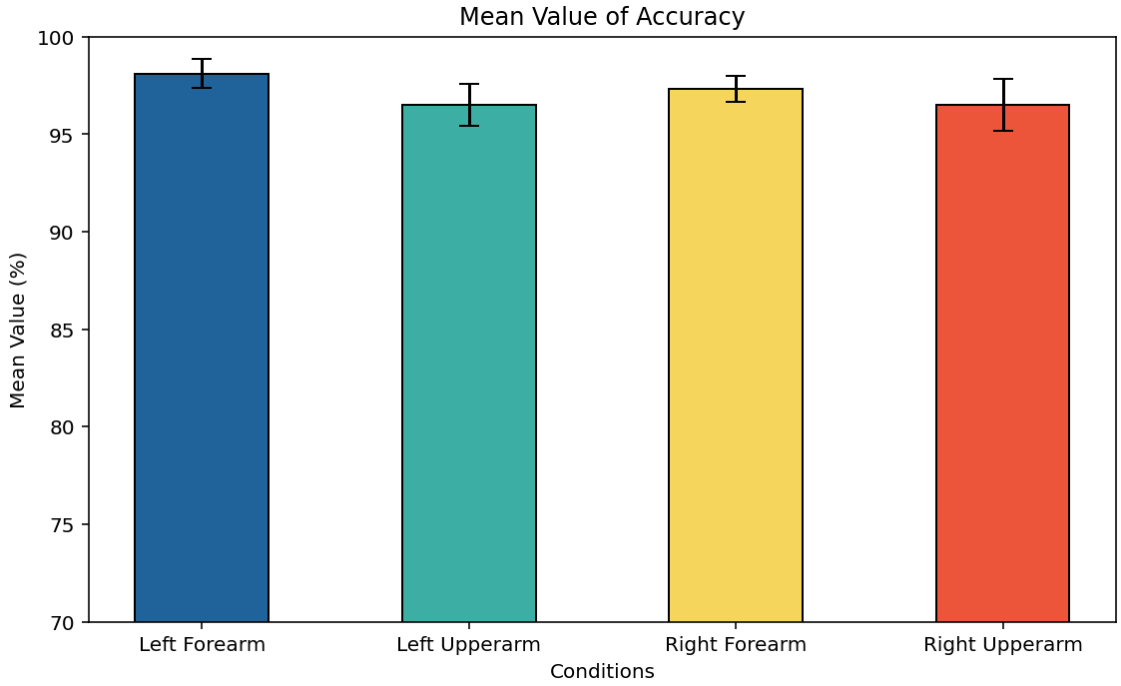


Figure 5.15: Accuracy Means per Arm Location (3Motors)

Upper arm (p = .021), Right Forearm (p = .015) and Right Upper arm (p <.001). Data related to the average time for stimulus identification were all normally distributed in all four locations: Left Forearm (p = .292), Left Upper arm (p = .110), Right Forearm (p = .181) and Right Upper arm (p = .254).

Task Accuracy

Friedman Test showed that there is no significant difference between the four hand locations based on the accuracy rate of task performance, LF (M = 98.12%, SD =.74%), LU (M = 94.1%, SD = 1.09%), RF (M = 97.32%, SD = .67%), RU (M = 96.5%, SD = 1.34%) x^2(3,12) = 1.724, p = .632.

Average Time of Task Completion

One-way repeated measures ANOVA was used to examine the average time between the four locations. The results showed there is no significant difference between the four conditions after the Bonferroni corrections (p = .0125), LF (M = 1473.71ms, SD = 100.82ms), LU (M = 1588.40ms, SD = 142.94ms), RF (M = 1757.06ms, SD = 153.04ms), RU (M = 1650.60ms, SD = 78.36ms). Wilk's Lamda = .405, F (3, 9) = 4.403, p =.036, which indicates a large effect size.

Motors accuracy

The accuracy rates of each motor across all four locations were combined to compare

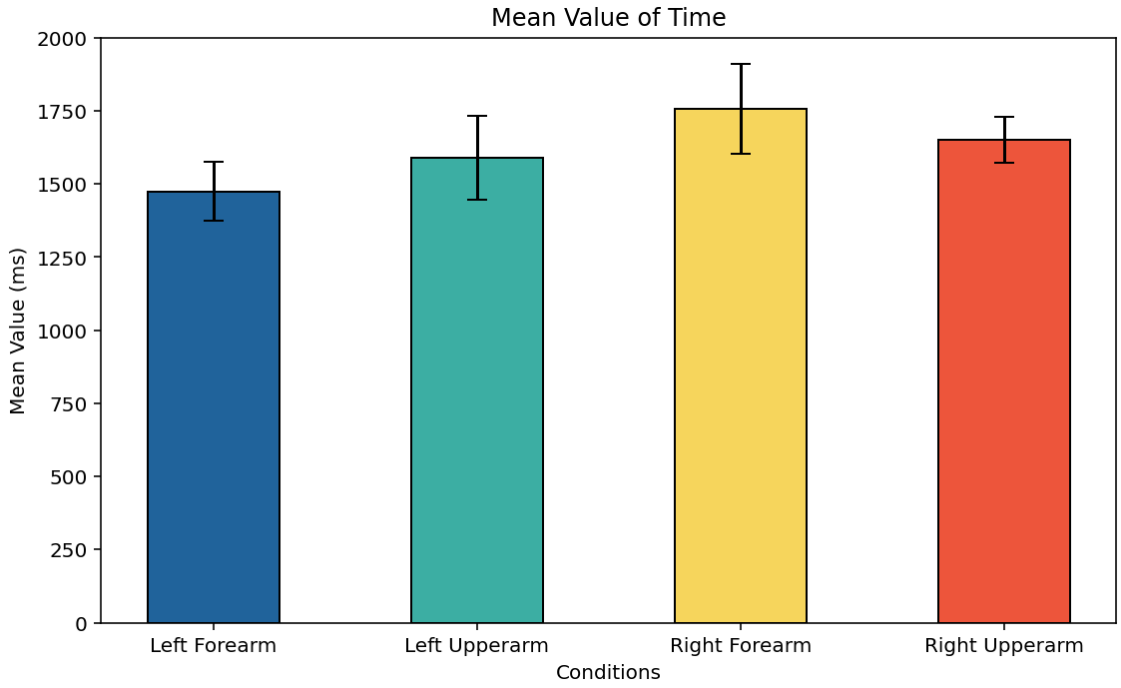


Figure 5.16: Time Means per Arm Location (3Motors)

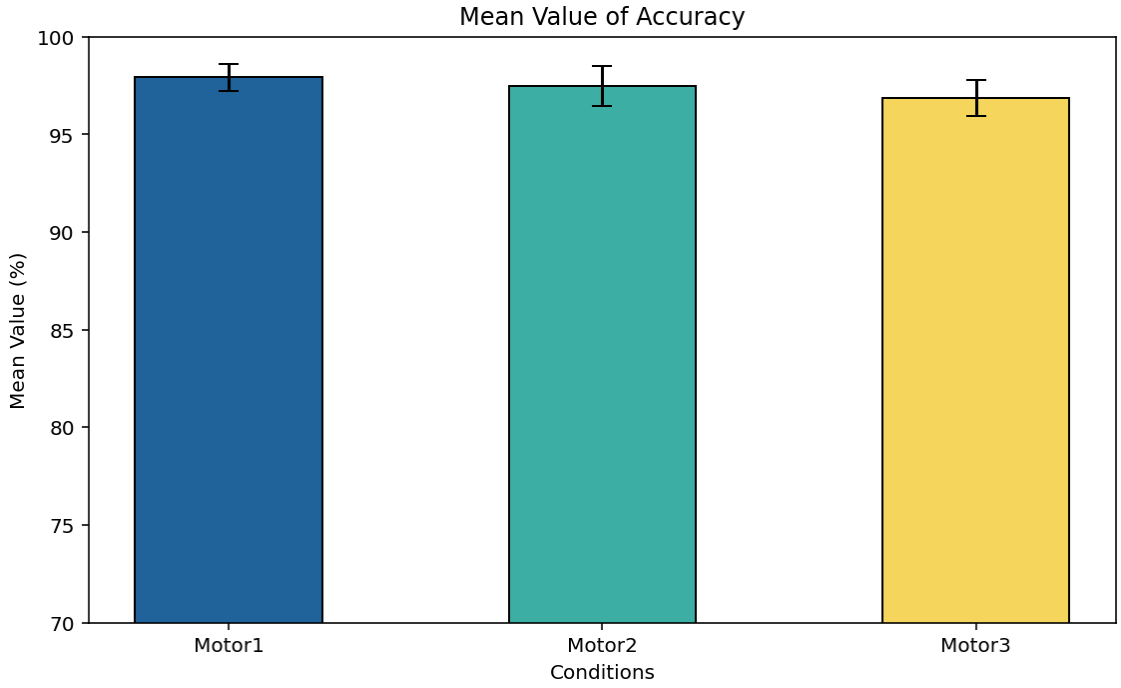


Figure 5.17: Accuracy Means per 3 Motors

the three motors and determine if there is a significant difference between them. The Shapiro-Wilk test indicates that the data are normally distributed in Motor 3 (p = .057), but not in Motor 1 (p = .002) and 2 (p < .001). Friedman test indicated no significant difference between the three Motors: Motor 1 (M = 97.92%, SD = .68%), Motor 2 (M = 97.5%, SD = 1.02%), and Motor 3 (M = 96.8%, SD=.93%), x^2(2,12) = .452, p= .798.

5.5.7 Results Discussion

The evaluation of the second prototype reaffirmed that the location of the device in the arm does not influence the accuracy of the responses. In this test, too, there is no significant difference in the accuracy of the answers between the different locations. However, unlike the first evaluation, there is no difference in task completion time, indicating that reducing the number of motors made the task less cognitively demanding and thus resulted in faster completion. Furthermore, a comparison of the accuracy of individual motor identification showed no difference between them. This demonstrates/indicates that the identification of the stimuli is the same in every location around the arm when the stimulus load is minimised due to the motors being more spaced apart. While the individual results from evaluating the prototype with three motors are valuable, the next essential step was to compare both devices to determine the optimal number of motors. Collectively, data from both evaluations can provide suggestions on the most suitable location on the arm where such a device should be worn.

5.6 Discussion

Two prototype devices were developed using the same technology configuration but with a different number of motors and component assembly. Individual evaluation studies indicate the benefits and limitations of this proposed device. Five motor devices indicated that different arm positions might influence the speed at which participants identify the 5 locations around the arm. Variables such as age and arm circumference might influence these results, too. The altered second prototype with three motors around the hand presented an improved design and easier wearability, as well as improved accuracy rates in the recognition of the stimuli. This section discusses both results of the two evaluation tests in parallel and concludes on the device that needs to be used in the following studies of this research, as well as the best location where participants should wear the device, ensuring accurate perception of stimuli and usability.

5.6.1 Comparing 5 to 3 motors

The observations from the first evaluation, (1) a difference in the performance of the individual motors and (2) a differentiation in the time for task completion in the different hand locations, suggested further exploration of the device design. Therefore, the second prototype evaluation presents the same test but with a device consisting of 3 motors. In the second, both differences were equalised, and the results showed no difference in time or individual motor recognition accuracy, indicating that having three motors outperformed five motors for the specific task. To support this argument, the accuracy and time average results were compared between the two devices (Table 5.6), which showed that the overall performance improved on the three motor tests. The average accuracy in all 4 locations across 5 motors was 71%, and 97% in 3 motors. Time similarly reduces from 2126ms in 5 motors to 1618ms in 3 motors. These results are supported by similar studies, such as Hong et al. (2017), which compares 4 to 8 motors, and Carcedo et al. (2016), which compares wristbands with 3, 4, 5, and 6 motors. In both cases, the least number of motors had the best performance. This result was anticipated, as a reduced number of options facilitates easier discrimination (Hong et al., 2017; Carcedo et al., 2016).

Equally important is the consideration of the task or the purpose of the device. As seen in the literature review, devices that consist of more than 6 motors and/or do not have a conventional arrangement approach of motors around the hand are often used for conveying more generic haptic sensations. Such examples include Rossa et al. (2016) and Reinschluessel et al. (2018), both of which feature eight motors around the hand, aiming to simulate hand movements and guide physicians during needle operations. Similarly, Sabry and El-Atabany (2024) utilised 18 motors in a grid around the hand, aiming to convey texture patterns, and Lin et al. (2024) used 16 motors in a grid around the arm to convey the deformation of the hand in VR. On the contrary, a significant number of wristbands with four or fewer motors are used in a context such as providing directions (Dobbelstein et al., 2016; Dupont et al., 2020; Paneels et al., 2013). In this case, four motors are especially helpful as they represent the four cardinal directions. Specifically for conveying information, such as actions, devices with four or fewer motors were observed, as in Carcedo et al. (2016), which codifies colours with vibration patterns using three motors, or Plaisier et al. (2020) with two motors that convey information through haptic Morse code. Although results indicated 3 motors are more suitable for conveying the exact location of a motor excitation around the arm accurately, the 5 motors device can present advantages in applications that utilise dynamic patterns (i.e., haptic animation) (Lo and Huang, 2024).

	5 motors					3 motors				
	LF	LU	RF	RU	Av.	LF	LU	RF	RU	Av.
Accuracy (%)	70.43	67.13	74.26	73.13	71.13	98.12	94.1	97.32	96.5	96.51
SD	2.95	3.08	2.26	3.04		0.74	1.09	0.67	1.34	
Time (ms)	2352	1993	2208	1951	2126	1475	1588	1757	1651	1618
SD	216	111	139	72		101	143	153	78	

Table 5.6: Performance data comparison between 5 and 3 motors.

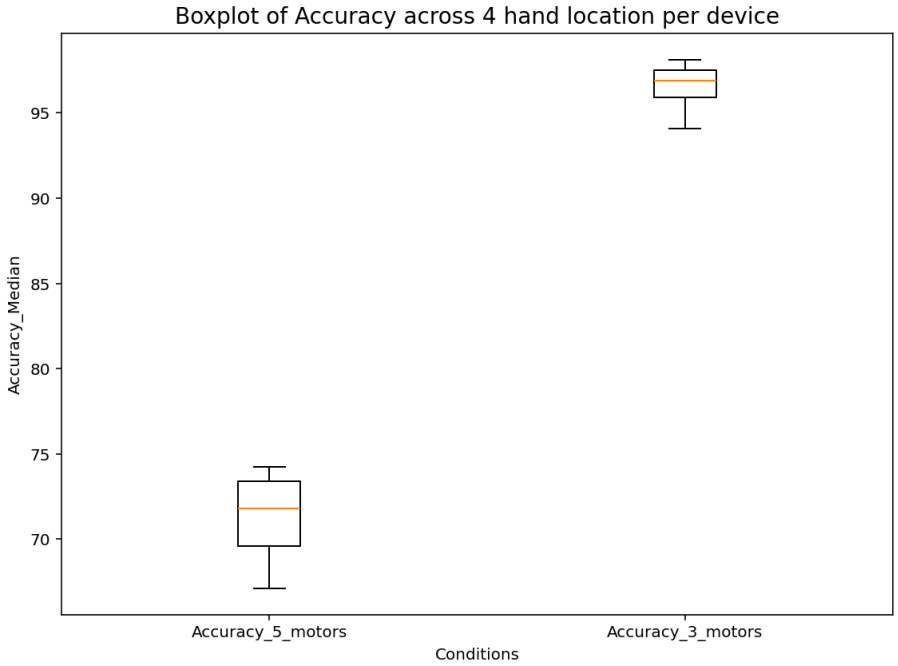


Figure 5.18: Accuracy across four hand locations in the two devices

5.6.2 Best Hand Position

The descriptive data (Table 5.6) show better performance in the Right arm, but no significant difference according to the ANOVA test. The most accurate was in the Right forearm, but the fastest performance was in the Right upper arm. On the contrary, the three motors performed most accurately in both forearm positions, Left and Right, and faster in both left-hand positions. This lack of significant differences may be due to the participants' diversity in individual characteristics. In addition, age could influence the perception of the stimuli (Sziebig et al., 2009). Similarly, Matscheko et al. (2010), and Carcedo et al. (2016) mentioned how the arm size might influence the perception and specifically how people with larger circumferences performed better in a greater number of motors than those with smaller. The qualitative data also showed that people had

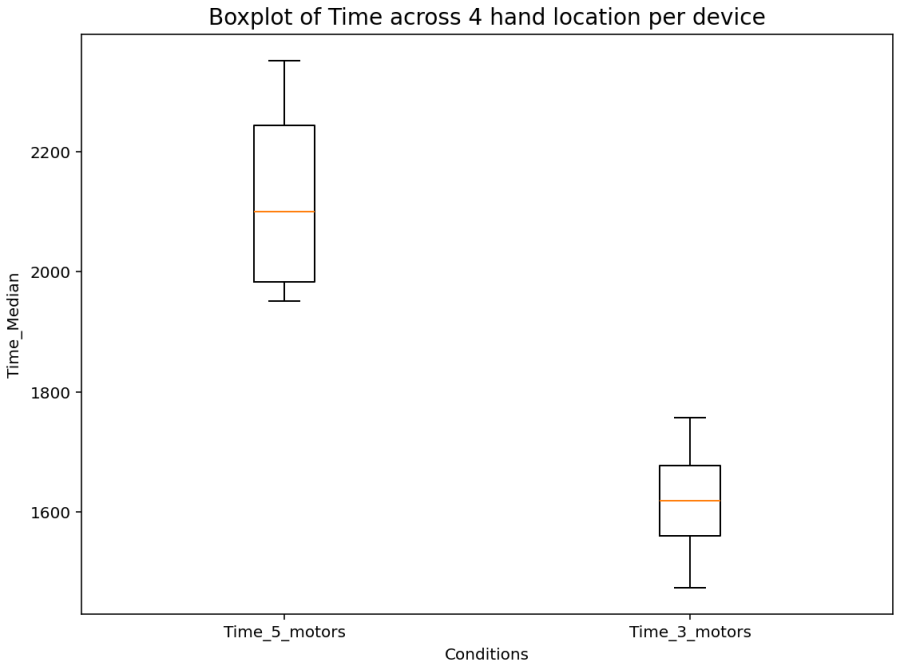


Figure 5.19: Times across four hand locations in the two devices

specific preferences in hand precision regardless of their performance. Given people's individuality, it was concluded that location in this use case can and should be up to the user's preference and needs. The design of the second iteration enables easy wearability and smooth movement of the device across the hand, as desired.

5.7 Limitations

The two devices are designed to convey discrete coded information using a spatiotemporal design (e.g., notification, language). Possible motor performance differences throughout the study due to low battery or the disposition of the motor around the hand might have influenced the results. This initial evaluation was primarily conducted with sighted participants and a limited number of visually impaired users. However, most studies indicate that BVI users have a better perception of haptic feedback than sighted users (Occelli et al., 2016; Kumari et al., 2022; Devarakonda, 2020; Horton et al., 2017), and the 3 BVI participants performed better by a very small difference than the average sighted user (section 5.3.6). Nevertheless, the limitation of comparing uneven populations is acknowledged. The following studies include only BVI users and evaluate the device usability and the location identification of the three motors in a scenario-based test that includes music production activities in a DAW.

5.8 Conclusion

Two prototype vibrotactile armbands, one with five motors and one with three, were designed and evaluated. The optimal placement of the device around the arm, as well as the ideal number of motors, was examined, answering the new sub-research questions of this research. No significant differences in performance were found between the various hand locations, indicating that the device can be worn wherever it is most comfortable and least cumbersome for the user. Three motors performed more accurately and faster than five motors in the task of identifying a specific location of the motor around the arm. Providing that future studies aim to evaluate such devices in use with spatiotemporal patterns for conveying information of interaction with music production software, it is suggested that three motors are optimal. Three motor device evaluation indicate that the patterns will be clear and easily understandable, which is essential for BVI people when using a computer. The identification of single vibrations was highly accurate, suggesting that the device will offer precision. The perceived workload will be examined in the next Chapter (6), especially in the presence of a music background, like in a realistic scenario of music production, to evaluate if this system has the potential to reduce cognitive load and make access to DAW more efficient for BVI creatives. Nevertheless, this design provides flexibility for use in a desk-like scenario, such as in a music studio, and enables straightforward interaction with computer keyboards and musical instruments. It also supports public use, allowing for working on a laptop in a public space, which meets the requirement that participants provided in Chapter 3 for portability. The following chapters 6 and 7 will utilise the feature of clear stimulus complex vibrotactile feedback patterns produced by this device for the accessibility of DAWs.

Chapter 6

Study 1: Evaluating the Use of Tactons for Perception of Information in DAWs.

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6.1 Introduction

Previous interviews with BVI music producers revealed the need for haptic technologies as an alternative solution for accessibility (Saha and Piper, 2020). Participants in Chapter 3 provided specific ideas and among those they suggested vibrotactile feedback that assists with navigation and perceiving information about FX parameters. This study examines the use of vibrotactile feedback as an assistive tool for BVI musicians and audio producers in the pre-interaction stage (Norman, 1984), where users assess the information before making a decision to act. This chapter explores the potential of this method to reduce perceived workload and improve the speed and accuracy of information identification in relation to the existing Screen reader method. To achieve this, a study was designed that compares task completion measurements in three conditions: haptic feedback alone, the existing screen reader method, and a hybrid approach combining both screen reader

and haptic feedback. The emerging guidelines in Chapter 3 indicated that the use of Tacton for the purpose of expressing numerical values, navigation, and information is the most suitable. To simulate realistic conditions, background music was used as a distractor during testing, mimicking the experience of processing audio in a DAW while using a screen reader. This generates a new research question: 'Is there a difference in the performance and perceived workload when receiving information about EQ effect through screen reader, haptics and screen reader with haptics?'

The following section details how EQ information was mapped from screen reader outputs to vibrotactile Tactons (section 6.2). Additionally, it presents the way EQ plug-in elements have been utilised in the mapping of the information to Vibrotactile feedback. The remainder of this chapter is dedicated to the evaluation of the proposed system through comparison with the existing screen reader method and a hybrid screen reader with haptic feedback. Section 6.3 outlines the methodology and the test procedure, whilst sections 6.4 and 6.5 present the results, discussion and interpretation of the findings in relation to the research questions.

6.2 Development: Mapping Screen Reader Information to Vibrotactile Feedback Patterns

The prototype device with three motors presented in chapter 5 was used in this study. Evaluation of this armband showed that users can identify the three different locations of vibration excitations around the arm at a rate of 98% accuracy. This indicated the suitability of the proposed device to convey Tactons and specifically the use of the *Logical* metaphors, a design approach seen in Chapter 2.

To support the study, a custom program was developed to trigger the stimuli that deliver EQ frequency centre values in the DAW, in three feedback conditions (screen reader, screen reader and haptics, haptics alone). The software is designed in the MAX 8 programming environment and has been made freely available on GitHub (Karpodini, 2025d). Its overall process workflow can be found in Appendix D.

6.2.1 ReaEQ-Reaper Equaliser

ReaEQ (Figure 6.1) is a free equaliser (EQ) plugin included in Reaper DAW. An equaliser is a complex tool that allows adjusting the frequency range of an audio signal by either boosting or cutting it. There are three elements that control this audio effect and comprise this type of audio processing: (1) The choice of the frequency (measured

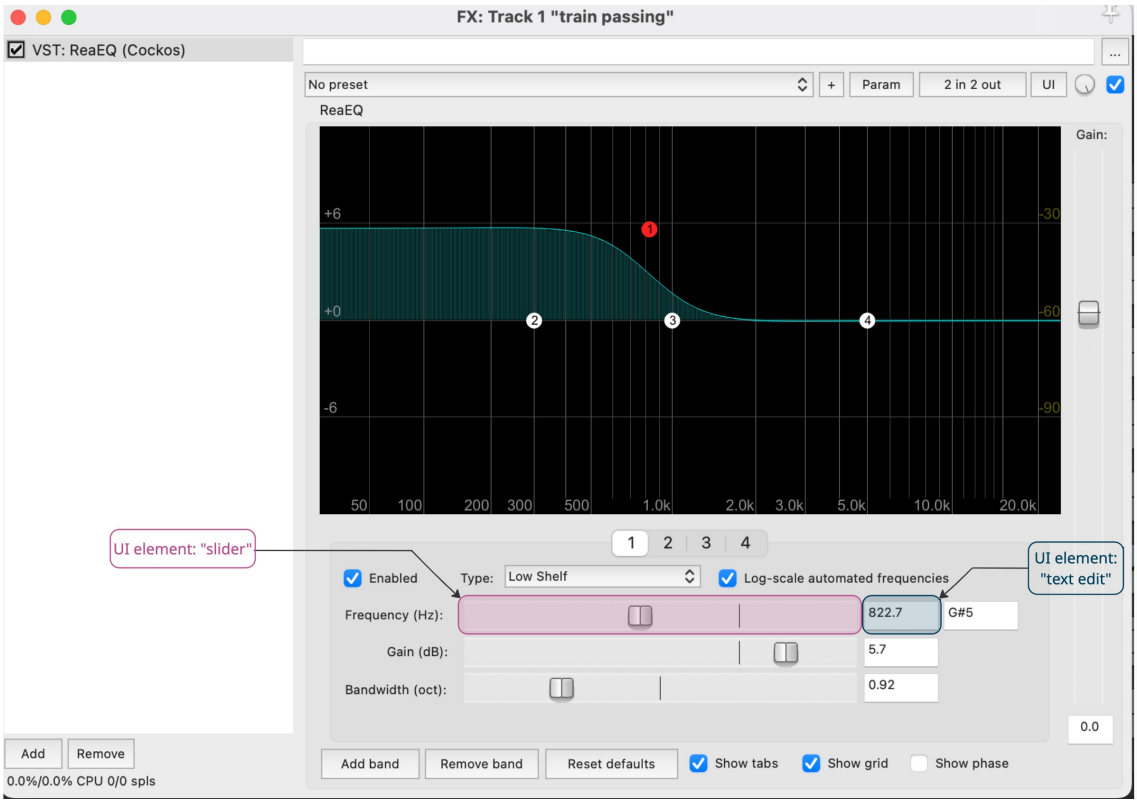


Figure 6.1: ReaEQ plug-in window in Reaper DAW. Highlighted interface elements: slider and text edit, allow users to adjust the Frequency Centre parameter

in Hz) range that will be edited; (2) the level (gain) that it will be boosted or cut (measured in dB); and (3) the bandwidth (Q value), how narrow or wide are the range of frequencies being adjusted. Traditionally, there are three types of filters: (1) Low-Pass, (2) High-Pass and (3) Band-Pass, which provide a simplified representation of the range of frequencies that are allowed to pass through the filter (Izhaki, 2017).

Sighted users can look at the EQ graphic representation and immediately understand the relationships of all three elements of information: Frequency, Gain, and Q (Figure 6.1). Even though there are three separate elements in an EQ, they all work as one to achieve the desired outcome. BVI users need to navigate a list of interface elements linearly in order to deduce the element that contains each piece of information (Saha and Piper, 2020). The screen reader presents each of the three EQ parameters separately rather than as a whole, as is the case with the visual representation. In addition to EQ information (i.e., frequency, gain, bandwidth), BVI users perceive the interface element they are currently using and the type of interaction with which they can edit the given numerical value. If they are in the slider element, they can move with the left and right cursor keys and edit the centre of the frequency range in relation to the current position. If they are in the text element, they can type a new value. This method presents barriers in perceiving the information due to inadequate representation of graphical information

and a complex navigation system using the screen reader (Chapter 3; Saha and Piper (2020)). Participants of both studies indicated how they use hardware devices to mitigate this problem, but are still missing an understanding of information apart from hearing the quality of sound, thus missing a connection and efficient interaction with the software.

In this study, two types of information were combined: one directly linked to the EQ element, the frequency centre and one related to the interaction with the system, the UI element from which the user can access this information. The frequency centre was chosen as it is the most important element of the EQ that determines the part of the sound spectrum that is being adjusted. Additionally, it is based on a clear visual mapping along the x-axis that aligns with our device's spatial arrangement of vibration motors (section 6.2.3). Frequency centres are grouped into three frequency bands representing the frequency ranges low (16Hz - 250Hz), middle (250Hz - 6kHz) and high (6kHz - 16kHz) (Izhaki, 2017). The UI elements used are the slider and the text field, as presented in the ReaEQ of Reaper. The participants were asked to identify the frequency range to which the given stimulus's frequency centre belonged, thereby identifying the type of filter that had been applied to the audio signal. Thus, they are asked to identify whether the information belongs to the low, middle and high-frequency ranges. In addition, they need to tell what type of interface element (i.e., 'slider' or 'text edit') they got this information from (e.g., low frequency, slider). The two types of information are inspired by the information provided by the SR (section 6.2.2). Therefore, six pieces of information will be assessed (low slider, low text, middle slider, middle text, high slider, high text).

6.2.2 Screen reader

A text-to-speech generator was utilised to produce the audio stimuli for this study. A total of 30 WAV tracks were created, each containing the stimuli used in the study. These audio tracks replicate the same voice feedback content employed by the VoiceOver screen reader for the ReaEQ tool in Reaper. This voice feedback is incorporated into two test conditions: one using the screen reader alone and the screen reader with haptic feedback.

Five distinct examples with different numbers that represent the frequency centre were generated for each of the six types of information being assessed (5 x 6 = 30 frequency centre number examples). This approach aimed to minimise learning effects and simulate a realistic scenario where the screen reader provides a specific number from the frequency band range. The numbers presented were chosen to introduce varying levels of interpretive complexity.

The anatomy of the screen reader message, as presented from VoiceOver in Reaper,

contains the number representation of the frequency centre, an indication of the possible interaction and the UI element. The 30 audio stimuli can be found in the GitHub page (Karpodini, 2025d). Figures in the Appendix D show the software's structure in detail.

Examples of SR stimuli (see the full list in Appendix (D.1)):

'95.0, content selected, edit text', *'4677.0, band frequency, slider'*

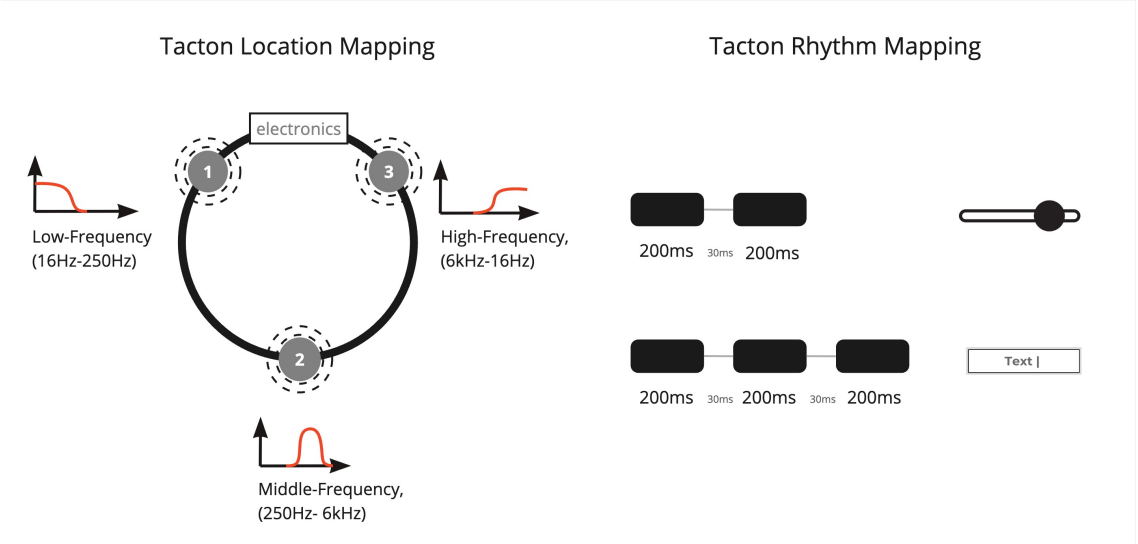


Figure 6.2: Tacton 1 (left image): Location of vibration = EQ Frequency Band, Tactons 2 (right image): Rhythm = UI element. Final Tactons example: (1) two vibrations on the motor 1 = slider element, low-frequency band. (2) three vibrations on the motor 3 = text field element, high-frequency band.

Modifier Tactile Patterns	**Tacton 1 / Location = Frequency Band**	**Tacton 2 / Rhythm = UI elements**
1. Low Frequency Slider	Left motor	2 short vibrations
2. Low Frequency Text	Left motor	3 short vibrations
3. Middle Frequency Slider	Middle motor	2 short vibrations
4. Middle Frequency Text	Middle motor	3 short vibrations
5. High Frequency Slider	Right motor	2 short vibrations
6. High Frequency Text	Right motor	3 short vibrations

Table 6.1: Tactile Patterns

6.2.3 Haptics

The Haptics (vibrotactile feedback) that was presented to users was inspired by the concept of *Modifier Tactile Pattern* by J. Oliveira and Maciel (2014). Modifier Tactile

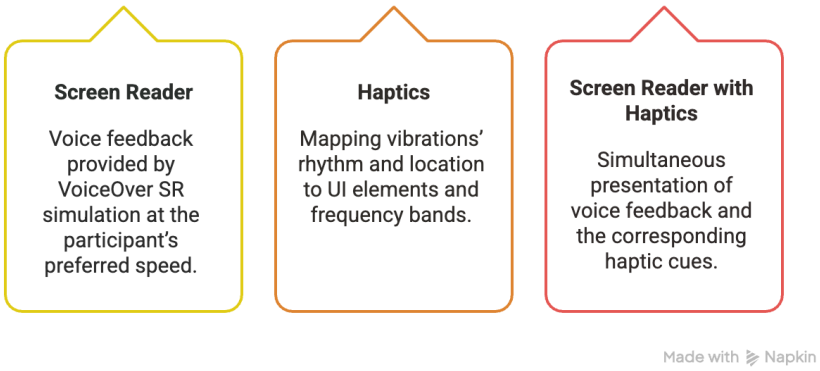


Figure 6.3: Stimulus Types across Conditions

Patterns consist of a combination of different meaning Tactons. In the example of two tactons, the change in one of them will partially change the meaning of the pattern. In this case, the first Tacton represents using *Logical* metaphor (Wittchen et al., 2022), the three frequency bands, low, middle, and high-frequency, are mapped to the three locations around the hand, representing low to high as left to right. The second Tacton is abstract and utilises two rhythmic patterns, a sequence of (1) two short vibrations and (2) three short vibrations (200ms duration and 30ms pause), representing the UI element that is being presented, text input or slider (Figure 6.2). Changing either parameter, the Rhythm or the location, will change part of the information conveyed. The combination of the two parameters creates the final Tacton, a spatiotemporal pattern that conveys both pieces of information simultaneously. Table 6.1 presents the six Tactons used in two conditions of the test: haptic alone and screen reader with haptics.

6.3 Methodology

A mixed-methods approach was employed to evaluate three conditions for conveying information about the EQ effect in the presence of a music background. The challenges in recruiting specialist participants (i.e., BVI individuals, music producers) result in a small sample size. In this context, utilising a hybrid methodology helps mitigate the limitations of the sample by enabling better interpretation of the results and preventing invalid generalisations. Therefore, due to the small sample, it is essential to consider the purpose of this study as exploratory rather than strictly experimental (Lazar et al., 2017). The evaluation included the collection of performance data (accuracy, time), which indicates the interaction patterns across each condition. This was complemented by semi-structured interviews, which allowed participants to provide feedback and help

justify the identified patterns of the quantitative data. Finally, standardised questionnaires such as NASA-TLX (Hart and Staveland, 1988) and UMUX (Finstad, 2010) were utilised to assess subjective workload and usability in a reliable, objective, and comparable manner (Tosi et al., 2021).

A scenario-based evaluation approach was adopted to ensure the tasks reflected realistic use cases of music production. This method helps participants engage with the task as if it were part of a realistic use case situation. When a system is designed for a creative task, it is important that participants perform the task without feeling observed or assessed (Dewey and Wakefield, 2014). Users feel more connected to the test by identifying themselves as actors in a situation they have previously participated in or suggested during the ideation stage of the research (Chapter 3). This results in rich qualitative feedback while participants are inspired to provide feedback on a system they can see the potential use in their workflow (Sahib et al., 2013). The extra stimulus of the music in the background, typical of the audio likely to be present in a real mixing task, is considered a distractor for the user, as it might influence their performance compared to its absence. Thus, the study design choices are influenced by the role the distractors play in the performance of a task and the cognitive load they create (Cauchard et al., 2012; Gonzalez and Aiello, 2019).

***Scenario**: In the scenario of an audio production process where music is playing in the background and the producer wants to navigate in an Equaliser effect and get information about the value of the frequency center, the perceived workload and performance (accuracy, time) are compared across three ways of perceiving this information: screen reader alone (SR), screen reader and haptics (SRH) or haptics alone (H).*

6.3.1 Participants

Six participants (all male) who were all music producers with varying degrees of visual impairments were recruited: 4 were registered blind, and 2 had low vision. Participants' ages range from 24 to 50 (M = 35, SD = 9.96). The study was advertised in the forum for Visually Impaired Users of Reaper (`https://groups.io/g/rwp`), which supported the recruitment of participants from the UK and Greece. Four studies were conducted in English and two in Greek language. Requirements for participation are a basic knowledge of using VoiceOver screen reader and the EQ effect in Reaper. From the collected information prior to the interview, participants have a variety of experience levels with VoiceOver and Reaper (Table 6.2).

	Age	VI	VO Exp. Level	Reaper Exp.Level	MP Exp. Level
P1	39	B	Beginner	Advanced	Intermediate
P2	50	B	Advanced	Beginner	Advanced
P3	41	B	Advanced	Beginner	Advanced
P4	24	LV	Beginner	Beginner	Intermediate
P5	28	LV	Intermediate	Intermediate	Advanced
P6	28	B	Intermediate	Advanced	Beginner

Table 6.2: Participant demographics, level of experience with VoiceOver, Reaper and Music production in general

6.3.2 Apparatus

The test was conducted on a MacBook Pro Laptop. Sony ZX310 stereo headphones were used for playing the audio element of the study. All oral feedback from participants during the study was recorded using a Zoom H4N microphone and a DSLR camera. The study included background music playing using the iTunes player on the laptop used for the test. The music was selected to be instrumental, as music with lyrics provides extra distraction in complex tasks (Perham and Currie, 2014). Based on previous studies (Cauchard et al., 2012; Gonzalez and Aiello, 2019), the post-rock song 'The Shaping of Helpless Joy' from the album The Exquisite Death of Saxon Shore by the rock band Saxon Shore was selected for this study. The track lasted 4:52 minutes, which was approximately the duration of the test per condition. To reduce participants' familiarity with the music, the use of mainstream artists was avoided, and participants confirmed they were unfamiliar with the artists' music used prior to the test.

6.3.3 Procedure

The Birmingham City University's ethical committee granted ethical approval to conduct the study. Participants who consented to take part in the study were contacted to schedule a meeting date. They were provided with an information sheet beforehand and asked to complete a consent form. The study was conducted either at university facilities or in the participants' home studios.

After completing the consent form, demographic information about their age, location, and type of visual impairment, primary DAW and primary SR were collected. The information submitted was cross-referenced with participants before the test to ensure the accuracy of the data. At the beginning of the test, participants were asked to describe how they use their SR during the mixing, if they switch it off at all, which

speed they are using and if they are using a different output from the one they are using for the mixing. Subsequently, participants were asked about the ways they interact with Equaliser in Reaper (section 6.1), for example, Slider, Text Input, and Hardware. Their level of knowledge regarding the use of the Equaliser was examined by asking how they would divide the frequency range into bands. These questions provided insights into participants' real music production set-ups, allowing us to compare them with the study's setup to better evaluate the results and understand any abnormalities.

Participants then wore the armband in the preferred location (five on the right forearm and one on the right upper arm). The researcher ensured that the wristband was adjusted properly and the motors were evenly placed. To build familiarity with the device, users participated in a practice session, identifying the three vibration points, and they confirmed they are comfortable with the vibration intensity. The rest of the test setup was checked for adjustments to ensure comfort too (i.e., headphones fit, volume of the music, and SR playback speed).

Participants received a demonstration of the test interface, which involved pressing the *spacebar* to receive the stimuli. The training session involved familiarisation with interpreting the study's six pieces of information (Table 6.1 using each of the three methods, helping minimise the learning effects). Following that, to ensure participants were familiar with the stimuli, participants had 2 minutes of free exploration where they could repeat any of the six examples again until they felt confident and understood the stimuli.

Participants completed a total of 90 trials, with 30 trials for each of the three conditions. Each set of 30 trials comprised five repetitions of the six pieces of information. Trials were randomised within each set, and the three conditions were counterbalanced to reduce learning effects. To mitigate fatigue, participants took a 5-minute break between each 30-trial set. The full trial list and order are available in Appendix D.

At the end of each test condition, participants were asked to complete a NASA-TLX (Hart and Staveland, 1988) and UMUX (Finstad, 2010) questionnaire. Finally, at the end of the study, participants were asked a series of questions via a semi-structured interview. The test lasted approximately 90 minutes.

Semi-structured Interview questions:

- How would you rate your experience using each method (screen reader alone, screen reader and haptics, haptics alone) for getting information in the EQ effect?
- Do you have a preference for any of the methods you have experienced?
- Do you have any additional comments or suggestions for improving the usability

of vibrotactile feedback (mapping of information to vibration patterns)?

- How satisfied were you with the level of information provided by each method (what do you think of the choice of EQ plugin specifications that are mapped in the haptics?)
- How do you think this test (methods) impacts your perception of accessibility? (How likely is it that you would use it for accessibility? What are the prospects of this technology?)
- How would you describe your experience of perceiving the information while listening to the music?
- Do you have any other comments/ ideas?

6.3.4 Measures

Participants triggered the stimuli through the *spacebar* key, and they provided their answers verbally. The verbal answers were captured via audio-visual recording of the test and manual note-taking. The **Accuracy** of the task completion depends on the correct answer in both sections of the task, the UI element and the Frequency band. Answers need to be correct in both elements to be considered correct. **UI Errors and Frequency Errors** are the percentage of the answers that users answered incorrectly in the relevant section of the question. The spacebar presses of participants were time-stamped and used to calculate the total **time** to execute the task. The accuracy of our MAX code was validated by comparing its output with manually recorded data across multiple trials, ensuring consistency and reliability in data collection. **NASA-TLX and UMUX** questionnaires were read aloud to participants who would reply verbally. Responses were captured with audio-visual recordings and in written form. The transcriptions of the videos and the written documentation were cross-referenced.

6.3.5 Measures' Analysis

Statistical analysis methods were applied, starting with the Shapiro-Wilk test, to evaluate the normality of the data in each of the three conditions. This evaluation included metrics such as Accuracy, Time, and the overall NASA-TLX score. For datasets that did not meet normality assumptions, the Friedman Test was applied. Normally distributed data were analysed using a One-Way Repeated Measures ANOVA. UMUX scores were calculated using the Lewis regression equation, which translates to a System Usability Study (SUS) equivalency score. The answers to the semi-structured interview questions

were analysed using Braun and Clarke's Thematic Analysis, which allows flexible interpretation of the data (Braun and Clarke, 2006). The two Greek interviews were manually translated into English, and all data were entered into NVivo software for the qualitative analysis. Following that, data coding employed the 'repeated reading' method, and participants' quotes were labelled based on their content (i.e., comparisons of methods and improvements in vibration patterns). Finally, labelled quotes were grouped by substance, leading to the generation of themes.

6.4 Results

This section presents the results of this study in three parts. Firstly, the participants' existing experience with the use of EQ effect in the DAW was established, confirming the patterns presented in previous work (Harrison et al., 2023; Saha and Piper, 2020). Then, the quantitative analysis presents the comparison of the performance metrics (accuracy and time) as well as the perceived workload and usability across the three methods examined (SR, SRH, H). The third part presents the four themes that emerged from the thematic analysis of the participants' feedback about the suggested new methods (H and SRH). The first theme highlights how vibrations were perceived faster than SR in conveying the information. The second theme presents the benefits of the multimodal experience offered by the suggested method. The third theme includes suggestions for improvement of the Tactons, and the fourth contains ideas for future work.

6.4.1 Participants' Existing Experiences

This section describes how each participant uses the screen reader in the DAW (e.g., how they utilise the different audio outputs, what speed and volume they use) and how they access the equaliser information (e.g., what UI element they use). It also explores the user's knowledge and understanding of EQ frequency bands, allowing a better evaluation of participants' performance in the test.

P1 uses the screen reader and the music on the same output because he does not have an audio interface to help him split the audio streams. The speed of his screen reader is moderate (50%). On the EQ, he tends to turn off the screen reader or has it in a very low intensity. He mainly edits the EQ through Osara's 'Parameter list' function. That means he is directly accessing the frequency value via a slider. He stated that the Text field is not useful to him, as different plug-ins might have different numerical representations of values. Specifically, in the EQ, he prefers to adjust the slider and find the desired frequency by focusing more on the audio quality than the SR feedback.

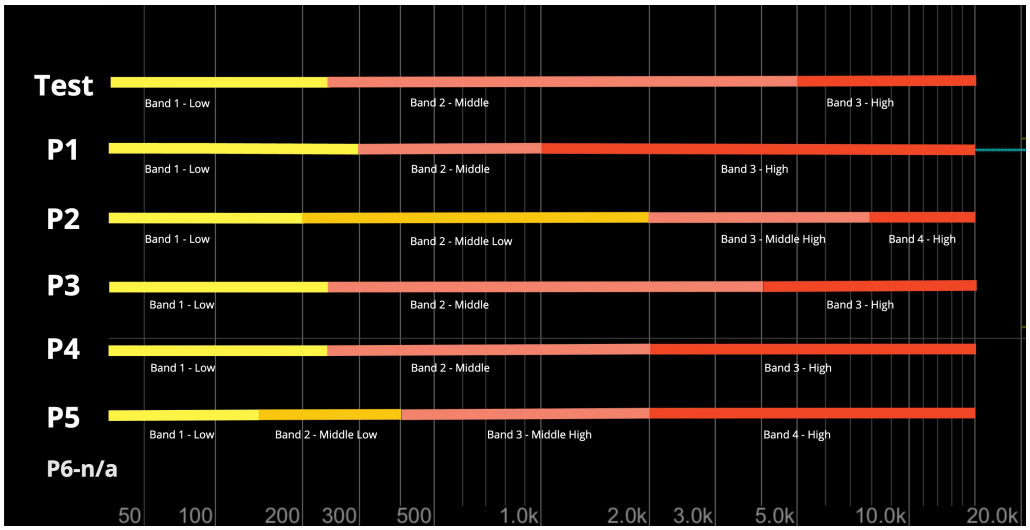


Figure 6.4: EQ bands

P2 uses the SR at a moderately fast speed (70%). He has the SR in the laptop speakers and the music in the monitor speakers using an audio interface to split the audio. When using the EQ, he mutes the voice feedback to concentrate more on the music he is editing. He will primarily use his hardware device, Console 1 (Softube), for EQ processing, which provides access to parameters through encoders and voice feedback for accessibility.

P3 is using SR at a very fast speed (100%). Usually, the SR is turned off when editing the EQ and turned on if the user wants to access the exact value. Once he has navigated successfully to the slider with the SR, he will turn it off. He will usually edit the value using keyboard interaction. He has SR on his laptop speakers and music on his monitor speakers.

P4 mainly uses the DAW with an enlarged screen and magnifying tools. He is only using an SR for accessing long text. To access the EQ, he uses both a mouse and a keyboard to adjust the slider. With the mouse, he will move across the graphical representation or use a slider across the frequency range to find the frequency that needs editing.

P5 uses SR at a moderate speed (50%), and using his audio interface, he has SR in the laptop and music in the speakers. When using the EQ, he turns voice feedback off. He describes how he usually sets the gain of the EQ to maximum and then uses the slider to scan through the frequency spectrum, finding the frequencies that require editing. He states specifically that it tires him to have the SR on, along with the music. He turns it on only to hear the exact value if needed. In the case he wants to access the information, he presses 'P' to access the Osara parameter list function and get the value from the screen reader.

P6 uses a braille display as well as the Screen reader. His screen reader speed is around 30%, moderate slow. He is switching SR off when doing audio processing, but he benefits from getting the information he needs from the braille display. He has the SR in his headphones and the music in the speaker, but he found the process of setting this up challenging. To use the EQ, he uses the slider and moves up and down with the arrows to navigate across the frequency spectrum. He only uses the text field if he knows he wants to set the frequency to a specific level.

P	SR in DAW	SR for EQ	SR/Music Output	SR Speed	SR When EQ	Interaction Type
P1	Yes	No / Very Low	Same Output	Moderate (50%)	Off / very low	Uses Osara 'Parameter List' to adjust sliders
P2	Yes	No	Split (Laptop: SR, Monitor: Music)	Moderately Fast (70%)	Off	Uses Console 1 hardware encoders with voice feedback
P3	Yes	No	Split (Laptop: SR, Monitor: Music)	Very Fast (90%)	Off	Uses keyboard after locating the slider with SR
P4	Limited (only for text)	No	N/A (Uses Magnification)	N/A	N/A	Uses mouse and keyboard, relies on graphical EQ representation
P5	Yes	No	Split (Laptop: SR, Monitor: Music)	Moderate (50%)	Off	Scans frequency spectrum using sliders, retrieves values via Osara Parameter list
P6	Yes	No	Split (Headphones: SR, Speakers: Music)	Slow (30%)	Off / Braille Display	Keyboard for accessing Slider, text field only for exact frequency

Table 6.3: Screen Reader (SR) Usage in DAW and EQ Interaction

Overall, most users split the audio from SR and audio mix into two different sources, and they mostly turn the voice feedback off when working with an EQ. SR is useful for helping users navigate to the UI elements (Slider) and getting the frequency value at the end of the editing process. The speed of the voice feedback varies across the participants, but most of them use it at a moderate speed. Finally, the way they split the frequency spectrum into bands when using the EQ is illustrated in Figure 6.4 and indicates a deviation, especially at the threshold between the middle-frequency range and the high-frequency range. Regardless, users will swipe through the range to find the frequency that needs to be edited, relying on the sound quality for this process. Table 6.3 presents a summarised version of participants' existing experiences.

6.4.2 Performance and Workload Data

The Shapiro-Wilk normality test was used to examine the normality of our data. The test showed that data related to the Accuracy Rate were normally distributed in all three conditions, but data related to the Time of task completion were not normally distributed. The NASA-TLX questionnaire data were analysed to assess the normality of both the overall scores and individual factors across all conditions. Overall Score data, as well as Temporal Demand and Effort, were normally distributed. The rest of the individual factors (Mental Demand, Physical Demand, Performance and Frustration) were not normally distributed across all conditions.

Performance

The participants had an average **Accuracy** in the Screen Reader condition of 95.51% (SD=2%), in the Screen Reader with Haptics condition 94.97% (SD=1.61%) and in the Haptics condition 96.65% (SD=1.55%). A one-way repeated measures ANOVA showed that there is no significant difference in the participants' performance between the three conditions, Wilks' Lambda = .852, F(2, 4) = 0.347, p = .726, partial $\eta^2 = .148$, indicating a large effect size (Figure 6.5). The Friedman Test indicated that there is no significant difference among the **UI errors** in the performance of the three conditions SR (M = 3.61, SD = 1.8), SRH (M = 3.61, SD = 1.74) and H (M = 1.11, SD = .82) x^2(2, N = 6) = 1.44, p = .486. No significant difference was observed in the pairwise comparison using the Wilcoxon signed-rank test. The Friedman Test shown no significant difference among the **Frequency errors** in the performance of the three conditions SR (M = 1.11, SD=.82), SRH (M = 1.94, SD = .51) and H (M = 2.22, SD = 1.02), x^2(2, N = 6) = .737, p = .692. No significant difference was observed in the pairwise comparison using the Wilcoxon signed-rank test. No significant difference found on the **Time** of the test completion between the different conditions after conducting Friedman Test SR (M = 5.02, SD = .47344), SRH (M = 4.4, SD = 1) and H (M = 3.47, SD = .61) x2(2, N = 6) = 4.333, p = .115. Post hoc test with the Wilcoxon signed-rank test showed no significant difference after the Bonferroni corrections. Table 6.4 shows all the means (SD) of all measurements.

Perceived workload

Table 6.5 summarises the results of the NASA-TLX questionnaire, presenting the mean scores and standard deviations for each of the six workload factors as well as the overall workload score across the three conditions.

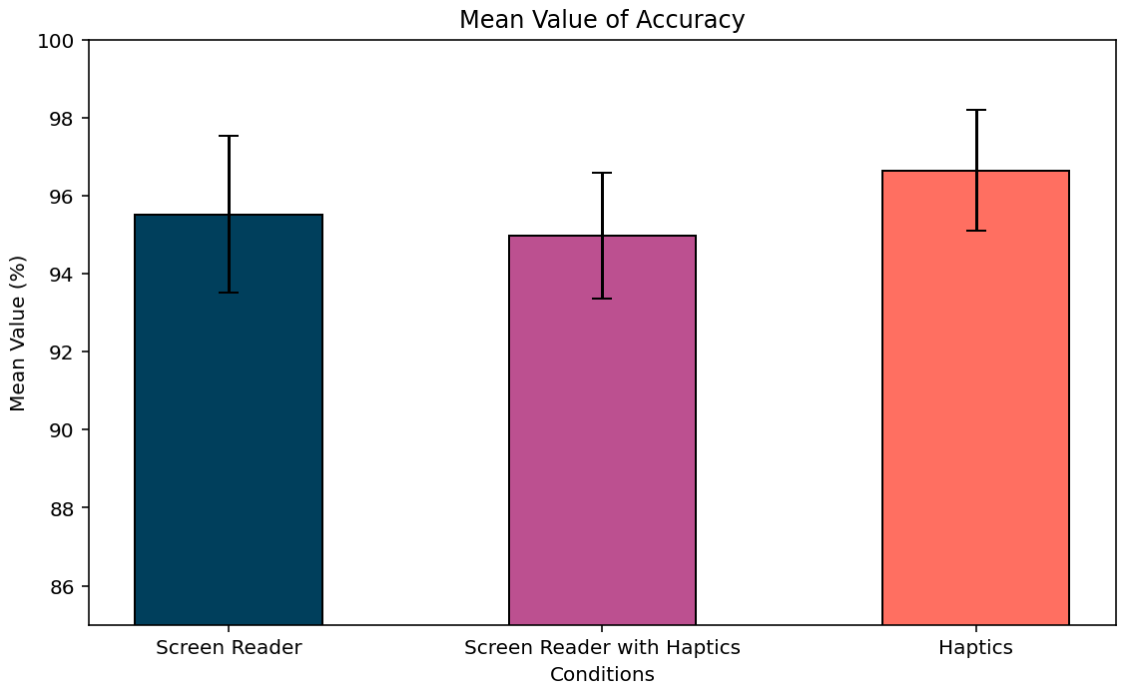


Figure 6.5: Mean Accuracy Scores for Different Three Conditions: Screen Reader, Screen reader and Haptics, Haptics

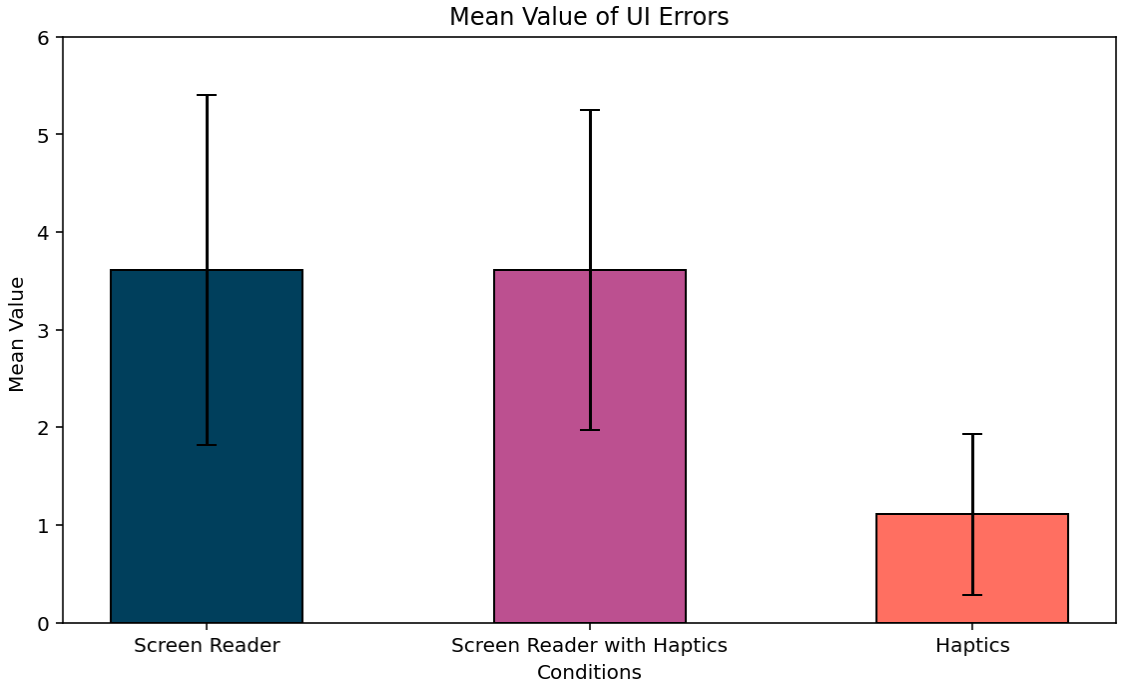


Figure 6.6: Mean UI Errors Scores for Three Different Conditions: screen Reader, screen reader and haptics, haptics

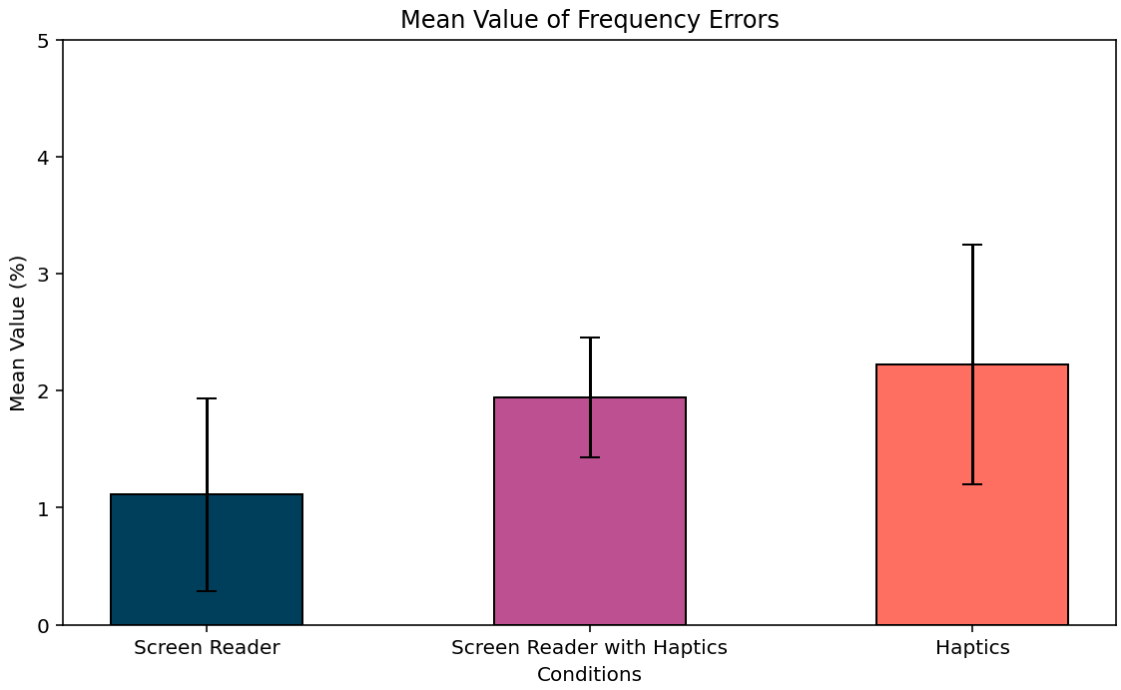


Figure 6.7: Mean Frequency Errors Scores for Three Different Conditions: screen reader, screen reader and haptics, haptics

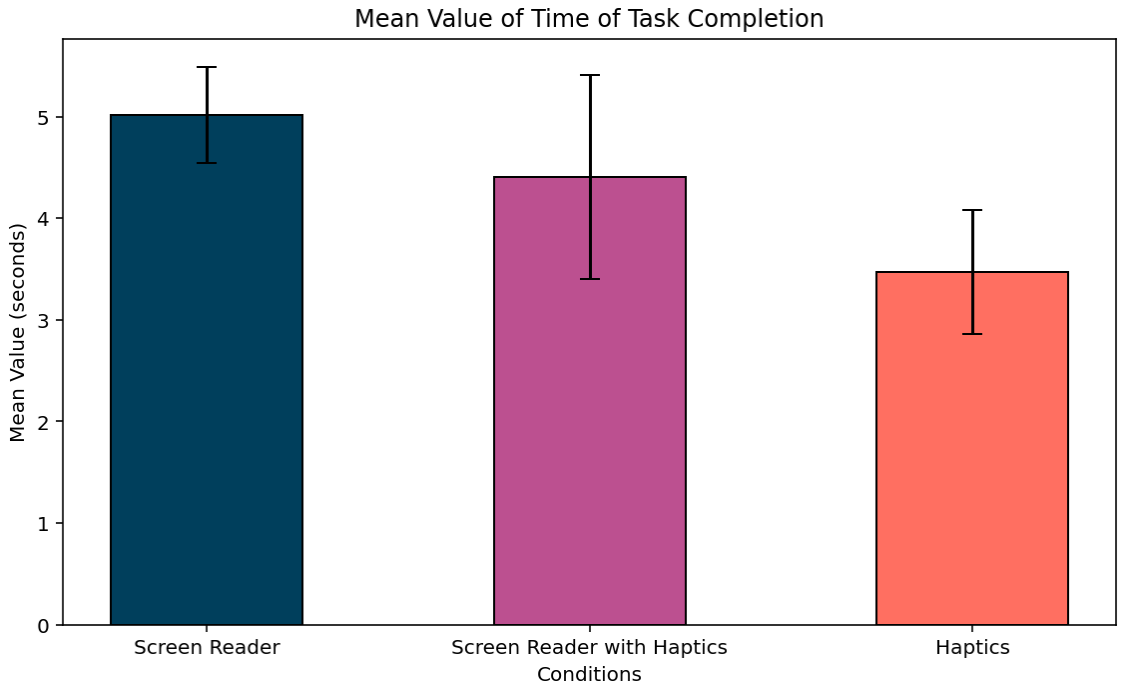


Figure 6.8: Mean Time Scores for Three Different Conditions: screen reader, screen reader and haptics, haptics

Measure	SR	SRH	H
Accuracy	95.51% (2%)	94.97% (1.61%)	96.65% (1.55%)
UI Errors	3.66% (1.8%)	3.61% (1.74%)	1.11% (0.82%)
Frequency Errors	1.11% (0.82%)	1.94% (0.51%)	2.22% (1.02%)
Time	5.02s (0.47s)	4.4s (1s)	3.47s (0.61s)

Table 6.4: Mean Measurements (SD) Across Conditions

Factor	SR	SRH	H
Mental Demand	54.17 (10.04)	64.17 (12.07)	50.83 (12.34)
Physical Demand	11.67 (7.82)	23.33 (9.97)	36.67 (13.76)
Temporal Demand	26.67 (12.56)	36.67 (11.08)	35.00 (14.14)
Performance	22.50 (10.23)	20.00 (7.19)	20.83 (6.38)
Effort	48.33 (7.82)	55.00 (13.29)	51.67 (12.56)
Frustration	27.50 (9.73)	16.67 (11.38)	11.67 (4.22)
Overall	**42.17** (8.25)	**45.28** (9.51)	**38.78** (7.72)

Table 6.5: Mean NASA-TLX Scores (SD) Across Conditions

One-way repeated measures ANOVA showed no difference in the **NASA-TLX Overall score** between the three conditions, Wilk's Lambda = 0.837, F (2,4) = .389, p = 0.701, **Temporal Demand:** Wilk's Lambda = .765, F (2,4) = .614, p = .585 and **Effort:** Wilk's Lambda = .956, F (2,4) = .092, p = .914. Similar Friedman test showed that there is no significant difference in the **Mental Demand:** between the three conditions x^2(2, N = 6) = 3.111, p = .211., **Physical Demand:** x^2(2, N = 6) = 5.636, p = .06, **Performance:** x^2(2, N = 6) = .0737, p = .0692, and **Frustration** x^2(2, N = 6) = 1.529, p = .465 (Figure 6.9).

Usability Metrics for User Experience (UMUX) The UMUX-Lite average score for the sample was SR (M = 76.39, SD = 1.37), SRH (M = 79.17, SD = 1.49), H (M = 90.28, SD = .89). Using the Lewis regression equation, this translates to an SUS equivalency score of SR = 72.55, SRH = 74.17 and H = 90.28. This suggests that the perceived usability of the screen reader and screen reader with haptics is 'Good', but the system of haptics alone is 'Excellent'.

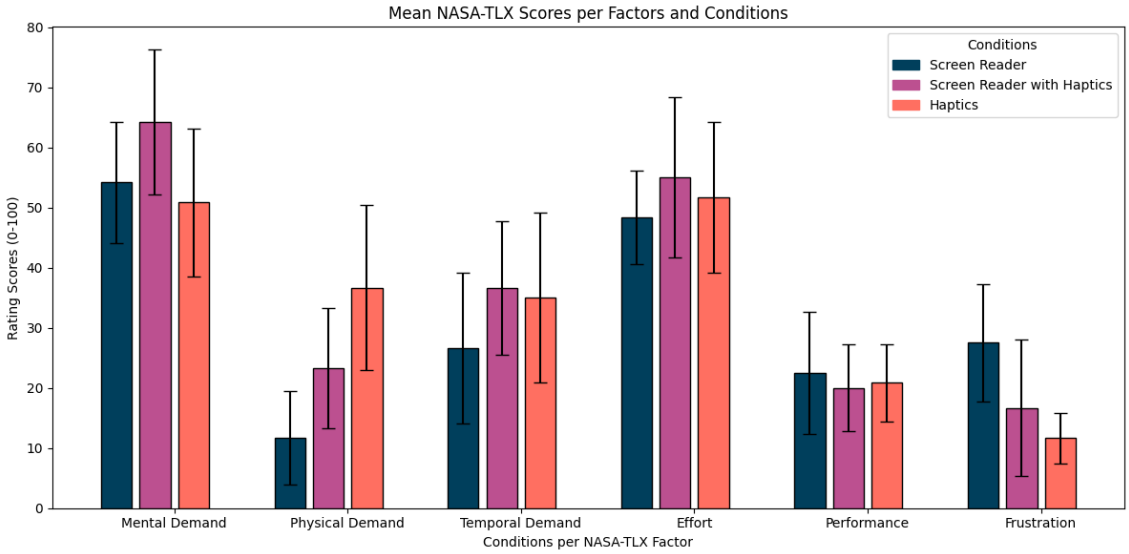


Figure 6.9: Comparison of Mean Time of Task Completion Scores with Standard Deviation lines Across Three Conditions: Screen Reader, Screen Reader and Haptics, Haptics

6.4.3 Participants' Feedback

The participants' feedback during the testing and through post-test semi-structured interviews provided insights that contributed to answering the second research question and to better understand the usability of haptics in this scenario and the potential of haptics as an alternative to the existing SR accessibility method. In the opening of the discussion, users were asked to comment on their experience. Although they have been provided with three methods of stimulus perception, they focused on commenting on the novice haptic method, indicating an impact on their existing impression of accessibility (Theme 1). Participants highlighted the benefits of integrating haptics into their system and compared them to SR (Theme 2). Specifically, they indicate the challenge of SR when editing audio. A number of comments were concentrated on the hybrid method (SR and Haptics) with a negative tone. Finally, the participants provided ideas for improving the haptic feedback design (Theme 3) and suggested other areas in which it could be used (Theme 4).

Theme 1: Haptics were perceived as faster than SR

All six participants expressed a positive feeling about the haptics. Adding to comments such as 'I think it was excellent' (P2), 'it was very useful' (P5), and 'I quite enjoy wearing it' (P4), participants also supported their positive feedback by providing the reasons behind it. The finding that advocates the most for the potential benefit of haptics was that the haptic method provided the information *faster* than the existing setup. Specifically, P3 expressed how haptics can potentially help him be as fast as

sighted music producers, highlighting its importance.

> 'If I am working on a client's piece of work, I need to be able to do that quickly because my sighted counterparts in the industry can do it fast. I need to be able to do it fast. And I just made a video on my channel the other day, about Logic Voiceover hotspots, where you use Voiceover and the number keys to jump to specific parts of the Logic interface. And I think that is just as quick as using the mouse to get from .1 to .2. So when I think of temporal demand, I think, can I get the job done quickly? If I have to listen to my screen reader announce something that I could find out with a band, then I will use the band. For the people watching this, hear Me!, I am, you know, I produce. I'm a producer. I'm the composer. All these things matter to me.' (P3)

P2 compared haptics with his existing workflow, stating that he could not imagine something faster than his screen reader. 'It made me realise that the screen reader might be a little bit slower. Since I use it every day, I don't really think about it, but I just think now this is a nice alternative method, and I'd like to see where it goes.' P1 compared haptics with the use of a Braille display, explaining how Braille gives tactile feedback but occupies the fingers; on the contrary, SR occupies the hearing; thus, a wearable tool like this can provide a good solution. 'Braille is Interesting, because Braille, you have to take a hands-off. Where with the screen, where you don't, the screen reader is trying to use your ears for listening. And so a system like this, where communicating something from a series of vibrations is perfect.' P6 also added that this device is a good alternative for people who don't have financial access to a Braille display.

Theme2: Multimodality Presents Benefits

All participants commented on how the Screen reader is obstructing their interaction with sound. Based on this, they consider haptic feedback a promising solution, as it offers an alternative way to perceive information. P6 stated, 'I think it helps a lot overall. Indeed, it is confusing to listen at the same time and try to understand what is happening. So it is better to listen and have a different stimulus to tell you what is happening.' and 'It helps to have them both, but if you want to edit a detail in the sound, it is better to have only the haptics.' P5 and P4 also commented that having SR and music at the same time is overwhelming.

> 'The voice feedback plus the haptics would sort of get in the way of the music. So, sort of trying to hone in just one of them or either on the VoiceOver or just on the music, was a bit trickier. Whereas with haptics, it's like using a

> different sense. So it's not sharing the same sense as if you're just having the Screen reader. So, for this scenario, if I was gonna use an EQ to do something, I'd rather have some sort of external stimuli that doesn't clash with my perception of things. I just find it a bit overwhelming, and it's a bit taxing to have to listen to the music and also listen to your VoiceOver on top of it.' (P4)

> 'I don't think the combination of hearing and feeling is very useful, cause I think you have two stimuli, and it is creating an overload, and you are getting distracted by hearing the sound. I think this tool needs to be only for haptics, not with SR. To help you when you don't have the SR.' (P5)

P3 experienced frustration because he needed to give his answers aurally on the test. Having an extra element of cognitive overload, he realised that haptics helped him in that case.

> 'I wasn't really frustrated this time (doing the haptics alone condition) because the screen reader talking to me slowed me down. When I can start to feel the vibrations, I can start to talk to you about the vibrations. And this is the parallel processing that goes on, like auditorily, I have to focus on one thing and then say that thing. And when I'm not having to hear it, I can feel that thing and say that thing, and it's an entirely different thing.' (P3)

Thus, users imagined how they could utilise this tool in this specific scenario, enhancing EQ plugin accessibility in a flexible, multimodal workflow. P2 suggested, 'What would be nice is if you have it, you can turn them on, off, and on and off. So, for example, if you use it like it would tell you, you are on a slider. I liked one or the other. I didn't like the hybrid.' He proposed the most suitable use along the SR and provided an example by comparing his workflow with Cubase, a DAW with limited access.

> 'To help you when you don't have the SR. You can turn it on when you need it. Usually, when you are editing the sound, especially with the frequency, you shouldn't listen to the SR; if I need to hear the value, I pause the music. I pause the music, hearing the value, then I turn it off, and I'm staying in the slider with the SR off, and it wants me to change the value. Or after the interaction is familiar, I'm just pressing the keys by memory, and I'm going to the next thing, which I know where it is. I believe only with the haptic it would be very effective.
>
> [...]In Cubase, for example, there is not much SR, 20% almost, I think I had a better workflow, I might be more confident here and have better access

> with the shortcuts, but it is still very annoying to hear the voice all the time, it distracts you from listening to the actual music. So this one (haptics) helps when you have the SR off, mostly in Slider when you scan to check the frequency. It helps to know when you scan through if it vibrates and you know you passed a threshold in the frequency range, like moving from one band to another.' (P5)

P1 suggested using vibrations that can tell even the number of frequencies:

> 'Obviously, you could, if you wanted to extend it, to them say the actual frequency. You know, vibrating on the left for the hundreds and the thingy in the middle for the 10s, and they could vibrate in a sequence, and you can have a long vibration on the 1000 or whatever, only if it was attempted in terms of extending what you want to achieve with the vibrations, maybe.' (P1)

He supported this by explaining that, at the moment, the system is quite simple, and the information about the frequency can be perceived with the SR off: 'I suppose with the low, my only thing would be with low, mid and high, I could do that probably anyway with the speech off because I would learn that once I'm in the parameter list. I could just go L for low, I don't know, M for mid, H for high.'

Theme 3: Users' perception of the Tactons and iterative improvements.

P1 gave examples of how to use the vibrations to tell the exact number. He elaborated that with time, users can get used to and learn the patterns, 'I mean, even the thing vibrating at the same time on other things, eventually your brain acclimatises, potentially to getting information really fast. I'm just saying I could imagine a scenario where you're using the screen reader less.' P2 indicated that different people might have different levels of perception, something that needs to be considered. 'This was perfect for me, but for different people who may be more sensitive and less sensitive, it would be nice. Definitely nice to have a scalable thing where you can set the intensity on your device.' (P2)

Participants answered whether the information about the Tactons was too much and whether more information could be added in future iterations. P6 replied, 'I believe once I learn a motif, I will be fine. I don't think I'll have a problem learning more patterns and what they mean.' P2 expressed that adding more information, for instance, a 3rd layer in the Tactons, might be too much for him. P4 added, 'I think the risk of making more patterns is that it can be quite disorienting. And then again, if the pattern is too long, then it will sort of defeat the purpose of it, you know. So I think 2 and 3 are nice.'

Ways of improving Tactons' design were suggested by participants, focusing on enhancements to both their functionality and usability. Most of the feedback concentrated on the speed of the rhythm, and that they needed a slightly larger gap between the vibrations to achieve greater precision. Additionally, some recommended a variation in the rhythmic pattern in comparison to three equally spaced vibrations. P6: 'Maybe a bit slower or a variation in the rhythm.'

> 'What I'd be curious to see is playing around with almost like sustained and detached notes on music. So like sustaining vibration for longer, or like making it shorter. So I feel like there could be variation within those two patterns. So you could have like short-long-short and long-short-short or long-long-long, almost like Morse code.' (P4)

P5 added, 'Another idea would be to have all three vibrate and use the duration as information. It could also be slower the vibrations so they are clearer. Not that I found those we did difficult, but a slightly bigger one might be a little easier.' P3 on the other side suggested that they could be even faster, like the Taptic Time in Apple Watch (Inc., 2024).

> 'I think I would like to be able to customise the speed of the vibration, you know, down the line. When I think of the speed of the Apple Watch, I realise that when you double-tap an Apple Watch with VoiceOver, you get the haptic feedback. So what you need to do is you need to enable the voice app on your watch, go into the settings, and enable the tactic time feature. And I have mine set to the fastest.' (P3)

Theme 4: Future Possibilities for Haptic Feedback in Music Production

Participants provided ideas on how this haptic feedback can be utilised in functions beyond the EQ. One idea that came up repeatedly was the peaking of the sound. P3 suggested, 'I would really like haptic motors that can pulse harder on your skin when you're getting to the peak.' Additionally, P5 and P6 proposed,

> 'It can work for many applications, it can work with a slider, or with the gain, or the peaks of the master mix. You hear the mix, and when it surpasses the -2 you have set as your threshold, it will vibrate. That would be great cause all DAWs are limited to that use. EQ, Compressor, and other different Text fields.' (P5)

> 'Peak Meter! Cause the sighted see the light of the audio card, but I cannot, but with the vibrations, it can inform you the same way.' (P6)

P4, who uses the enlarged screen and edits the EQ with a graphical representation, proposed using vibrations in plugins that lack visual elements.

> 'Could be controlling other things like all the parameters, like a virtual instrument or other things in general. because I've been so used to visual equals. I don't know how effective it would be for me. Yeah, but I do think unless visual plugging is like a compressor or anything that is less visual, not as graphical as in EQ. I feel like that would have quite a lot of feedback on my workflow. Especially with compressors, because then it's much more about hearing it rather than trying to see how it looks, you know. So I feel like if I was to just use the haptics, that would be a stronger focus on the listening side of it rather than the visual side of it for some of it.' (P4)

P2 proposed a system that informs about the state of buttons and another that informs about the tempo in the DAW projects.

> 'I can see it working with things like text boxes, if something is on or off, you know, to give you a double vibration if it's on and one if it's off. Even like when they're buttons with more than one state, like, you know, three states. You could have it, to tell you each one. Tempo might be interesting. You know, to feel like when you set any tempo in DAW.' (P2)

6.5 Discussion

A new way of perceiving information was investigated in the scenario of accessing the frequency centre of EQ in Reaper and the UI element that provides this information (slider, text field) for BVI music producers. The use of this method was evaluated by comparing its performance and perceived workload with that of existing methods, including a screen reader, a hybrid screen reader, and haptics alone. The statistical analysis of the Accuracy, Time, and NASA TLX factors showed no significant difference between the three methods of perceiving the information. The accuracy rate in all three methods was over 94% (SR: 95.51, SRH: 94.97, H: 96.65). UMUX questionnaire scored 'Good' for SR and SRH but 'Excellent' for H. That is supported by the qualitative data, which showed that participants 1) enjoyed the new method of haptics, and 2) saw haptics' potential in comparison to the screen reader. In support of the good performance, participants confirmed that the two-parameter Tactons provide a good level of information. However, they suggest that further exploration would be beneficial and provide further insights into the use of haptics for accessibility of DAWs. Most importantly, users highlighted how they would like to see this system work in real-life

scenarios, suggesting a flexible system where they can use SR and H where needed at their own preference, expanding on other applications that can be utilised by the system as well.

6.5.1 Reasons for no distinction between methods

Literature in the field indicates a gap in directly comparing the perception of information from screen readers to haptics. However, relevant studies like in Alirezaee et al. (2020) compared performance between visual and audio feedback with haptic feedback, Feitl et al. (2022) compared tactile feedback with sonification of touchscreen map specifically for BVI people, and Goodman et al. (2020) compared visual with haptic feedback for deaf and hard-of-hearing people showcase the mixed results in significance across the various measurements. Thus, although it is important to acknowledge these results, a direct comparison is not applicable, as there are significant differences in the independent variables, such as the type of stimuli presented and examined, and the participants' varying access needs. At the same time, similar studies provided qualitative feedback that supports the use of the new method of haptic feedback for completing each task compared to the other methods presented.

These results indicate the complexity of the test, and it is interpreted as a positive indicator for the use of the suggested haptic feedback. Although there was no significant difference, the mean score is considered as high, within an average of 95%, and the qualitative feedback explained why having a difference in the accuracy between the methods would not be a realistic expectation in this study. Screen reader is expected to result in a high score while participants are familiar with the method and have more experience perceiving and interpreting information using that method, whereas haptic stimuli was something completely new to four of the participants while the other three had experienced it one more time on the evaluation of the armband (Chapter 5). Text-to-speech is the primary method BVI people use to access digital content. However, some participants did not use the specific screen reader (i.e., voice, speed, order of presenting information) with which they are familiar and trained to perceive information through audio feedback given in various forms. The lack of a significant difference in task completion time was also unexpected, as Tacton stimuli were shorter in duration, and users also supported this in their feedback, indicating that it was perceived as faster for them. This is likely another consequence of the participants' familiarity with the SR, as well as the small sample size of this study. Nevertheless, qualitative data support that participants would prefer the haptics over the SR, confirming insights from interviews with BVI creatives (Saha and Piper, 2020; Harrison et al., 2023; Karpodini et al., 2025).

Consequently, the absence of a significant difference in accuracy and time, along with high-performance results, indicates that haptics is a promising option for conveying information to individuals with a visual impairment (BVI). Participants performed an average of 96% on the haptics-alone conditions despite the fact that it was the first time they were trying this device and technology.

6.5.2 Understanding the result of the perceived workload

There is a lack of studies comparing the perceived workload of vibration perception and audio feedback in the presence of a music background. The existing studies that measure the perceived workload of vibrations varied in their significant results. For example, Baker and Rolf (2020) compared vibrations with visual or with no vibration and found that vibrations lower the perceived workload. On the other hand, Hossain et al. (2025) compared vibration patterns between them and with no vibration and found no significant difference between conditions in the post-hoc analysis of the overall NASA-TLX score. However, the conditions in both studies differ significantly from the current study, making direct comparisons with their findings irrelevant.

Focusing on the effect of music background on perceived workload, although a scenario of a music production routine was used, the actual task entails passive recognition of information, which simplifies the process of recognising the presented information. Participants were not deeply engaged with music, as they would have been if they were processing it. Thus, there were moments when they admitted that they ignored the music completely or that it didn't really distract them. At the same time, they highlighted that it is tiring to hear music and SR all the time or that it is not practical to interact with EQ having the SR on as well.

Overall the perceived workload was lower in the Haptics condition, although no statistical difference. From the individual factors, it is useful to highlight the Mental Demand and the Frustration which were lower in the Haptic condition, indicating the potential of this device to reduce the cognitive load that is caused by the use of SR. While Physical Demand and Temporal Demand and Effort where higher in the Haptics that could be interpret as a result of lack of familiarity and perhaps trust to the new haptic method. NASA-TLX provided some initial indications of the possitive effect of the new technique to users perceived workload which is important in the design of new accessibility features.

6.5.3 Tactons: a useful design technique for BVI users

This research aimed to evaluate the use of Tactons as a haptics design technique for conveying information to BVI people. Literature has extensively utilised the method of

Tactons to convey information with varying complexities of patterns, employing variations of 2 or 3 parameters simultaneously. Hoggan and Brewster (2007a) presented Tactons with three parameters and suggested that participants who trained while listening to equivalent Earcons accomplished a 76.5% recognition rate. González-Cañete et al. (2021) also tested 16 haptic feedback patterns, including patterns that use rhythm, duration or intensity variation, with both sighted and visually impaired users. The results showed an overall recognition rate varying from 70% to 100%.

Our results confirmed what is known from the literature, users can accurately identify two-parameter Tactons. The number of patterns presented as well was limited to six, which is a relatively small number that enables easy memorisation and recognition. The way Tactons were designed, based on mapping low, middle, and high to the three equally spaced motors, facilitated the understanding of one of the levels of information by associating it with the space left to right, a *Logical* metaphor.

In the qualitative data, participants commented that they had no problem with the three locations, but they had ideas on how the rhythm could have been different. They suggested a longer pause between the individual vibration stimuli. P3, who is using SR at the fastest speed, suggested having flexibility in the pattern's speed, while, like SRs, people might prefer different speeds. He is also particularly influenced by the use of the Apple Watch and Taptic Time, which provide the time with vibration patterns. Participants also suggested using different rhythms to create more patterns. P1 suggested incorporating haptic feedback to provide more specific information about the numbers, and P4 and P5 proposed this to make the patterns more distinct and limit confusion. Overall, this initial evaluation of two-parameter Tactons showcases the opportunities that this design technique provides. Accompanied by a music background and active screen reader feedback, participants who are blind and visually impaired demonstrate a high recognition rate, supporting the idea that aural distractors may not influence the recognisability of haptic feedback.

6.6 Limitations

The design of this study involves a consistent set-up that is the same for all users, with very limited options for adjustments (i.e., SR speed and language) and the only main difference being the location where the test took place. This creates limitations in evaluating the system in the 'best-case scenario', meaning it is too early to understand if this new technology is indeed useful in the user's real workflow (Lazar et al., 2017). Our participants use different screen readers (e.g., NVDA, VoiceOver), which present information in varying ways (e.g., syntax). Participants use different speeds, and two of

our participants use different languages in their regular workflows. Despite that, adapting the test to users' specific setups was not possible at this stage of evaluation. Evaluating the perception and recognition rate of information through a new technical configuration, such as haptics alone or haptics with a screen reader, requires a more conservative testing approach. Limiting the variables that might influence the results would lead to more accurate results. Although the sample size of this study is representative of the target population of BVI music producers, its small size limits the statistical power of the analysis and reduces the ability to detect significant effects. For this reason, future studies employing methods such as co-design sessions, focus groups, and testing within individuals' settings could further strengthen and expand our current findings.

6.7 Conclusion

The results of this study demonstrate that haptic feedback can effectively convey EQ information to BVI people in the presence of background music, equivalent to the current accessibility method, the screen reader. The results indicated that participants are positive about using such tools in their future workflow. Six two-parameter Tactons were evaluated in this test; their recognition rate was 96%, and there was no significant difference in the performance and the perceived workload between the three conditions, SR, SRH and H.

Although participants were familiar with using the screen reader, unlike with haptic feedback, the equally high performance with haptic feedback indicates that such a technique has considerable potential to be integrated smoothly into users' workflows. Participants explained how SR is cumbersome in situations where they listen to music as part of working on a mixing task, and that support from haptic could be a beneficial alternative or complementary modality. They also expressed a preference for flexible, user-tailored integration, allowing them to adapt the system to their needs at the time. Tactons were perceived as a suitable method to convey the specific information. Adaptability in the rhythmic element of the vibration pattern was suggested as area for improvement.

This chapter explored the potential of using Tactons in the pre-interaction stage by evaluating the perception of EQ information from BVI music producers. It provided insights for the improvement of the system and broader suggestions on how to integrate vibrotactile feedback in DAW. These findings offer motivation to further explore vibration design methods for conveying information during interaction. The following Chapter will build on this work by examining the 'during-interaction' state in music mixing scenarios, focusing on the design of vibration patterns during active engagement with the audio. Feedback regarding the Tactons design from this study will directly inform the

development of the vibration patterns to be used in the following study. Additionally, the background music distraction will be replaced with music-interaction tasks to assess whether active engagement influences the perception of the haptic feedback.

Chapter 7

Study 2: Interaction task: Comparison of Three Vibrotactile Feedback Mappings to the Volume Fader.

7.1 Introduction

Chapter 6 examined the potential of Tactons in conveying EQ information during the *pre-interaction* stage, in a comparative study against the current accessibility method, the screen reader and a hybrid of both. Results indicated that participants held a positive attitude towards the new technology (i.e., vibrotactile patterns), and they scored a high accuracy rate across all conditions. These findings suggest that Tactons hold promise as an alternative or complementary accessibility method for BVI music producers.

This study shifts focus to examining the *during the interaction* stage (Norman, 1984), where participants will execute an action and evaluate the result of their action. The emerging guidelines introduced in Chapter 3 show a variety of vibration design techniques suitable for conveying information in DAW, beyond the Tactons used previously. This study investigates three different vibrotactile mappings supporting real-time control of musical parameters, such as volume, using interface elements such as a slider. Design methods include the use of vibration intensity, spatial distribution, and Tactons, following examples from previous work such as Jack et al. (2016) and Turchet and Barthet (2019). Additionally, this study investigates how vibrotactile feedback design influences users' performance and preference.

The interaction task is based on adjusting a slider to control volume while mixing two audio tracks. This scenario has been used previously in literature by Mycroft et al. (2018) and Gelineck and Overholt (2015), indicating the potential of haptic methods to reduce reliance on visual cues. Unlike the study in Chapter 6, here music is an active part of the task, simulating a realistic creative workflow.

This chapter addresses the second research question by developing a system that allows users to mix two audio tracks using the keyboard while perceiving numerical information about the volume level through three different types of vibrotactile feedback mappings: 'Intensity', 'Spatial', and 'Tactons'. The following section presents the development of the three design techniques and how they have been used alongside the mixing fader (section 7.2). Following that, the methodology of the evaluation of the three methods will be presented, including participants' details, apparatus, test procedure and measurements, as well as their analysis methods (section 7.3). Section 7.4 presents the results of this evaluation, organised by the research questions. Finally, the discussion interprets the results and answers the research questions of this chapter (section 7.5).

7.2 Prototype design: Mapping UI interaction with Vibrotactile feedback

This section presents the mixing faders of Reaper DAW, explaining how they are utilised in the mixing process by both sighted and BVI producers, as well as the rationale behind the selection of the interface elements used in the study. Following this, the three vibrotactile feedback design methods are presented, along with their mapping strategies to the faders' values.

The wearable haptic display presented in Chapter 5 and previously employed in Chapter 6 is utilised in the current study. Its motor configuration enables the use of haptic parameters such as frequency, intensity, location and duration, allowing for the creation of more complex and diverse vibration patterns.

The design of the patterns draws on taxonomies discussed in Chapter 2 (section 2.6), specifically the concepts of Tactile Notification and Tactile Translation by Giordano et al. (2018) and Magnitude by Wittchen et al. (2022). The proposed mapping designs are informed by research into the perception of amplitude, frequency, and spatial location of vibrotactile stimuli (Stein et al., 2017) (Chapter 2) as well as by participant insights gathered in previous studies (Chapter 3).

A custom program, developed in the Max 8 environment, simulated the DAW mixing

faders. It mapped the keyboard-based interaction with the *Volume Fader* that can be found in all DAW mixing consoles (Figure 7.1) with three distinct vibrotactile feedback designs (mappings). A detailed overview of the software process workflow, as well as pictures of the software, can be found in the Appendix E. The program used in this study can be found in the GitHub page (Karpodini, 2025c).



Figure 7.1: Mixing console in Reaper

7.2.1 Mixing Faders

Mixing faders are skeuomorphic representations of the physical faders and allow users to increase and decrease the perceived loudness of the track by dragging the fader icon up and down. The scale used for measuring the loudness is the decibel (dB). This is a logarithmic scale, and it reflects the perceived loudness. Fader's maximum volume is set at 0dB (also called unity gain). Values below zero are reducing the volume of the audio; specifically, every 6dB reduction halves the perceived loudness. For example, -6 dB corresponds to 50% of the track's volume, and -12 to 25%. These values are usually displayed visually next to the fader to help the users make precise adjustments. Values above 0 increase the gain and are very likely to cause distortion to the sound (if the source is also peaking at full dBFS); for that reason, they are avoided to maintain audio clarity and prevent clipping. Sighted users, beyond the visual representation of the fader's position and its value, also receive visual feedback of the signal level, known as the meter. In the form of a vertical line next to the fader, this colour-based feedback quickly shows users when the signal is too high (yellow or red) and the volume needs adjustment (Figure 7.2).

Research by Payne et al. (2020) and Saha and Piper (2020), and Harrison et al. (2023),

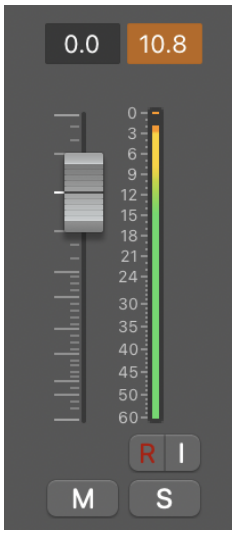


Figure 7.2: Example of visual representation of audio peaking, in Logic Pro

supported by the interviews in Chapter 3, showcases that participants prefer to turn off the voice feedback of the screen reader when undertaking a manipulation of the sound that involves the increase or decrease of a parameter (e.g., reverb, volume, compressor). This is supported by participants' insights from interviews in Chapter 3 and 6, which indicated that screen reader feedback does not provide meaningful feedback and instead creates a further cognitive load. On some occasions, they need confirmation of their interaction, and the use of a screen reader is the only option, yet it is time-consuming.

This study explores ways of representing important milestones in the fader value ranges such as 0, -6, -12 and suggests an alternative to the screen reader method that would be non-intrusive and effective in providing feedback about the interaction beyond relying on the sound of the mix. This aims to provide BVI creatives with more confidence when doing keyboard interaction without the voice feedback and by working faster. To achieve this, three mappings of vibrotactile feedback to the Fader's range were introduced. The first 'Intensity' mapping is continuous vibrations that change in intensity and frequency. The second 'Spatial' mapping is also continuous vibration based on location change across the three motors, and the third 'Tactons' are short vibrations that rely on location in the armband, like in the 'Spatial' condition. These mappings emerged from the literature review; their design rationale and technical implementations will be presented in the following sections.

7.2.2 Intensity Mapping

Intensity mapping draws inspiration from the *Tactile Translation* (Giordano et al., 2018) and the *Magnitude Tactons* (Wittchen et al., 2022). Tactile Translation is linked to

audio-driven vibration feedback used frequently in music-related applications. This method maps vibration parameters, such as intensity or frequency, to the sound equivalents. The perception of vibration intensity is analogous to the perception of sound, where frequency plays a crucial role. However, unlike sound, where amplitude and frequency are perceived differently, it is suggested that vibrations are perceived in a similar accelerating manner across different frequencies. This implies that both the amplitude and frequency of vibrations contribute equally to the perception of vibration intensity, creating a more integrated sensory experience (Merchel and Altinsoy, 2020).

Magnitude design metaphor by Wittchen et al. (2022) suggests using Tactons designed to express quantities, for example, an increase in frequency to express the magnitude of an event, such as the volume of the sound. The mapping used in this test suggests the mapping of sound level (–inf to 0 dB) to the duty cycle (0-100%) of the ERM motor (controls the intensity) and to the frequency of the vibration (10Hz - 200Hz). Based on (Brown, 2007), (Merchel and Altinsoy, 2020), (Jones and Sarter, 2008), (Wang et al., 2016) humans can perceive a maximum of 9 frequency levels. The design approach includes 5 levels to be mapped to 5 ranges that create 4 thresholds of the sound amplitude levels –24, -12, -6 and 0. To make changes more distinct, intensity changes are made in the same milestones, except for the range between -5 and +6, which stays the same. For this mapping motors 1 and 3 were vibrating at same time. Table 7.1 demonstrates the levels of frequency and intensity as they change in each sound level range.

dB Range	Frequency (Hz)	Duty Cycle (%)
≥ -40 dB and ≤ -24 dB	10Hz	20%
≥ -23 dB and ≤ -12 dB	20Hz	30%
≥ -11 dB and ≤ -6 dB	50Hz	70%
≥ -5 dB and ≤ 0 dB	100Hz	100%
$\geq +1$ dB and $\leq +6$ dB	200Hz	100%

Table 7.1: Mapping of dB Range to Frequency and Duty Cycle

7.2.3 Spatial Mapping

Spatial Mapping draws on Giordano et al. (2018) *Tactile Translation* and Wittchen et al. (2022) *Body Tactons*, aiming to convey the sensation of moving a slider across its physical limits. Using a different location/ motor has proven effective when conveying information through vibrotactile feedback (Giordano et al., 2018) and especially when the information is spatially oriented (Tang et al., 2020; Salazar et al., 2018). Here, the sound level range was split into three ranges from -inf to –24, –24 to –6 and –6 to

+6. For each of those ranges, a different motor (Table 7.2) is activated continuously at 100% Duty Cycle and 250Hz frequency, as long as the user is interacting with the slider within the range. To enhance the perception of the location change, a small gap at -24 and -6 was added (i.e., no vibration). This technique of using continuous vibrations with pauses to indicate the target number has been reached, as used in existing work from Jack et al. (2016), who used this technique for indicating in-tune performance on a digital instrument.

dB Range	Motor Location
$-\infty < dB < -24$	Motor 1 (left)
$-24 < dB < -6$	Motor 2 (center)
$-6 < dB < +6$	Motor 3 (right)

Table 7.2: Mapping of dB Range to Motors

7.2.4 Tactons

The last mapping utilises the concept of *Tactile notifications* (Giordano et al., 2018), which is mainly related to Tactons design technique. *Logical and Magnitude* metaphors (Wittchen et al., 2022) were also utilised in the design process. Providing a short vibration (250ms at 250Hz and 100% Duty Cycle) notifies the user that they have surpassed the predetermined thresholds at –24, -12, -6 and 0. Adding to the provided notification information, the spatial arrangement of motors indicates which threshold has just been passed. With the logical and magnitude metaphor, the more to the right of the armband the stimulus is felt, the higher the threshold number. The mapping is the following: -24 in motor one, -12 and -6 in motor two-middle, and 0 in motor three (Table 7.3). In literature (Jack et al., 2016) used this design method of notification in music interaction to present when performances were in-tune.

dB Threshold	Motor Location
-24 dB	Motor 1 (left)
-12 dB	Motor 2 (centre)
-6 dB	Motor 2 (centre)
0 dB	Motor 3 (right)

Table 7.3: Mapping of dB Thresholds to Motors

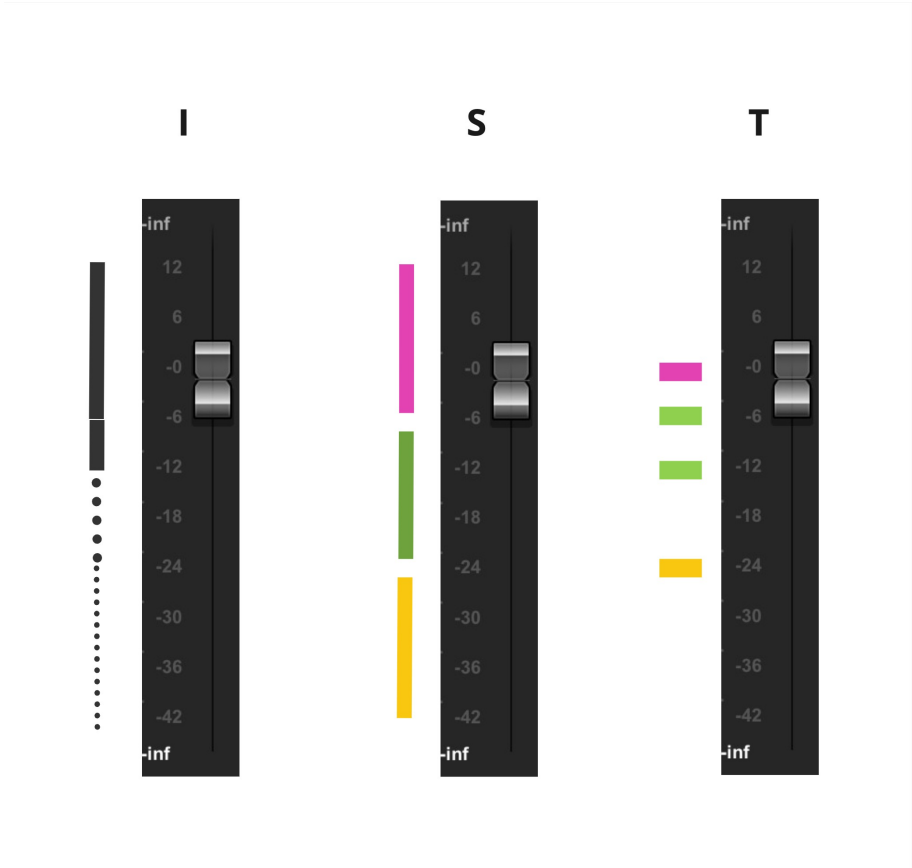


Figure 7.3: Graphic presentation of vibrotactile feedback mapping to slider range

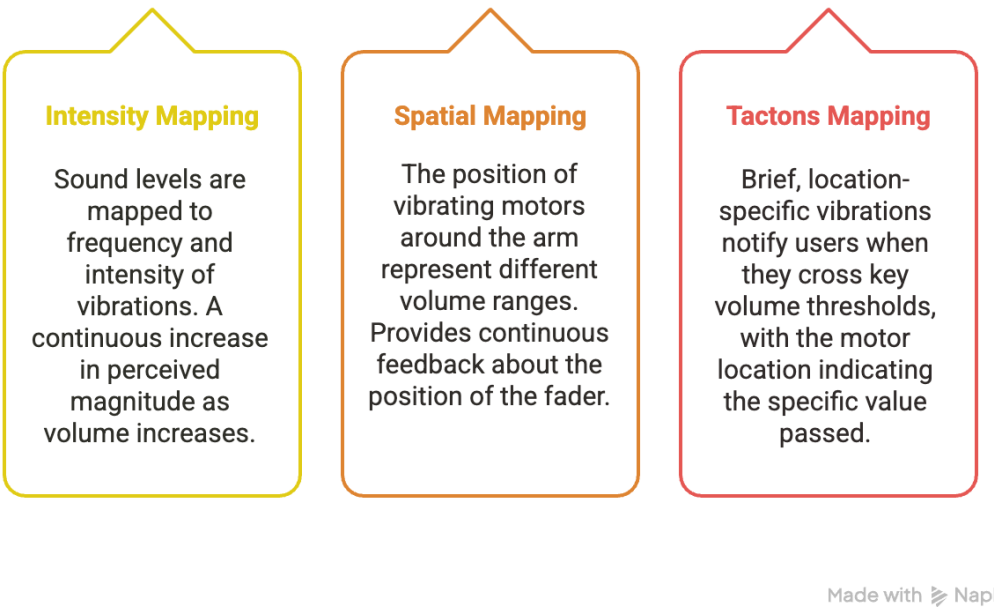


Figure 7.4: Vibrotactile feedback mappings

7.3 Methodology

This study employed a mixed-method approach to evaluate the three different mappings of volume fader values to vibrotactile feedback with a direct engagement with the music material. The rationale followed is the same as the one in Chapter 6. To mitigate the challenges of the small sample size, this study captures both quantitative data related to the participants' task execution (i.e., accuracy, time, and number of keyboard interactions) and qualitative data.

While this study examines the vibration feedback during interaction, it is essential that a scenario-based task is utilised. Musical creativity requires a distinct approach compared to traditional HCI techniques (El-Shimy and Cooperstock, 2016). Following the guidelines set by Wanderley and Orio (2002) and Dewey and Wakefield (2014), a scenario-based test was constructed that allows users to develop their creativity by applying their knowledge and experience in mixing and combining audio and haptic feedback, similar to a real case scenario. Participants are allowed to interact more naturally with the system without feeling scrutinised. Nevertheless, the music engagement involved in the task is still considered a distraction, and it might increase the perceived workload of the task. For that reason, this study explores the way the different vibration mappings are influencing participants' performance and preference through an observation of the individuals' ways of completing the task, along with the collection of their feedback.

Scenario: Two audio tracks are mixed using a keyboard-controlled slider and no access to voice feedback, but only three different vibrotactile feedback mappings: (1) *Intensity* (I), (2) *Spatial* (S), and (3) Tactons (T).

7.3.1 Participants

Seven participants were recruited (all male), all of whom are music producers with varying degrees of vision impairment: five are registered blind, and two have low vision. Five participants took part in the previous study (Chapter 6), and two additional participants were recruited through word of mouth. Participants' ages range from 24 to 50 (M = 34.7, SD = 10.4). Five studies were conducted in English and two in Greek language. The facilitator assessed each participant's experience level with DAWs by combining their self-evaluations with insights from previous interviews (Chapter 3). Based on this assessment, participants were categorised into three experience levels: Advanced (5), Intermediate (1), and Beginner (1). All participants use screen readers, specifically VoiceOver (4), JAWS (1), and NVDA (2), with two also employing magnification tools. Regarding DAW preferences, two participants use Reaper, two use Cubase, two use Logic

Pro, and one uses Pro Tools.

	Age	VI	Exp. Level	Accessibility	DAW	Slider Interaction
P1	27	B	Adv.	VoiceOver	Logic Pro	Keyboard
P2	50	B	Adv.	VoiceOver	ProTools	Keyboard + Hardware
P3	45	B	Adv.	JAWS	Reaper	Keyboard
P4	41	B	Adv.	VoiceOver	Logic	Keyboard/Hardware
P5	24	LV	Int.	Magnification	Cubase	Mouse
P6	28	LV	Adv.	NVDA + Magnification	Cubase	Keyboard + Mouse
P7	28	B	Beg.	NVDA	Reaper	Keyboard

Table 7.4: Participant demographics, accessibility tools, DAW, and slider interaction method. Adv.= Advanced, Int.=Intermediate, Beg.=Beginner, B= Blind, LV= Low Vision

7.3.2 Apparatus

All tests were conducted with a MacBook Pro Laptop. Vibrotactile feedback was transmitted through the prototype three-motor armband haptic display (Chapter 5). Sony ZX310 stereo headphones was used for playing the audio element of the test. All aural feedback of participants during the task was recorded using a Zoom H4N microphone. This study is based on interaction with music (i.e., mixing two audio tracks to the requested levels). The music selected contained no lyrics, as music with lyrics has demonstrated to lead to additional distraction in complex tasks (Perham and Currie, 2014). To avoid participants already being familiar with the music, a free, online, generic multitrack music recording suitable for beginner music producers as exercise material was chosen. Multitrack used can be found in this link: (https://www.cambridge-mt.com/ms/mtk/#ImpossibleColours).

7.3.3 Procedure

Ethical approval was obtained from Birmingham City University's ethical committee to conduct this study. The recruitment criteria are the same as those in the previous study. Participants need to be blind or visually impaired music producers of any level of experience with DAWs and users of assistive technologies such as screen readers, magnification tools and braille displays. Participants who agreed to participate in the study have been contacted to arrange a date of meeting. They have been given in advance an information sheet and requested to fill out the consent form. The study

took place in university facilities or participants' home studios. As part of the consent form, participants also submitted demographic information such as age, gender, visual impairment (Low vision, Blind), hearing impairment (if any), level of experience with mixing, DAW and the screen reader they use. On the day of the test, the participants' submission of the consent form and the accuracy of related demographic information were confirmed.

At the beginning of the study, participants were engaged in a conversation about their approach to a mixing task, focusing on their particular use of SR or other tools. Participants then wore the wristband in their preferred location as they were all familiar with the device from previous tests. The researcher made sure the device was adjusted correctly, that the motors were equally distributed, and that participants felt comfortable with the device. Then, participants were asked to wear the headphones, and the use of an appropriate level of music was ensured.

Participants received a demonstration of the experimental prototype (keyboard-based interaction) where they were required to complete 10 trials for each of the three conditions (30 trials in total). Before each condition, they familiarised themselves with interpreting the stimuli to minimise the learning effect during the test. During this training session, they were given 2 minutes to explore the interaction with each vibrotactile feedback method while the researcher confirmed the corresponding number for their interaction and vibration stimuli, since this study does not provide screen reader feedback. Following that, participants were asked to explore the interactions freely for an additional 30 seconds.

Each of the 10 trials of the study contains a selected pair of musical instrument recordings, part of a multitrack recording with four instruments (Bass, Guitar, Piano, Drums). For each trial, one instrument is at a set audible level (between -13dB and -2dB), and the other one, which needs to be edited by the participants, is at a much lower level (between -28dB and -19dB). Participants were asked to adjust the level of the low-volume instrument to a specific target level (between -11dB and -4dB) in order to be 'mixed' with the second instrument. Participants listened to the music of both instruments during their task performance. See Table 7.5 for the setup of the instruments in the test; also, the GitHub page (Karpodini, 2025c) contains all the tracks used for this test. The 10 trials were presented in a different order in each condition. The presentation of three conditions to participants was counterbalanced using the Balanced Latin Square in order to avoid potential learning effects.

	Instrument	Set-up	Target	Instrument	Set-up	Target
0	bass	-6		drums	-22	-5
1	bass	-12		guitar	-27	-8
2	drums	-4		piano	-20	-7
3	guitar	-5		piano	-21	-5
4	guitar	-8		bass	-25	-9
5	bass	-22	-5	drums	-7	
6	bass	-24	-10	guitar	-6	
7	drums	-20	-4	piano	-2	
8	guitar	-19	-5	piano	-3	
9	guitar	-28	-11	bass	-13	

Table 7.5: Pairs of instruments, the way they are presented in the test (set-up), and the requested target. The highlighted instrument is the one that is being edited at each time.

Participants completed each set of 10 trials at the time and had a 5-minute break between each set to mitigate against possible fatigue. The study lasted approximately 70 minutes. During the breaks, participants answered a series of questions about their satisfaction with their performance and how much they rely on audio (music) or haptics (vibration feedback). Additionally, they were asked to reply to the Microsoft Desirability Toolkit (MDT). At the end of the test, they were asked a series of questions about their experience with the task. They were also asked about their preferences and any adjustments they would make to the patterns. These questions are part of a semi-structured interview where participants can openly include any additional comments about their experience.

Semi-structured Interview questions:

- Overall, how would you rate your experience with using the slider with the help of vibrotactile feedback?
- What do you think about the use of vibrotactile in place of the screen readers?
- Do you have any preference over any of the presented vibration mapping techniques and why?

- Can you think of a way we can improve any of the presented vibrations?
- At what level were you relying on audio vs haptic feedback?
- Do you have any other comments/ideas?

7.3.4 Measurements

Participants used the computer keyboard to interact with the experimental prototype. The *spacebar* key triggered the play and stop of the music playback, and the up and down arrows increased/decreased the level of the sound amplitude by 1 dB at a time.

Participants' keyboard interactions were recorded internally from a bespoke program in Max 8 and saved in text files (Appendix E). The program has been evaluated for its consistency and reliability through pilot studies. The slider value input, corresponding to up and down keyboard interaction, is saved in a local file. **Accuracy** was calculated by comparing the last keyboard input (arrow) with the requested target value. **Distance from Target** was calculated by the absolute difference between the last keyboard input and the requested target. **Keyboard Activations:** were represented by the total number of arrow keyboard interactions.Spacebar button data are used to calculate the task completion **time**. For each task, the *spacebar* activation at the beginning (music plays) and the end (music stops) was exported to a CSV file for later analysis, labelled with the task number.

Microsoft Desirability Toolkit was used to evaluate user satisfaction, preferences, and emotional responses to the three vibrotactile feedback designs during usability testing. Twenty words were selected by the researcher (10 positive, 10 negative) from the list that relate to the test (Dewey and Wakefield, 2014).

> **Words:** *Predictable, Effective, Advanced, Fast, Creative, Easy to use, Useful, Comprehensive, Clear, Comfortable, Effortless, Incomprehensible, Slow, Disconnected, Hard to use, Busy, Distracting, Difficult, Complex, Time-consuming, Confusing, Frustrating*.

MDT words were read aloud, and participants were asked to verbally indicate if the work represented their experience. Responses were documented with audio recordings and through the researcher completing them in a digital form. The transcriptions of the audio and the completed forms were cross-referenced.

7.3.5 Analysis

A Shapiro-Wilk test was applied to assess the normality of data distributions for Accuracy, Distance to Target, Keyboard Activation, and Time. For datasets that did not meet normality assumptions (Accuracy, Distance, and Keyboard Activation), a Friedman Test was used, followed by Wilcoxon Signed-Rank tests for post-hoc analysis. For Time, which was normally distributed, a one-way repeated measures ANOVA with pairwise comparisons for post-hoc analysis was utilised. Bonferroni corrections were applied to control for multiple comparisons.

The MDT word frequency was analysed in groups of positive and negative words, a statistical analysis was conducted to identify the difference in average word frequency between the conditions, and key themes and attributes that define the participants' performance were identified.

Participants were asked open questions about their experience after each condition test as well as open feedback and ideation after completing all tests. The feedback received from the participants was analysed using Braun and Clarke's Thematic analysis (Braun and Clarke, 2006). The two interviews conducted in Greek were manually translated into English, and all transcripts were imported into NVivo software for analysis and coding. The 'repeated reading' approach was applied and facilitated assigning labels to participants' quotes according to their content. The labelled quotes were then organised based on their commonalities and formed the themes.

7.4 Results

This section provides a detailed analysis of the collected data, structured into two sub-sections to address the research questions. The first part focuses on the comparison of the three methods' performance in the task (*Intensity*, *Spatial*, and *Tactons*), through the analysis of quantitative data (accuracy, distance to target, time and number of keyboard interactions), and qualitative data, including semi-structured interviews and MDT questionnaire. The second part is focused on understanding how participants utilised the different vibration patterns and how each method influenced their performance and final preference. To explore this, keyboard input data were visualised in relation to time and were used to identify specific interaction patterns. These observations are supported by participants' feedback.

7.4.1 Performance Differences Between the Three Mapping Approaches

Quantitative Data

The normality of our data was tested using the Shapiro-Wilk normality test. The test showed that accuracy and distance to target data were normally distributed in the *Intensity* condition but not in the other two, *Spatial* and *Tactons*. The keyboard Activation data were not normally distributed in any of the conditions. Time data were normally distributed in all conditions.

	Intensity	**Spatial**	**Tactons**
Accuracy	41.42% (12.23%)	74.29% (14.45%)	72.85% (13.75%)
Dist to Target	4.07 (1.49)	0.99 (0.81)	0.71 (0.36)
Keyboard Activation	57.5 (20.01)	29.76 (4.43)	29.19 (5.06)
Time (s)	32.22 (4.51)	16.25 (1.88)	14.23 (1.91)

Table 7.6: Mean scores and SD of Intensity, Spatial, and Tactons Across Various Metrics

A Friedman test was conducted to evaluate differences in **Accuracy** across three conditions: *Intensity*, *Spatial*, and *Tactons*. The test suggested a not statistically significant difference, x^2 (2, N = 7) = 4.73, p = .094. The results of a Friedman test indicated that there is a significant difference between the three conditions in their **Distance from the Target** scores, x^2(2, N = 7) = 6.87, p = .032. A post hoc analysis using the Wilcoxon Signed Rank Test indicated no difference after the Bonferroni corrections. A Friedman Test showed a statistically significant difference in the **Keyboard Activation** scores among the three conditions x^2(2, N = 7) = 10.571, p = .005. The Wilcoxon Signed Rank Test post-hoc analysis revealed no significant difference after the Bonferroni corrections. Finally, a one-way repeated measures ANOVA was conducted to compare **Time** scores across the three conditions, and showed a significant difference between *Intensity*, *Spatial* and *Tactons*, Wilk's Lambda = 0.119, F(2,5) = 18.477, p = 21.005, multivariate partial eta squared =0.881, which indicates a very large effect size. Bonferroni-corrected pairwise comparisons revealed significant differences between the conditions. The *Intensity* was significantly different from *Spatial*, with a mean difference of 14.98, p = .033, 95% CI (1.44, 28.51). The effect size for this comparison was large, d = 2.57. *Intensity* was also differed significantly from *Tactons*, with a mean difference of 16.99, p = .007, 95% CI [6.05, 27.93]. This comparison showed a very large effect

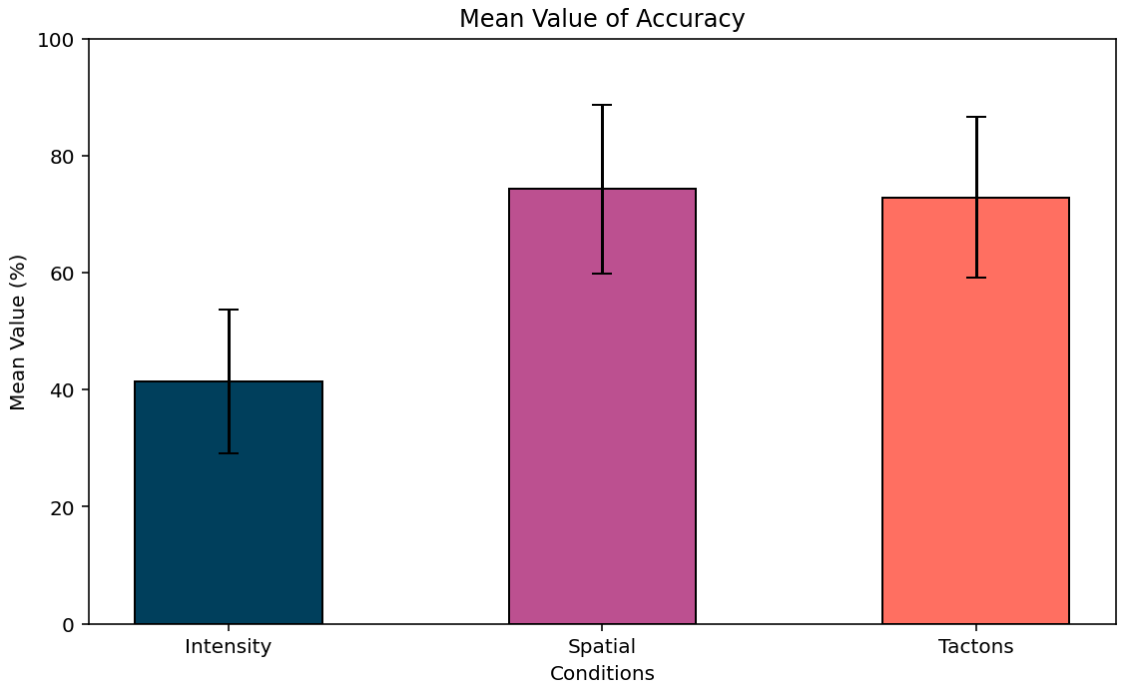


Figure 7.5: Mean Accuracy Scores for Different Vibrotactile Feedback Conditions (*Intensity*, *Spatial*, and *Tactons*)

size, d=3.61. No significant difference was found between *Spatial* and *Tactons* (Figure 7.8).

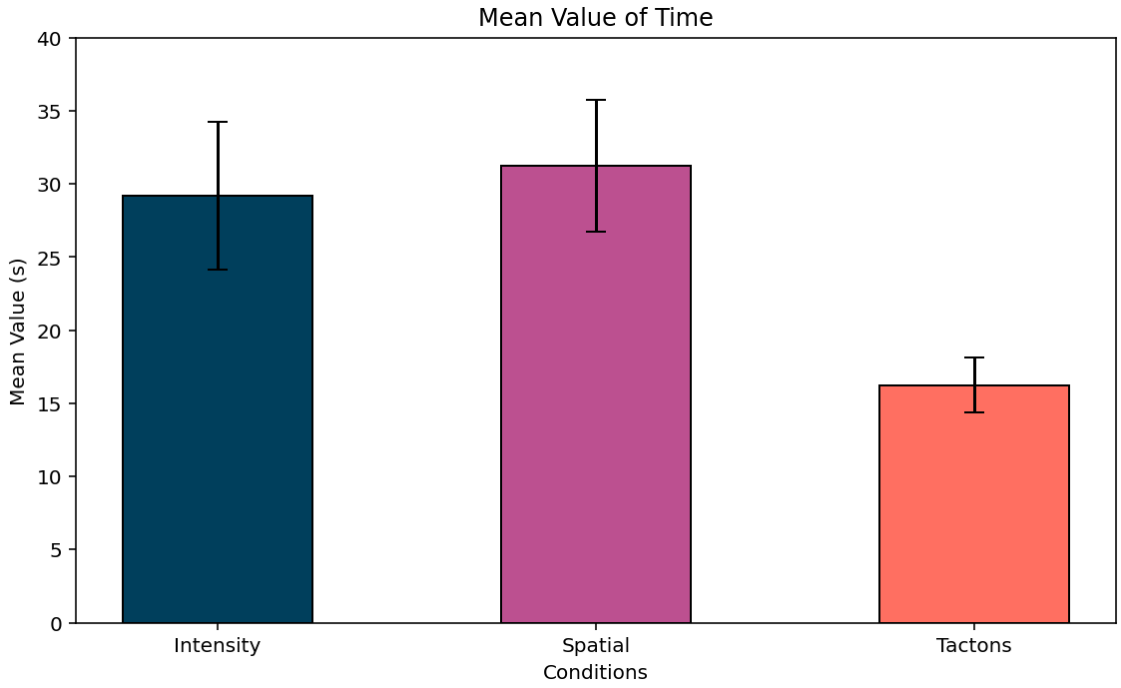


Figure 7.8: Mean Time Scores for Different Vibrotactile Feedback Conditions (*Intensity*, *Spatial*, and *Tactons*)

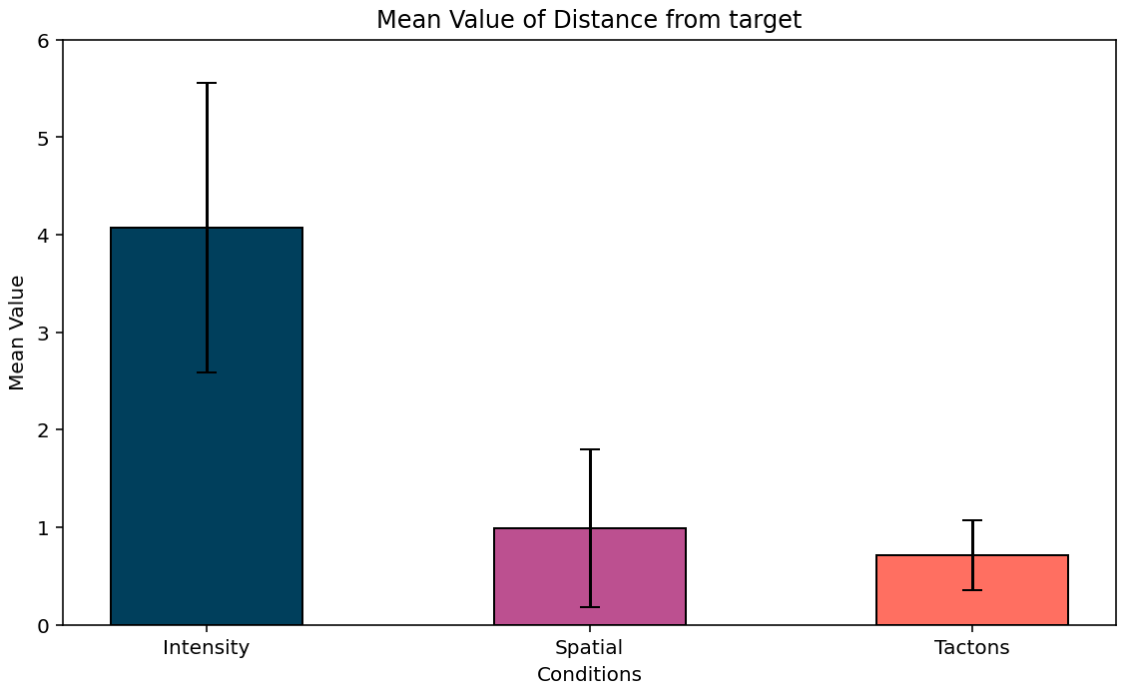


Figure 7.6: Mean Distance from Target Scores for Different Vibrotactile Feedback Conditions (*Intensity*, *Spatial*, and *Tactons*)

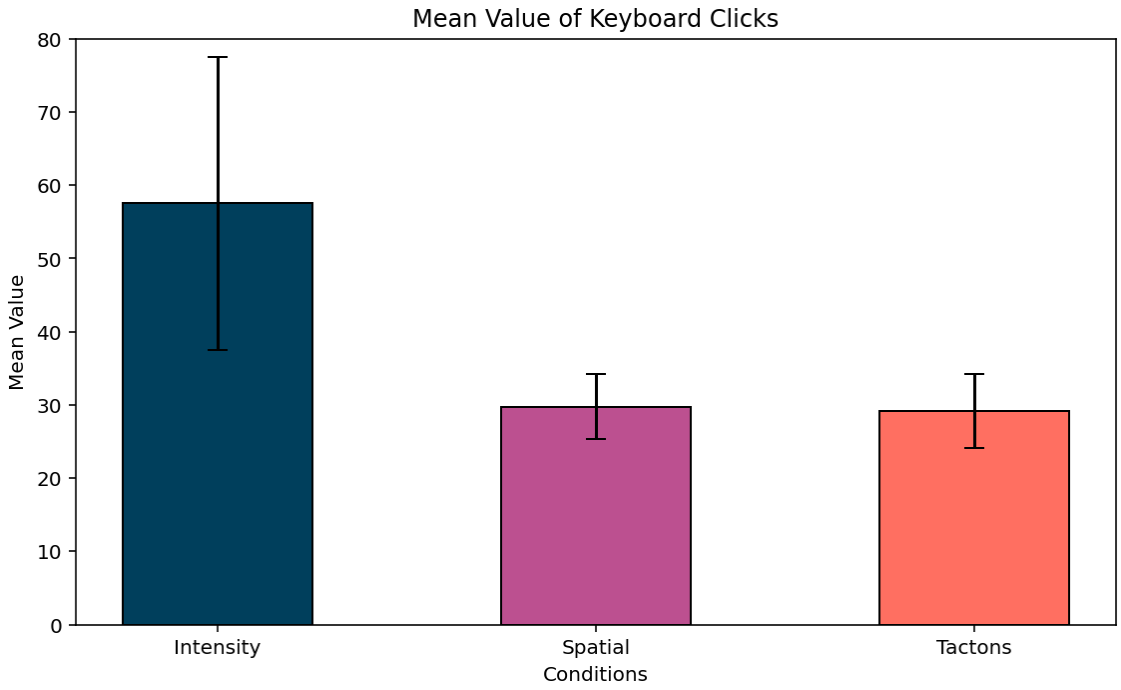


Figure 7.7: Mean Keyboard Activation Scores for Different Vibrotactile Feedback Conditions (*Intensity*, *Spatial*, and *Tactons*)

The **Microsoft Desirability Toolkit** provided insights into participants' perceptions of each condition. For the *Intensity* condition, responses were predominantly negative: all participants described it as *Confusing* and *Difficult*, with six out of seven also labelling it as *Slow*. Over half of the participants agreed it was *Time-Consuming*, *Busy*, and *Hard to Use*, though some also used positive descriptors like *Creative* and *Useful*. In contrast, *Spatial* and *Tactons* conditions received mostly positive feedback. For *Spatial*, all participants agreed on terms such as Effective, Fast, Easy to Use, and Useful. Nearly all (6 out of 7) described it as Creative, Comprehensive, Clear, Comfortable, and Effortless. Similarly, for *Tactons*, participants agreed on terms like Effective, Easy to Use, Useful, Comprehensive, Clear, and Comfortable, with six out of seven also describing it as Fast and Creative. These descriptors provide a clear view of how each design condition was received (Figure 7.9)

Word	Intensity	Spatial	Tactons
Predictable	14%	57%	71%
Effective	43%	100%	100%
Advanced	57%	57%	43%
Fast	14%	100%	86%
Creative	71%	86%	86%
Easy to use	43%	100%	100%
Useful	71%	100%	100%
Comprehensive	43%	86%	100%
Clear	0%	86%	100%
Comfortable	57%	86%	100%
Effortless	0%	86%	57%
Incomprehensive	43%	0%	0%
Slow	86%	29%	14%
Disconnected	29%	14%	0%
Hard to use	71%	0%	0%
Busy	71%	14%	14%
Distracting	29%	14%	0%
Difficult	100%	0%	0%

Complex	57%	29%	0%
Time-consuming	71%	14%	14%
Confusing	100%	29%	0%
Frustrating	57%	14%	14%

Table 7.7: Mean word frequency

Participants' Feedback

Participants provided distinct comments regarding their preferences and perceptions of each condition immediately following the test. There was a clear preference for the *Spatial* and *Tactons* conditions, with only minor distinctions between the two, while the *Intensity* condition was generally disliked.

Intensity received very few positive comments, limited to the tactile sensation of the device's vibration rather than its usability. Most comments focused on the inability to identify differences among the given milestones (P1, P2, P5, P6). These comments varied among participants, depending on the level of perceived difficulty in completing the task. For example, P2 commented that intensity perceivable differences might not be sufficient for what a user needs.

> 'I don't think there's too much of a range for the intensity to be effective. You know, like going from -30 to all the way up to 0. There's not enough range. It's too many very small changes, as opposed to possible options with the intensity.' (P2)

P5 described his experience as responsive in terms of vibration stimuli, but found it easy to lose track of specific numbers. He compared it to perceiving absolute dB levels in sound, where one can estimate the range but not pinpoint the exact value.

> 'I mean, it's easy to use in the sense that you press up and then you feel different vibrations and then you feel like it is responsive but it's hard to use, at the same time. Because I've not been using this for a long time, I felt at the moment I was a bit lost in the change of the vibrations. I don't know which one was the weakest, which one was the medium, and which one was the strongest. So I felt like I got lost within that.[..] And it's like, listening to an instrument and saying, yeah, that instrument is sitting at -6. It's hard to do that with just my ear.' (P5)



Figure 7.9: Word clouds representing user feedback on three vibrotactile feedback conditions

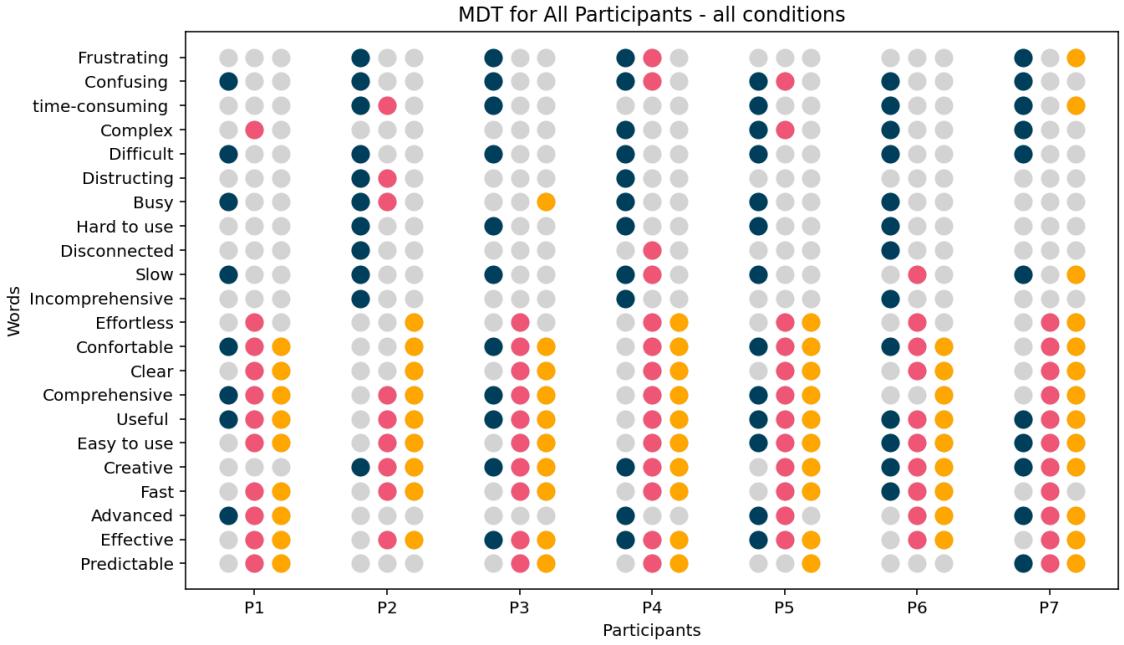


Figure 7.10: Word selection per condition and per participant. Blue dots (left) represent *Intensity*, Pink (middle) the *Spatial* and Orange (right) the *Tactons* mapping.

P6 found *Intensity* disconnected as he struggled to perceive the changes in the intensity. He specifically expressed that all he felt was a vibration getting stronger without any particular differentiation between the levels. That led to a sense of disengagement, and he did not feel motivated to put much effort into the test.

> 'I'm going to call it a little disconnected because I didn't understand it, I just felt a vibration. Was it just stronger? It didn't have anything substantial; my mind didn't even want to think about it. The point is that whatever device is created is just advisory and is meant to provide some numbers, not to tell you that you have to go there.' (P6)

Similarly, other participants commented negatively by highlighting the cognitive load or the barriers they faced due to the design of this condition. For example, P1 stated: 'Having it stop vibrating when I'm not interacting, I think I didn't prefer that. I think I would like totally continuous vibration, so I could stop and sort of assess the vibration for longer.' (P1) For P4, the intensity mode created a cognitive load that slowed down his performance. He needed to concentrate more on the haptic instead of the sound to complete the task, which is undesirable. He compared-09'6AZ0 this experience to his experience with screen readers.

> 'So when I say it didn't have to be slow, I feel like I'm relying too much on what my body's telling me and less on what my ears are telling me, and I feel like because I'm a screen reader user I could have benefited from both of those things. Perhaps. Relying solely on the sense that I don't use it all the time because we don't, I mean we have haptics in our pockets every day, but this is an entirely different use case for it, and I feel like relying solely on that is making me far less effective.' (P4)

On the other hand, *Spatial* and *Tactons* received almost only positive comments with small variations across the participants, similar to the quantitative data. Three participants chose *Spatial* as their favourite and most preferred vibrotactile feedback design. Participants commented on the effectiveness of *Spatial* methods by describing how it helped them concentrate on the music without getting distracted from the information perceived from the vibrations (P1, P3, P6). For example, P1 mentioned enjoying the balance between feeling the vibrations and listening to the accompanying sound.

> 'That one was my favourite. I preferred having the continuous vibration; it was much more what my brain liked. Having the stops on the target values was great, too. It felt like the nicest balance as well between reading the data and listening to the sound, you know, I felt most sort of comfortable

with that.' (P1)

P3 felt confident using this mode and noted that he could interact with the slider in a way that felt comparable to how sighted people do, allowing him to work efficiently.

> 'The haptics let me know what the actual fader position was as opposed to, did it sound right. So I think this is like where a sighted person would be, you said not that bass up to -4 they can just look at the slider and do that and this allows me to get closer to that sort of. Being able to do what I needed it to do.' (P3)

The main benefit for P6 was the ability to fully concentrate on the sound, allowing him to receive the information without losing his attention to the audio task.

> 'I believe that with this one, you don't need to get distracted from the essence of the sound, cause it gives you a continuous vibration that you can even check with the other hand and understand without losing your attention.' (P6)

In addition, P1, P4, and P7 highlighted how the design, specifically the role of the gaps, facilitated the usability of this condition. 'This one seems good, even if the location of these two motors (he showed the two side-by-side motors) is not always clear, the gaps make it very clear.' (P7)

Tactons received highly positive feedback too, with four participants selecting it as their preferred design. Most comments highlighted the intuitiveness and clarity of the vibrations, which made the experience both straightforward and effective. Participants noted that this clarity allowed them to complete tasks confidently and without distraction.

> 'It was very, very responsive, like there was something that felt very intuitive about it. Pressing the arrow and waiting for the vibration, and then moving like that. I would say the strength of the vibration is good. It was strong enough to be noticed, but it wasn't distracting.' (P1)

P5 found them sharp and familiar, aligning with his previous experiences with vibration feedback. He emphasised his confidence during the test, knowing exactly where he was and how to find the requested target by counting up or down.

> 'It feels like it works alongside my own experiences with this. I just felt like I went into it with my confidence, and I knew exactly where I was, so it felt a bit sharper in that sense, it felt like, yes, I'm here and I just need to count up or count down and I'll find myself.' (P5)

P3 and P6 noted that minor adjustments are needed and emphasised that mastering this condition will require practice.

7.4.2 Impact of Design on Performance and Preference

In addition to gathering participants' feedback on the designs and performance measurements (i.e., accuracy, time, keyboard Activation), participants' strategies for achieving these outcomes were captured. Plots 7.11 illustrate how users navigated the slider over time using keyboard input to reach the specified number. Qualitative data complements these performance insights by revealing how particular design elements influenced participants' task execution. The main themes emerging from this analysis focus on how participants engaged with the designs and suggested potential adjustments to enhance usability. These themes offer a deeper understanding of how specific design elements shape both user performance and preferences.

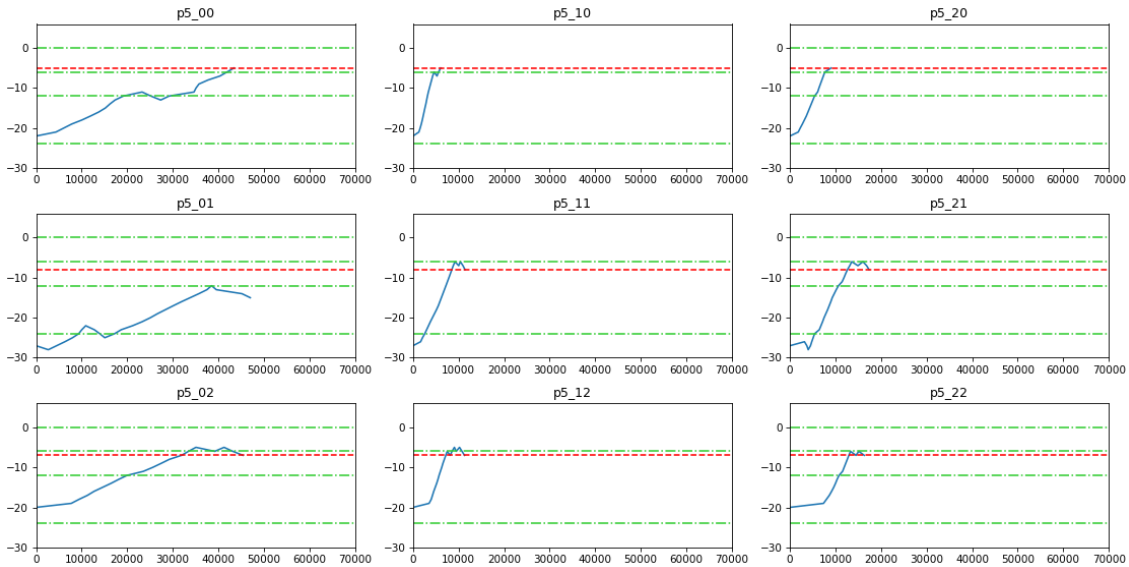


Figure 7.11: Slider movement over time using all three conditions

Theme 1: How participants use the designs

Observing the slider movement plots over time revealed that, despite differences in timing and accuracy across participants, some common behaviours emerged for each design condition. In the *Intensity* condition, interactions were generally more exploratory. Participants frequently moved the slider up and down repeatedly as they tried to perceive differences in vibration intensity. Performance tended to improve over the course of the study, suggesting a steeper learning curve for this condition compared to the other two.

The majority of participants' movements centred around the requested target range,

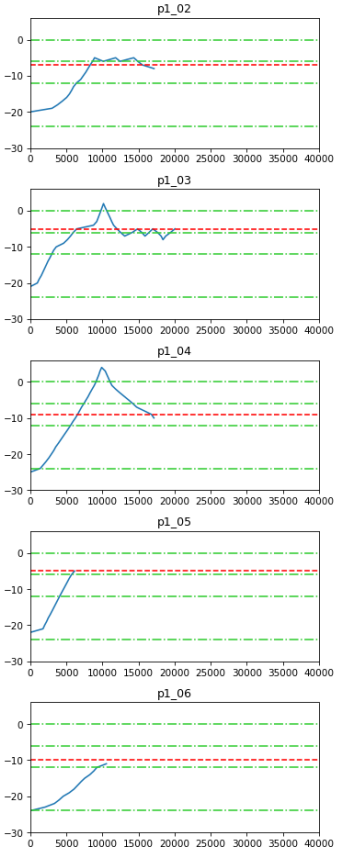


Figure 7.12: Slider movement over time using the Intensity condition

between -12 and 0. The plots, along with qualitative feedback, indicate that participants were often confused by changes within the range from -12 to -6, corresponding to varying intensity percentages and frequency in our design. For example, P3 noted that while they could perceive a change at -12, they felt less confident about detecting the difference at -6. 'It's seamless, like I can feel it jump from minus, as soon as I hit -12.' (P3)

P5's strategy was to start from the weakest point and gradually build his perception from there. Out of the entire range, P5 identified a notable change at -5, which served as a reference point and helped him successfully complete the task.

> 'I was always starting to go down first, then instead of going up, so that I could go down to the weakest preference and then try to build up from there. [...] Because I felt like, I'm sure that this is the weakest one, and then I can go from there.'(P5)

From the qualitative data, it was also observed that participants (P1, P3) needed more time (than the given 1 second) to understand the vibration intensity and assess the changes in the milestones. That explains the exploratory movement observed in the plots. 'Having it stop vibrating when I'm not interacting, I think I didn't prefer that.

I think I would like totally continuous vibration, so I could stop and sort of assess the vibration for longer.' (P1)

Tactons and *Spatial*, on the other hand, had similar performances and graphs, with most users being quicker, more direct and accurate in their task performance. Due to differences in design, it was noticed that participants engaged with each stimulus in distinct ways. In the *Spatial* condition, participants (P1, P2, P3) aimed to quickly get to the -6 milestone and then move up and down to find the target (Figure 7.13). P3 particularly mentioned that since he knew that -24 was not clearly audible, he recognised that the gap he was hitting while pressing the up arrow corresponded to -6. This confidence, however, occasionally led to errors when he moved too quickly and missed the intended gap, forcing him to backtrack and search for it. In this case, there were instances where participants felt confident in finding target numbers above -6 without extensive exploration (P1, P2, P7). Participants (P5, P6) highlighted the importance of the gaps in the design. Given that the location of the vibration was changing (inf -23 = left motor, -22 to -7 = middle, -5 to +6 = right motor), the gaps helped to better understand the location change as well. For example, the device in the upper arm provided more sensitivity, which was noted to be helpful in recognising the exact motor location, although it wasn't always easy.

'The gaps worked in favour of it, so the main characteristic of this was the location. Basically, it's changing location according to where we are and the rate, and I found that the gaps are like an addition to helping differentiate these gaps.' (P5)

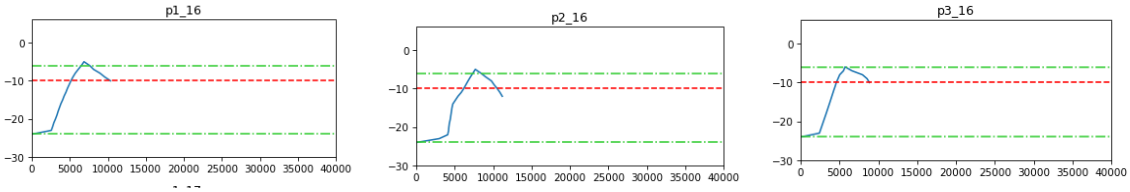


Figure 7.13: Slider movement with Spatial mapping, (aimed for -6 and then down to target)

In the *Tactons* condition, participants displayed two distinct performance approaches. Some aimed for 0 (P6, P7) or -24 (P1, P6), which were the endpoints of the range, and they were clearly marked by unique vibrations at specific motor locations (Fig. 7.14. Others, including P2, P3, P4, and P5, explored more slowly but with greater confidence, aiming for -6. This variation in approaches indicates that the shared motor for -12 and -6 led users to explore and confirm the milestones. For example, if the track volume was set above -24, participants struggled to distinguish whether the first milestone was -12 or -6. To resolve this, they often moved either down to -24 or all the way up to 0 to confirm which vibration corresponded to the middle motor.

For example, P1 initially aimed for the nearest milestones, such as 6 or 12. However, he soon realised that he had to move outside this range to confirm whether the vibration he felt on the middle motor corresponded to 6 or 12, leading to some confusion during the interaction.

> 'So before I would try to move towards the parameter I was getting to, or the value I wanted, I was trying to find which landmark it was closest to and then move from that landmark. If I were between -6 and -12, and I needed to go outside of that range. Whenever I got to one of those landmarks, I didn't know which one it was, because I didn't know if I was coming from above or below. So that was confusing, but it just took a little bit of extra confirmation for me.' (P1)

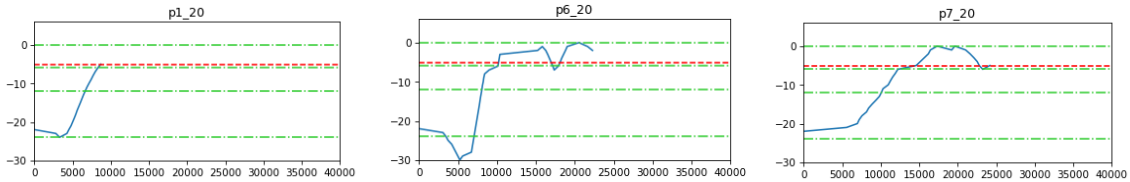


Figure 7.14: Slider Movement with Tactons mapping (aimed for 0 (P6, P7) or -24 (P1) first)

P4 described his approach as moving up to 0 and then counting down to locate the target. However, he noted that sharing the same motor for -6 and -12 could lead to confusion. P5 oriented himself by either moving down to -24 and then up, knowing he would reach -12 first, or by moving up to 0 and then down, knowing -6 would come first. 'For me the problem is again the 6 and 12. They are in the same place, so you don't know if it's 6 or 12. You go all the way up to see where you are when you go down.' (P6)

Theme2: How to change the design to improve usability

Participants provided concrete suggestions for improving the designs and enhancing usability. *Intensity* did not receive a significant number of suggestions, indicating that participants largely disregarded this condition. In contrast, both *Spatial* and *Tactons* received several suggestions, many of which were shared across participants, allowing us to identify common themes.

Spatial As seen in the previous comments, participants commented on how the two vibration pauses (gaps) were far apart from each other, and therefore, they suggested adding more gaps or changing the represented thresholds.

P3 suggested adding more gaps at -12 and -18, as well as including a marker for 0, as it is a crucial point on the mixer's fader. P4 design suggestions included adding extra

gaps at intervals of 10 or introducing milestones at -10 and -5. P5 suggested adding another gap in the middle, as he believed the gaps greatly helped differentiate between locations. P6 proposed replacing –24 with -12 instead of –6, highlighting how –24 is not audible.

Tactons: The main issue in the *Tactons* condition was that -6 and -12 shared the same motor, which caused confusion for some participants. To address this, some participants suggested reducing the number of milestones, while others recommended adding more milestones with a rhythmic pattern to make them easier to distinguish.

Fewer vibrations: P6 suggested simplifying the design by unifying -6 and -12 into one vibration at -10, leaving only three key milestones –20, -10, 0. He supported this idea by pointing out that sound levels typically change every 3 dB, a difference that is not always perceptible. He argued that it is unnecessary to frequently know the exact dB level, making fewer milestones more efficient. 'I would change the two vibrations in the middle, they seem the same. And maybe I would make it every 10 again. like 0, 10, 20.' (P6) P7 suggested that it would be easier for him if the gaps corresponded to numbers that were simpler to remember, such as 5, 15, and 25 (multiples of 5). An interesting example comes from P5, who initially suggested adding another motor but quickly reconsidered, worrying that it might complicate navigation. He also proposed having -18 share a motor with -24, though he expressed similar concerns. He concluded that 'less is more' and that the current design might be the best option.

More Vibrations: P2 suggested more stimuli in additional numbers, specifically, -3, -9, -18. Also, he suggests that adding more stimuli means that more vibrations will share the same location; to make this work, different patterns for each number should be designed that will help distinguish them. P3 also suggested altering the spatial arrangement of the vibrations by assigning major values like 0, -6, -12, and -24 to the centre motor, with secondary values like -3, -9, and -18 assigned to the outer motors.

Rhythmic patterns to distinguish –6 –12: Multiple participants suggested creating rhythmic patterns in order to distinguish the two vibration stimuli (P1, P2, P3, P4). P1 followed his suggestion by acknowledging that while this would require more time to learn, it would ultimately enhance clarity.

P3 and P4 suggested a particular vibration for -6 and two quick vibrations for -12. 'I think I would like the -12 to beep once and then the -6 to go twice. So that you know that you're hitting the end of the boundary.'(P4)

7.5 Discussion

In this chapter, the research questions were addressed by developing three vibrotactile feedback mappings to the volume fader of the DAW mixer and comparing the effectiveness of their use in an audio mixing scenario. Seven blind and visually impaired music producers completed a series of mixing tasks, and were requested to adjust one of the tracks to a specific level of dBFS scale using keyboard interaction, no voice feedback, but only one of the vibrotactile feedback mapping at a time. Findings showed that there is a significant difference in the performance of the vibrotactile feedback, which is designed based on *Intensity*, and the other two, which are based on spatial distribution and tactons. This difference has been explicitly identified in the Distance from Target scores, the number of Keyboard activations to get to the target, and the Time for task completion. Qualitative data from the MDT questionnaire support this difference, with negative word frequency for *Intensity* mapping and positive for *Spatial* and *Tactons*. This study also explored how users utilise the designed vibration stimuli and what they would like to change to make them better, as well as the factors that influence their preference and performance across the different modes. The answers help structure guidelines for the future design of vibrotactile feedback for sound interaction.

7.5.1 Examining Expected Differences in Vibrotactile Feedback Design

Existing literature, as well as participants' insights from the interviews on 3, provided a series of possible vibrotactile feedback approaches (i.e.,intensity, frequency, location, and duration of the vibrations) that could be used in this study. Previous studies suggest these parameters can influence both user performance and preference across different vibration designs. Our finding shows no significant difference in the accuracy of task completion across the conditions, although the mean of the Intensity condition was lower; it shows a difference in the rest of the measurements, indicating that intensity is not a suitable choice for conveying changes in numerical values in the context of interaction with a slider. Previous studies, although not identical to the current study, suggest that such vibration parameters can influence both user performance and preference across different vibration designs. For example, Pascher et al. (2023) on a directional cue-related task compared frequency and location, frequency, intensity and location, and intensity and location, found that intensity-location mode performed the weakest of the other two, something similar to our findings, where the intensity-based VFT performed worse than the location and the Tactons. Similarly, Tan et al. (2019) in his test with three intensity levels and varying numbers of vibrations or vibration durations, showcases how intensity

can influence the perception of other properties as well. Alirezaee et al. (2020) compared three mappings to visual cues, location/motion-based, Tactons (number of short vibrations) and duration of pulse vibrations, and identified a difference in the performance of the Tactons in comparison to the rest conditions, indicating the strong preference of Tactons among the different designs. Lastly, in Jack et al. (2016) study, which is also related to music interaction task, vibration-in-tune (similar to Tactons mapping) and vibration-out-of-tune (similar to *Spatial* mapping) both performed better and were preferred by the participants in contrast with beating, which is based on frequency (similar to *Intensity* mapping).

These studies showcase participants' diverse preferences in vibrotactile feedback designs. The commonality among all of these is the use of intensity and frequency, which performs worse than any other suggested mapping, a finding confirmed in our study as well. However, our results reveal an important distinction: while there is no significant difference in accuracy, intensity-based feedback lags in overall performance. This suggests that while intensity-based feedback may be sufficient for completing tasks accurately, it is less efficient, requiring more time and greater keyboard interaction. The following section (7.5.2) delves deeper into the understanding of the performance results and participants' feedback with the *Intensity* method to determine if this mapping needs to be abandoned or iterated to improve efficiency, like the other two.

7.5.2 The Limitations of Intensity-Based Vibrotactile Feedback

Although the statistical analysis indicated a significant difference between the *Intensity* and *Spatial* and *Tactons*, more detail is needed on the design attributes that contribute to this result to understand the effect of vibrotactile feedback in this interaction context. The analysis of the qualitative and quantitative results revealed some indicative reasons that *Intensity* mapping did not work. Participants extensively commented that they needed more time to understand the changes in the vibration pattern and that they often struggled to comprehend them. Literature extensively refers to the complexity of perceiving the intensity and frequency of vibrations. Haghighi et al. (2020) mentions that the duration of the exposure to the stimulus might change the user's perception of the stimulus itself, which is highlighted that in their findings. In this study, a deviation is observed between individuals who required more time (P1, P3) and the those who did not, who did not mention this at all. Another study that supports this comes from the findings of Tan et al. (2019), which indicated that users required multiple repetitions of exposure to stimuli when the intensity was low, but fewer repetitions when it was higher,

demonstrating the link between amplitude and time of exposure. The participants' need for longer exposure to the stimuli suggests that a higher cognitive load is required to interpret intensity and frequency. This challenge was also reflected in their negative MDT word choices, with the most frequently selected terms being 'difficult', 'confusing', and 'slow.'

Although the literature indicates that intensity and frequency are distinguishable, they may not be suitable for all tasks and types of interaction. The combination of interactive task scenarios with audio might add to the cognitive demand for recognising the different levels. Participants mention that the *Intensity* condition did not feel natural for the task (P4, P6). Supported by Stein et al. (2017), intensity might be more suitable for events like alerts or haptic representation of lines. In the case of music production, features like the Peak Meter or volume automation lines would benefit from intuitively representing values by intensity rather than using abstract vibration patterns (i.e., Tactons).

7.5.3 Influence of Spatial Arrangement on Tacton Perception and Mapping Performance

Spatial and *Tactons* share a common parameter, the spatial arrangement of the information in the motors. The spatial arrangement of information has been widely examined in studies in terms of the contribution to the perception of different vibration patterns (Alirezaee et al., 2020; Linden et al., 2011; Wittchen et al., 2022), also called spatiotemporal. In this design approach, the vibrations become distinguishable due to the change in the location of the stimuli. In the case of the *Spatial* mapping, vibrations are continuous, and the location changes when a specified threshold is surpassed. Two small pauses of vibration in the two thresholds (-24dB and -6dB) create a clear indication of the vibration location change and thus the different numerical ranges represented. This design choice was made to mitigate the change of the small distance between the motor, which might have created difficulties in understanding the location change, according to Carcedo et al. (2016) and Hong et al. (2017). The three motors initially created an opportunity for three ranges to be mapped, but only two milestones to be effectively expressed through the pause between the three locations.

On the other hand, the Tactons conditions provide stimuli only when the user surpasses the given milestone, giving an opportunity to utilise the three distinct locations and provide a minimum of three different pieces of information. In this test, in order to provide a fourth milestone, two milestones were represented by the same motor (middle) location. Considering the participant's performance and feedback, it was identified that the use of the three motors in our device design created some limitations. Participants'

feedback showed that accommodating two milestones in the exact location was confusing and misleading. According to the tests in 5 and literature (Carcedo et al., 2016), users would not be able to identify the absolute location in a device with a larger number of motors. Therefore, parameters such as rhythm or duration should be employed to enhance design clarity.

According to Erp et al. (2020), blind people can memorise up to 5 spatiotemporal patterns while walking. Although studies have shown a capability to memorise more patterns, those were conducted with sighted users in a static, non-interactive context and with different levels of pattern complexity. As the number of patterns increases, so does the cognitive load, especially when an audio distractor is present. This study highlights the importance of designing within the constraints of the available technology, such as the number and arrangement of available motors. Consequently, it is important to consider participants' perceptual threshold in understanding the vibrations produced by the device in its current configuration. Finally, the type of information being conveyed, along with the device's capabilities, should inform which vibration parameters (e.g., location, duration, rhythm, frequency, and intensity) are used to create clear and meaningful mappings.

7.6 Limitations

The results of this study are influenced by the small yet highly targeted sample size. While the testing conditions allow for the extraction of meaningful insights into the use of vibrotactile feedback in DAWs, the study would benefit from being replicated with a larger and more diverse group of participants. Individual preferences, experiences, and perceptual differences may have influenced the results. Additionally, the requirements of this study, which involve blind music producers, interaction with interface elements, and active music manipulation, make it difficult to directly compare with other studies.

Other variables that limit the comparability of the results are the use of a unique haptic design configuration, including the number, type and arrangement of motors, as well as the wearability approach. Additionally, the vibration pattern design possibilities are also limitless. This diversity, although it allows flexibility and adaptability, which is important for inclusive design, hinders standardisation and comparability with previous work.

Finally, the seven participants of this study provided a rich dataset with their feedback on how they use the suggested mappings. Among the collected data, there was a variety of responses that did not necessarily contribute to the creation of distinct themes and were not reported in the results. This highlights the diversity in people's experiences

with vibrotactile feedback and the challenges in making firm and generalised conclusions. However, this observation highlights that future tools incorporating vibrotactile feedback should be designed with adaptability in mind, accommodating users' individual preferences and perceptual differences.

7.7 Conclusion

This study evaluates three diverse vibrotactile designs to enhance interaction with a slider interface element, the volume fader, that represents and edits the volume of an audio track. In the presence of an audio track that corresponds to the user's interaction, the three suggested patterns were examined to identify which enables users to complete the task of placing an audio track at a requested dB level more efficiently. Results showed that *Intensity* mapping, which is based on the manipulation of intensity and frequency of vibration, is not the ideal choice for such a task, as the changes in the vibrations do not convey numerical information clearly. This led users to spend more time on the task and engage in more keyboard interaction to find the requested number. On the contrary, *Tactons* and *Spatial* methods performed significantly differently from the *Intensity* method, while participants completed the tasks more accurately, faster, and with less interaction with the keyboard. Tactons relied on spatial allocation and short duration to convey information, and Spatial allocation was facilitated by continuous feedback. Findings support the existing literature regarding the effectiveness of location and duration in designing vibrotactile feedback for conveying information. Participants provided rich qualitative feedback that supported their performance results and clearly stated their opinion on the dysfunctionality of the *Intensity* mapping. Among their feedback, they provided clear suggestions for improvement of the given mappings. These are concentrated on the way each chosen location is mapped to the information (i.e., improving the information mapping rather than the technology) and the use of rhythms as an additional way to convey more detailed information.

This study offers insights into the design and application of vibrotactile feedback in DAWs. Future work includes examining more possible mappings to other interactive areas of the DAW, such as FX parameters. Additionally, an interactive process, including co-design sessions for further exploration of the vibrotactile feedback, will enable a deeper understanding of user preferences and the most effective feedback design strategies. This collaborative approach will help refine the design of vibrotactile interactions, ensuring they align with the needs of all users.

Chapter 8

Conclusion

In the Introduction of this thesis, a lack of work was identified in the ways vibrotactile feedback is designed to enable accessibility of DAWs for BVI creatives. This led to the formulation of two core research questions: RQ1: How do BVI music producers currently use haptic feedback in their DAW workflows, and how do their unmet needs inform the design of new haptic devices? RQ2: Which vibrotactile feedback design strategies are most effective for supporting DAW interactions, and how do they compare to existing accessibility solutions? To address these questions, this thesis first examined the gap in the existing literature and investigated the requirements for creating a new tool for the accessibility of DAWs. BVI musicians use the available tactile feedback tools to make their workflows more accessible. Participants provided insights about the use of musical hardware to make navigation to FX parameters quicker and more accessible, especially when there is no screen reader alternative. Participants also highlighted the use of vibration feedback in their everyday lives to access information discreetly. Tools like smartwatches inspire the design of new tools that provide information about DAW functions and speed up the workflow. Participants also presented concrete ideas on how to map different DAW functions to vibration designs. After combining these findings with a review of existing vibration design techniques, guidelines for mapping DAW functions to vibration design techniques were developed. A review of wearable vibrotactile feedback devices helped identify the arm as the most suitable location for wearing the intended new device. An armband with three actuators around the hand was then developed to convey information associated with DAW interaction.

The thesis then focused on the development and evaluation of a prototype method for conveying information from DAW with vibrotactile feedback, providing an alternative non-audio-based method of interaction. First, an armband with three actuators around the hand was developed to convey vibration to the user. Consequently two evaluation

studies were conducted and indicated that: (1) two-parameter Tactons based on location and rhythm are as effective for conveying non-interactive information on screen as the screen reader or a hybrid mode, although, participants favoured the haptic solution, highlighting their potential, and (2) for continuous interactive information, location needs to be the primary design choice, but also Tactons in the form of short vibrations can be useful, indicating preset thresholds in a range of values. The following section in this chapter discusses the contributions of this research by answering the two main research questions and presents the design principles that emerged from each study. Subsequently, the threats to validity of this research are presented, followed by concrete technological and design recommendations for future studies that include disabled participants, creative processes, and innovative technology.

8.1 Contributions

8.1.1 Accessibility of Music Production using Haptic Technologies

The first research question aimed to expand the current knowledge on accessibility barriers in DAWs for BVI creatives by examining how tactile and vibrotactile feedback, already used in music production workflows and everyday tasks, can inform the design of more accessible music production tools.

Although key research from Metatla et al. (2011), Saha and Piper (2020), Payne et al. (2020), Pedrini et al. (2020), Harrison et al. (2023) provided critical insights on the barriers created by screen readers, they overlooked the peripheral tools the BVI producers use in their workflows.

This thesis demonstrates that, with current accessibility methods, BVI music producers are constrained by delays in their creative flow and additional cognitive workload due to the linear presentation of information and the high demand for memorisation skills. Hardware devices offering haptic feedback are rarely referred to within the literature- for instance, only Saha and Piper (2020) and Harrison et al. (2023) have expanded on the role of haptic feedback for DAW accessibility to date and suggest ideas for future incorporation in the DAWs. This thesis contributed to the understanding of hardware devices' usage in music production by investigating how BVI music producers use them in their workflows and by suggesting leveraging this new knowledge for the design of inclusive music technology.

BVI producers have developed multimodal workarounds using commercial hardware devices not originally intended for accessibility. Additionally, the list of DAW-featured participant access through hardware is almost identical to the features they suggested needed an alternative accessibility method, such as vibrotactile feedback, indicating participants' familiarity with a potential haptic feedback language for making these features more accessible.

The key findings that support this contribution and advance future design principles are:

- There is currently no 'perfect' device, while choosing one type of technology might limit access to the benefits of another.
- BVI users still need voice feedback for full access, despite the use of tactile interaction and the benefits of music hardware.
- Although the devices offer precision, speed, tactile feedback, and sometimes portability, they remain inflexible and expensive.

BVI people use tools not intended for accessibility, such as surface controllers, to mitigate their challenges and make their workflows more efficient. The key takeaway of this contribution is that multimodal tools for digital music production is a functional requirement rather than an optional enhancement. The overall design considerations that should be highlighted include making cost-effective tools, flexible in their use of voice feedback, and certainly providing tactile feedback.

8.1.2 Haptics: Utilising a wearable vibrotactile feedback device for inclusive music production software.

The second contribution aligns with the second research question, 'What vibrotactile feedback design strategies are most effective for supporting DAW interactions, and how do they compare to existing accessibility solutions?' by suggesting wearable vibrotactile feedback as a viable alternative accessibility method for creative software such as Digital Audio Workstations. Developed across four interconnected findings, this contribution answers this RQ by providing a framework for mapping design techniques of vibrotactile feedback to DAW features, identifying the affordances of body location when it comes to designing wearable vibrotactile feedback devices, and identifying the most suitable vibration parameters in designing vibration patterns for presenting information.

Mapping design techniques of vibrotactile feedback to DAW interface interactions.

This thesis presents a framework mapping vibrotactile design parameters to specific DAW interaction types for BVI producers. This contribution provides the foundation work that generates opportunities for future research and development. Previous literature has provided design guidelines and taxonomies for vibrotactile feedback in music (Giordano et al., 2018), but not specifically for accessibility for BVI people nor for use in music production software such as DAWs. The framework was grounded in both a review of existing vibrotactile design literature and direct input from BVI music producers, ensuring it reflects real workflow requirements rather than theoretical mappings alone.

Exploring Body Location Affordances for Wearable Vibrotactile Feedback in Relation to Use Contexts and Performed Interaction

This thesis identifies the arm as the optimal location for a wearable vibrotactile device in the DAW use context. This conclusion was drawn based on a body-location affordances analysis focused on wearable devices with vibroatactile feedback. The analysis of existing wearable devices enables the accurate mapping of technology's possibilities to users' suggestions and contributes to the understanding of how wearable devices with vibrotactile feedback should be used for inclusive DAWs. The optimal location satisfies the unique constraints of not interfering with concurrent hardware devices' interaction, such as a braille display, a computer keyboard, music controllers, and musical instruments. To our knowledge, no prior body location analysis had applied this specific constraint. Additionally, it identified the potential arrangement (i.e., around the arm) and number of motors (i.e., five or fewer) on an armband that could be beneficial for conveying interaction information from the music software.

A design framework for a vibrotactile feedback wearable device for BVI DAW users.

While the upper part of the body and specifically arms is specified as the most suitable location for a wearable device in the use case of music production with DAW for BVI users, the opportunities for motor arrangements were still vague and underexplored. This thesis establishes that three ERM motors spatially distributed around the arm are sufficient for accurate vibration localisation.

The device with three motors around the hand performed better than the one with five motors in terms of accuracy and time, indicating that fewer motors will enable a more accurate and consistent perception of vibrotactile feedback. The accurate localisation of the vibrations around the arm was important to evaluate, as the vibration patterns

conveying DAW-related information were designed to exploit spatial arrangement as a communication technique.

The evaluation also facilitates the identification of the optimal location for wearing an armband device by the user. For the 5-motor device, upper arm locations (both left and right) provided statistically significantly faster identification of stimulus locations, but no difference in the accuracy level. The 3-motor device showed no difference in performance (accuracy and time) among the four examined locations. These results indicated that a larger circumference (upper arm) influences the performance when there are more motors. The results also support the notion that three motors will allow for more adaptability and flexibility in the device's usability, enabling users to choose their preferred location while maintaining accurate identification of the stimuli. Nevertheless, human factors remain unpredictable when using a device, and design should not be based on a "one size fits all" approach. Lastly, the two devices differ in their wearability: the first uses a Velcro strap, and the second uses an elastic band. These two designs also allow exploration of the most usable, easy-to-wear method for this device, especially for BVI users. This design framework emerged from the evaluation findings and suggests that (1) the location of the device in the user's arm is flexible, (2) three is the optimal number of motors around the arm, and (3) an elastic band is a preferred type of wearability method for the device.

Identifying Rhythm and location as the most useful parameters in designing vibration patterns for presenting information.

Across both evaluation studies, spatial location emerged as the primary reliable parameter for conveying DAW interaction information. The two conditions using the spatial arrangement of vibration performed similarly and were much more accurate than the condition using intensity variation of vibration. That indicates that using spatial arrangement enables a better, more intuitive perception of stimuli and, therefore, of the information.

The Tactons design presented in Chapter 6 is based on two primary methods: body location-based cues (Wittchen et al., 2022) and arbitrary rhythmic patterns. It is argued that the use of location enables an intuitive understanding of Tactons similar to the findings in Chapter 7. Together, these results demonstrate that spatial mapping enables users to perceive and interpret vibrotactile information more effectively.

This thesis also confirms the recognisability and memorisation of six two-parameter Tactons by Blind participants, while their accuracy results were 97% in a 30-task study, after a training session. While the literature supports high Tactons' recognisability (Phanomchoeng et al., 2017; Alirezaee et al., 2020), results vary across pattern types, and testing

conditions differ from those in the studies of this thesis (e.g., including participants with disabilities, a music background, and a new prototype device), limiting comparability.

This thesis provides a coherent set of design principles for DAW accessibility using vibrotactile feedback:

- BVI producers' existing haptic preferences and suggestions, developed through commercial hardware use, should directly inform vibrotactile DAW design.
- Three motors provide a flexible and accurate solution for a wearable device with vibrotactile feedback used in music production.
- The spatial location of vibration patterns should be prioritised.
- Design should be adaptable rather than fixed.

8.2 Threads to Validity

Challenges and Limitations in Testing Multimodality for Accessibility and Creative Activities

This research suggests the need for inclusive and adaptable technological tools; however, the human-centred design techniques applied during the development and evaluation processes identified challenges and potential threats to the research's validity. Conducting empirical research in the HCI field takes many forms and methods. Qualitative methods, such as interviews, provide rich insights that facilitate the understanding of users' perceptions of a new system. However, this method inherits subjectivity, which limits the researcher's control over the participants' realistic reaction and task performance with the system. In task-centred metrics, in contrast, there is careful planning of the conditions of the task, what is being measured and how, allowing more concrete measurements of human-system interaction. When it comes to testing with participants with disabilities, the conditions might vary. Individuals' abilities will most likely be more diverse based on their specific medical condition Lazar et al. (2017). That creates a dilemma between testing for individually tailored setups and getting more realistic results (especially in heuristic evaluations) or keeping conditions identical across participants and producing more generalisable findings, but not necessarily representative.

This research tried to mitigate the challenges of conducting empirical studies with people with disabilities in a creative context. Our test design took into consideration the following special conditions: (1) testing with a new device/prototype, (2) testing with people with disabilities, and (3) testing in a multimodal scenario that included sound

and haptics. The following sections expand on the individual challenges and limitations of each specific condition.

8.2.1 Testing with a New Device/Prototype.

In HCI research, especially in disability studies, a new prototype device is often used, raising questions about the validity of the research. This is due to the lack of established evaluation methods (Marquardt et al., 2017) and to differences between prototypes and production-level devices (Kang et al., 2025). Chapter 5 evaluated the device in terms of its technical efficiency (Simpson, 2010), examining the optimal number of ERM motors and ensuring their distinguishability. Additionally, the ergonomics and wearability of the tool were evaluated, ensuring practical placement and comfort for music production tasks (Figure ??). Although it is a prototype device, it was necessary to design it to closely resemble a fully developed tool, with easy onboarding that enables a more straightforward training process and greater learnability. That secures less testing time, less frustration, and lower cognitive load. Those are very important to ensure accurate results and impartial feedback.

In the following chapters 6, and 7, the second level of evaluation by Simpson (2010) was employed (i.e., clinical evaluation of usability and acceptance), examining usability and acceptance in real-world use cases with BVI participants (e.g., navigating EQ settings through vibrotactile cues).

One of the limitations of this research is the lack of longitudinal studies (i.e., third level). Although very important for the evaluation of an assistive tool, are not always possible due to time and resource constraints. A prototype device that relies on non-commercial components is not always sustainable for long-term use, so participants may need to troubleshoot the system, which might not always be accessible. Therefore, it would not be able to ask participants to use the device without supervision.

One of the main challenges of prototype devices is the lack of comparable benchmarks. Bespoke devices created for a narrow user group often rely on qualitative evaluation methods (Metatla et al. (2015)). That limits the opportunities to align test accuracy or task-completion metrics with other studies. To mitigate this, our device was designed based on literature guidelines and similar studies on vibrotactile feedback (Jack et al., 2016; Phanomchoeng et al., 2017; Wang et al., 2019), providing at least an indirect basis for comparison.

8.2.2 Testing with People with Disabilities

Working with BVI music producers required adaptability and flexibility in every stage of this research, from the recruitment to the design of the individual studies. This research's limitations mirror Xu et al. (2025)'s observations of challenges in testing with people with disabilities in VR settings. Some of the challenges faced included recruitment, communication, travel to the experimental site, and understanding participants' lived experiences. Recruitment for this research primarily occurred via DAWs' accessibility forums and later through word of mouth. Charities and non-profit organisations offered limited support, while announcements were often lost among the high volume of messages on this mailing list. Nevertheless, building connections and trust with community members was most helpful in the recruitment process. Testing with BVI users required an inclusive communication approach. All information sheets and consent forms demanded flexibility from the researcher and access to accessible formats or alternatives (e.g., plain text files) where requested. In remote interviews (i.e., Chapter 3), participants' access to technology varied in terms of technical knowledge and access to equipment. For instance, some participants were confident about how to share their screen during video calls (e.g., Microsoft Teams, Zoom, Skype), while others faced challenges or were unable to do so. Flexibility was essential on this occasion, providing an alternative and being prepared to work without access to share-screen recordings. In cases like the interviews, one of the biggest challenges was caused by the screen reader often interfering with the recorded audio. In cases where participants had a screen reader on the computer speaker, our recordings also included their screen reader voice. That created a challenge in the transcription process, where it was necessary to manually transcribe some parts as the audio was not clear enough to be comprehensively transcribed by the computer system. This challenge was mitigated in the in-person testing as SR was only used as part of the test and in controlled times, and via provided headphones.

BVI people often face challenges in travelling with public transport. This niche population of BVI music producers involves people living across the country. Thus, having the flexibility and the support to travel to users' locations was vital for the realisation of this research. Nevertheless, that makes the research conditions more challenging by demanding careful planning from the researcher regarding personal safety, equipment safety, fatigue and time management. In the event that users travel to our location (university), this involves accommodating participants' needs, including escorting them to and from public transport stations. That demands that researchers be familiar with or undertake training on how to be a sighted guide (Xu et al., 2025).

Another challenge that needed to be mitigated was the study design and the consideration

of participants' individuality. Starting with testing the prototype device (Chapter 5), two challenges emerged that had to be considered in the analysis of the data: first, the participants' different body types and second, the use of an accessible prototype test interface. Although the same device and task were used in the tests, the perception of the vibrations varied depending on the arm's circumference. When testing was conducted with BVI participants, an alternative, accessible test interface was created, allowing responses to be given via keyboard rather than through visual representation (GitHub Karpodini (2025b)).

In Chapter 6, the use of a screen reader (SR) was included and compared to the new haptic feedback system. As mentioned by Lazar et al. (2017), the use of SR varies across participants, in terms of speed, voice, language, and syntax, which differ across different SRs and computer operating systems. The choice of SR that is used in the experiment influences the results. Participants might have different expectations and be surprised by the provided feedback; they might also feel uncomfortable or unable to interact with the system. To better understand any unexpected results, documentation was prepared prior to the SR's use in participants' workflows. The test interface was also designed with accessibility in mind, taking into account the different uses of SRs. For example, in the interface used in Chapter 6, the SR speed was moderate to ensure understandability for both users who use it at different speeds and those who use different SR (NVDA instead of VoiceOver). Participants from Greece were also provided with a Greek screen reader.

The challenges in conducting research with disabled participants include accessing participants (e.g., recruiting and visiting), using accessible technologies as part of the test design, and considering individual differences in how accessible tools are used. This research considered these possible limitations and suggests using a mixed-methods approach to cross-validate results. It is concluded that research involving disabled participants requires multiple studies across a variety of settings to fully understand users' needs and their interactions with a new system (Gibson et al., 2014; Theil et al., 2023).

8.2.3 Testing in a Multimodal Scenario that included Sound and Haptics.

Designing multimodal interactions for people with disabilities can greatly enhance inclusivity. Multiple channels for conveying information and interacting with content offer greater opportunities for usability (Freeman et al., 2017). However, the design process should account for the different capabilities of the intended users to access these modalities. In this research, for instance, only audio and haptics were included in the design,

as visuals are not available to blind users and might not be preferred by people with low vision. The aim is not to design a system that translates the existing visual interface into another modality, as happens with the SRs, but to create new, alternative ways of interaction. In this process, it is essential to carefully consider participants' feedback, review empirical evidence on perceptual limits, and commit to designing adaptable tools that respect users' individuality. Perception limits and preferences might vary based on their medical condition or even their experiences.

For these reasons, evaluating a multimodal system is challenging and calls for a mixed-methods approach. These methods include multifaceted evaluation methods such as performance metrics, cognitive load measurement (NASA-TLX), other usability metrics (SUS, UMUX) and qualitative interviews. Even then, it is difficult to determine at any given time which modality contributed to the results. For example, in the study described in Chapter 6, where users tested both haptics and a screen reader (audio) simultaneously, participants were asked to explain which modality they relied on to identify the EQ information provided, as no direct means of measuring this were available. In Chapter 7, where participants performed an active listening task, mixing two audio tracks by matching the requested dB value based on vibration feedback, they were asked whether they relied on the audio quality (i.e., audio volume being close to the requested level) or ignored the sound and focused solely on the haptics. This research aimed to explore how haptics can coexist with audio material during music production tasks without interfering with audio processing, in contrast to the existing audio-based feedback from the SR. Meaningful insights have emerged that enable the presentation of design guidelines for haptic feedback in DAW interface interaction; however, they also provide substantial scope for future work to understand the broader impact of haptics on sound-processing workflows.

All of the approaches that examine threats to the validity of this research lead to similar suggestions for mitigating the challenges and for the procedure of subsequent work. A greater volume of smaller studies, with a variety of content, is needed, including adaptable prototypes, standardised setups, longitudinal studies, free-for-exploration studies, and task-based studies. Mixed-method approaches offer a better understanding of participants' interactions with systems and provide opportunities for more valid findings.

8.3 Recommendations

This work explored the role of tactile interaction in the music production workflows of blind and visually impaired creatives. It showcased how vibrotactile feedback can enhance accessibility by being used instead of, or alongside, current screen reader methods. To

apply these findings in future design efforts for reducing barriers to access to the musical industry, designers, researchers, and developers should address changes across two domains: design and technology. The adoption of the following recommendations benefits not only the blind community but also the general audience by supporting more engaging and usable music-creation workflows.

8.3.1 Technical Recommendations

- **Create a DAW plug-in/toolkit for mapping DAW parameters to vibration patterns.** The first recommendation is to create a plug-in that allows mapping any DAW parameter (e.g., buttons, sliders, value indicators) to an assigned vibration pattern generated by the armband described in this thesis. For example, users could map the peak meter output value to a vibration design that vibrates whenever the value exceeds -6 dB. Every time a user navigates to the peak meter, they will receive the value through vibrations rather than voice feedback, providing a less intrusive, faster way to obtain the information. Technically, DAWs are currently providing limited integration with external devices beyond MIDI controllers. To enable meaningful interaction with the vibrotactile system proposed in this thesis, the suggested plug-in must interface with the DAW's back-end code, especially to access keyboard interactions that are the typical input method for screen reader users. Once developers have access to such hooks, the plug-in will allow users to assign DAW parameters to the vibration patterns of their choice. The plug-in should include a library of preset mappings based on research findings (Chapters 6, and 7), enabling an easy 'plug-and-play' integration into the workflow.

- **Examine hardware devices with low-latency wireless communication.**

  In order to create an efficient wireless interaction system, minimising latency is crucial. Our device demands small, light electronic components to be suitable for wearables; at the same time, wireless communication with the computer is essential while aiming to enhance accessibility of computer interaction. Commercially available tools with embedded wireless communication provide an average latency ≈ 5–15 ms. The I/O device used in this research, x-OSC, offers one of the lowest latencies; other alternatives are ESP32 (Systems, 2025), Raspberry Pi Pico (Foundation, 2024), and Nordic nRF52840 (Semiconductor, 2024). Devices with lower latency than those do not include wireless communication, but they do have a low latency of less than 2ms; such tools are the Bela (Bela, 2025) and the Teensy 4.1 (PJRC, 2025). Future iterations involving the armband device with three motors should consider using low-latency wired i/o boards and evaluate the effect of faster

vibration responses. With the advancement of technology, wireless devices with lower latencies than those used should be prioritised as an option.

- **Release open-source development resources.**

  Allowing users to make their own devices is an alternative way to enhance accessibility. This solution lowers financial barriers as users can use off-the-shelf DIY electronics materials instead of committing to buying a commercialised assistive device. This requires the adaptation of the system to accessible commercial components such as the micro:bit, which features built-in sensors and supports screen-reader-compatible coding environments, also previously used to convey vibrations to BVI musicians by Lu et al. (2025b), and the Raspberry Pi, which is also accessible through a Linux-compatible screen reader, Orca. Additionally, further hardware documentation should include the 3D printing files for casing the electronic components (i.e., motors, i/o boards, battery), open-source code for the DAW plug-in and clear setup guides for adapting the system to individual needs.

8.3.2 Design Recommendations

Design recommendations are often put forward to hapticians, interaction designers and researchers. The design of vibrotactile feedback and wearable haptic devices must be derived from real users' insights and reflect their needs. Recommendations are derived from human-centred research and a combination of findings from both quantitative and qualitative data analysis. Designing with adaptability and modularity in mind, allowing users to tailor the tools to their needs (Atata and Odedeyi, 2025). Findings also indicate that using different body locations is one of the most efficient ways to convey clear information.

- **Prioritise body location and rhythm.** Intuitive understanding of vibration patterns is linked with the use of the spatial distribution of cues around the arm as proven in Chapters 6 and 7. Participants preferred information mappings that relied on the location of the three motors more than rhythm or intensity. Nevertheless, rhythm is a useful method to convey information (e.g., haptic Morse code). The variety of rhythmic patterns that can be composed showcases the vast possibilities of associating them with pieces of information; however, this is not as intuitive as body location mapping since users need to memorise the meaning of each pattern potentially creating cognitive overload.

- **Allow a modular and user-configurable wearability.** Three motors are suggested to be the optimal number of motors around the hand in Chapter 5. However,

modularity and the ability to add motors to the armband by preference will provide the flexibility to tailor the tool to the user's needs. Over the long term, participants' needs might change, as might their bodies (e.g., ageing, gaining or losing weight or muscle), and so might their sensory perception. Age, physical condition, and individual experiences influence the relationship with and use of the device. Allowing adjustments promotes inclusivity and long-term device use. Besides the number of motors, the location of wearability should also be adjustable. On the suggested device, users can wear it on any hand or at any location on the hand (e.g., forearm, upper arm) without altering the perception of the vibration. However, the study of the optimal location and number of motors remains essential for the design of a tool with clear usage and affordance.

- **Design for multimodal interaction, not replacing the screen reader.** While designing for computer interaction for Blind people, this research does not aim to replace the current method of the screen reader, but a new way of interaction that suggests the use of additional sensory channels for perceiving information. Insights from Chapter 3 established that Voice feedback is important for BVI producers and should be maintained as the main accessibility method. Screen readers are an established way of interacting with and accessing computers; they provide detailed information about the available screen content and enable accurate interaction with it. However, adding haptics or a hybrid mode will enable a less cognitively demanding interaction, especially during active listening. Allowing flexibility in the interchangeability of the sensory modes through which users perceive information is the most inclusive way to use this new system of haptic feedback in computer interaction, especially in the context of DAWs.

8.4 Conclusions

This thesis examined the use of vibrotactile feedback for inclusive and multimodal music production workflows. The design and evaluation of this new system, grounded in users' needs, suggest a movement beyond simple accessibility solutions to inclusive interactions with DAWs for BVI music producers. Rather than using vibrotactile feedback as a retrofit solution, this work conceptualises a new interaction paradigm for music production workflow.

This thesis used human centred methods to explore and design a new system for music production interaction. Through this process, this thesis established that BVI musicians already use tactile interactions for accessible and efficient workflows. This information led to the deeper understanding of participants existing experiences, established vocabulary

and potentially confidence to use a novel interaction system. Leveraging this finding, a set of guidelines for potential mappings of vibrotactile feedback design methods to DAW functions has been provided. This novel contribution led to the following studies of the thesis and provides opportunities for future work.

This research also presented a 3 motor armband device and suggest that this number of motors is the optimal for conveying information from DAW to BVI users. Through this study, the individuality of participants highlighted the need for adaptable and flexible designs especially in wearable technologies, contradicting the idea of one-size-fit-all.

Using a participant-inspired scenarios, vibration design techniques were evaluated in representing potential DAW interactions in the presence of a music background. The perception of interface information in the presence of passive engagement with music (EQ frequency centre combined with slider/text) was assessed using Tactons. At the same time, interaction (volume fader), while actively listening to music, was examined using three design techniques: Intensity, Spatial, and Tactons. It was found that Tactons could be recognised with similar accuracy when used with screen readers or in hybrid mode $\sim 95\%$. Participants perceived Tactons even in the presence of a music background and suggested ways in which they could be improved. For continuous interaction with interface elements of the software, spatial distribution of vibrations was found to be the most intuitive method for conveying information. Tactons using duration and spatial allocation performed equally well as the Spatial-only method and received feedback from participants, including suggestions for greater freedom of adjustment and adaptability to individual needs.

Putting together all contributions of this thesis, including utilising user's existing experiences in design, building adaptable devices and interfaces ensuring all users can perceive the stimuli, a new design method for inclusive and multimodal interaction with music software has been established. These principles are relevant not only to DAW accessibility but to the broader challenge of designing vibrotactile feedback for any creative software used by BVI people.

Overall, this research highlighted the unique nature of testing with BVI participants, new technological systems and creative process and allowed for the identification and suggestion of a new approach to research. This work moves beyond assistive design paradigms anchored in the medical model of disability, where impairment is framed as an individual problem to be fixed. It is suggested that design processes should begin by prioritising inclusivity and adaptability, laying the foundation for a digital world free of discrimination and barriers. This thesis closes with the bold ambition that multimodality and utilisation of all available senses in the interaction process enhance human capabilities

regardless of their physical abilities, limit social exclusion and isolation, promote equal access to creative expression and its application as a hobby or profession.

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Appendix A

Chapter 2 - Literature Review

Motor Model	Link [Accessed: 06-02-2025]
ERM-310-003	https://catalogue.precisionmicrodrives.com/product/310-003-10mm-vibration-motor-3mm-type
ERM-307-103	https://catalogue.precisionmicrodrives.com/product/307-103-9mm-vibration-motor-25mm-type
LRA-C10-100	https://www.precisionmicrodrives.com/product/c08-00a-8mm-lra-linear-resonant-actuator-vibration-motor
LRA-C12-003	https://www.precisionmicrodrives.com/product/c12-003-12mm-lra-linear-resonant-actuator-vibration-motor
Coicecoil C2 Tactor	https://eaiinfo.com/product/c2/
Piezoelectric	https://search.kemet.com/component-documentation/download/specsheet/AE1010D44H40DF
LRA Apple Taptic Engine	https://apple.fandom.com/wiki/Taptic_Engine

Table A.1: Example of vibration motors.

Appendix B

Chapter 3- Interviews

B.1 Hardware Devices Reference Links

Device	Link [Accessed: 06-02-2025]
Akai MPK	https://www.akaipro.com/mpk-mini-mkii
Arturia Keylab mk2	https://www.arturia.com/products/hybrid-synths/keylab-mkii/overview
Avid S1	https://www.avid.com/products/avid-s1
Avid S3	https://www.avid.com/products/avid-s3
Behringer XTouch	https://www.behringer.com/product.html?modelCode=P0B1X
Mackie C4	https://www.soundonsound.com/reviews/mackie-c4
Komplete Kontrol S61	https://www.native-instruments.com/en/products/komplete/keyboards/komplete-kontrol-s49-s61/
Komplete Kontrol S88	https://www.native-instruments.com/en/products/komplete/keyboards/komplete-kontrol-s88/
Komplete Kontrol A61	https://www.native-instruments.com/en/products/komplete/keyboards/komplete-kontrol-a25-a49-a61/

Komplete Kontrol M32	https://www.native-instruments.com/en/products/komplete/keyboards/komplete-kontrol-m32/
Korg M3	https://en.wikipedia.org/wiki/Korg_M3
Korg mikroKey	https://www.korg.com/uk/products/computergear/microkey/index.php
Korg miniLogue	https://www.korg.com/us/products/synthesizers/minilogue/
Korg nanoKontrol	https://www.korg.com/uk/products/computergear/nanokontrol2/page_1.php
Novation Circuit Rhythm	https://novationmusic.com/en/circuit/circuit-rhythm
Novation SL61 MKIII	https://novationmusic.com/en/keys/sl-mkiii
Roland Jupiter X	https://www.roland.com/uk/products/jupiter-x/
Roland Fantom 8	https://www.roland.com/uk/products/fantom-08/
Roland RD-700SX	https://www.roland.com/uk/products/rd-700sx/
Softube Console 1	https://www.softube.com/console1
Softube Console 1 Fader	https://www.softube.com/fader
Bricasti M7	https://www.bricasti.com/en/pro/m7.php
Casio CT-S500	https://www.casio.co.uk/ct-s500bk
Kurzweil K2661	https://kurzweil.com/k2661/
Native Instruments Maschine MK3	https://www.native-instruments.com/en/products/maschine/production-systems/maschine/whats-new-in-mk3/
Nektar Impact LX	https://nektartech.com/impact-lx49-61-plus/
Pultec EQ	https://www.uaudio.com/uad-plugins/equalizers/pultec-passive-eq-collection.html

Table B.1: List of hardware controllers and synthesizers referenced.

Appendix C

Chapter 5 - Development of Device



Figure C.1: Armband with 3 motors around the arm

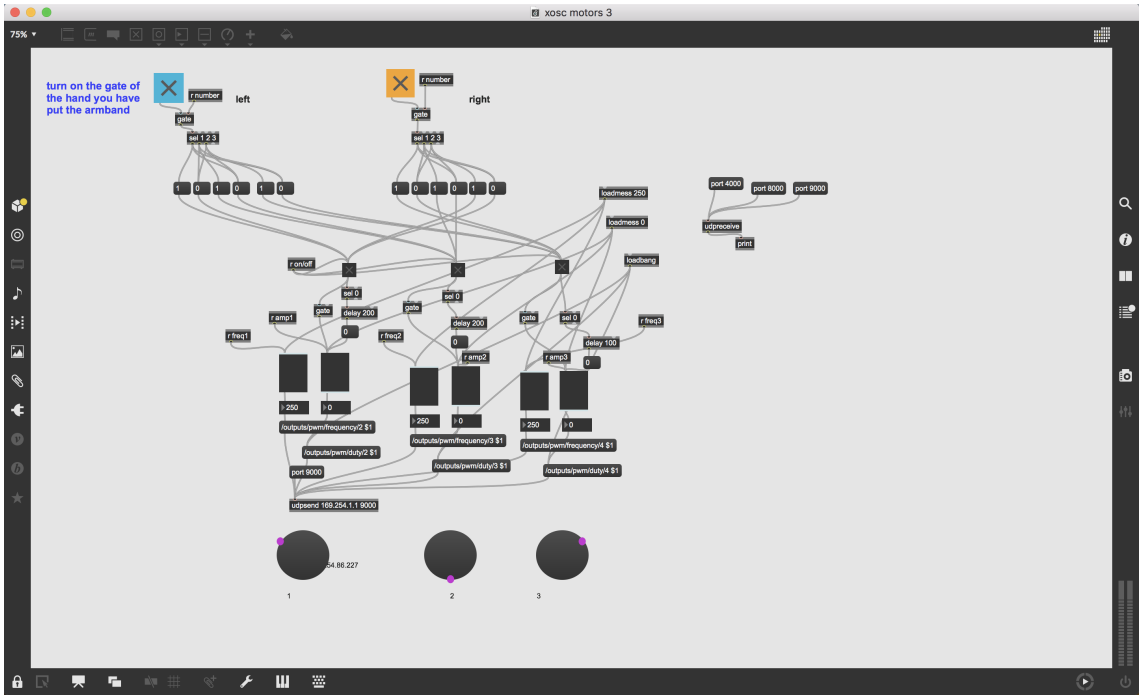


Figure C.2: Maxpatch sending OSC data to 3 motors device- triggering the vibrations

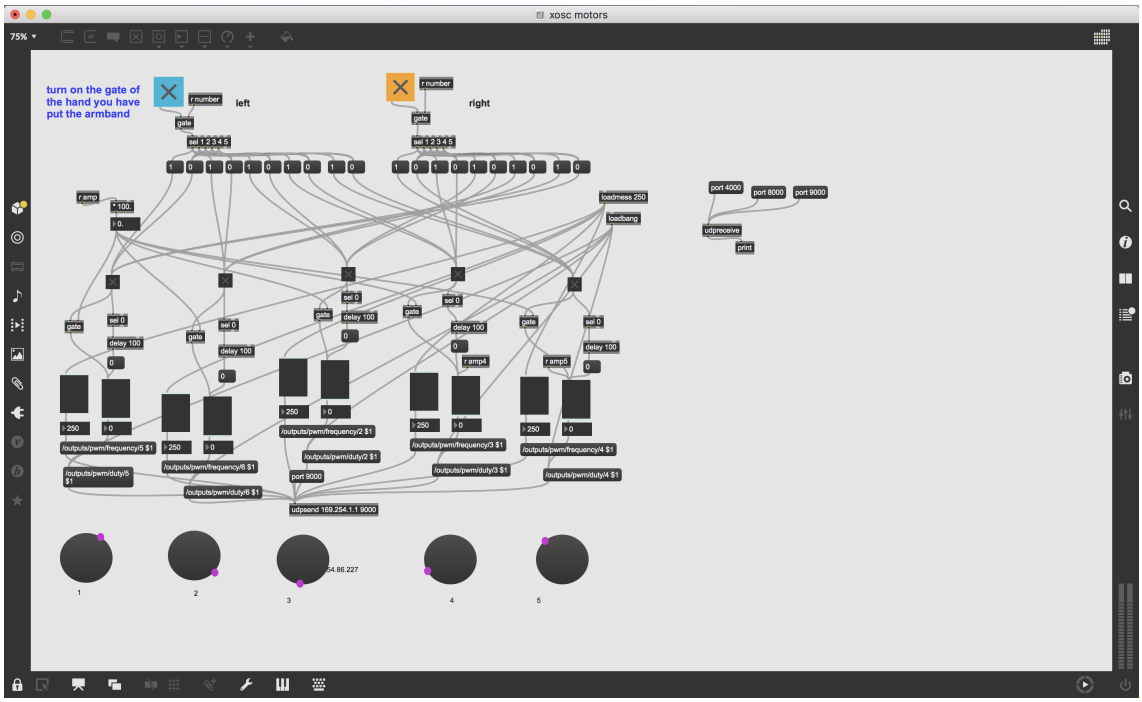


Figure C.3: Maxpatch sending OSC data to 5 motors device- triggering the vibrations

Appendix D

Chapter 6: Study 1: Evaluating the use of Tactons for perception of information in DAW.

D.1 Pre-test questions

- Are you using the SR all the time, or are there times you are switching it off
- What speed are you using your SR when you are using the DAW
- Are you using the SR in a different speaker than the one with the music you are mixing
- How do you usually edit the EQ (Slider, Text input, hardware, other)
- What range of frequencies is low, middle, and high according to your knowledge?

D.2 Stimuli used in the test for the screen reader and screen reader with haptics condition

Information	Screen Reader stimuli	Haptic stimuli
Low-frequency band, text	95.0, content selected, edit text	3 vibrations on the left motor
Low-frequency band, text	154.0, content selected, edit text	3 vibrations on the left motor

Information	Screen Reader stimuli	Haptic stimuli
Low-frequency band, text	191.0, content selected, edit text	3 vibrations on the left motor
Low-frequency band, text	76.0, content selected, edit text	3 vibrations on the left motor
Low frequency band, text	82.0, content selected, edit text	3 vibrations on the left motor
Middle-frequency band, text	1343.0, content selected, edit text	3 vibrations on the middle motor
Middle-frequency band, text	4677.0, content selected, edit text	3 vibrations on the middle motor
Middle-frequency band, text	928.0, content selected, edit text	3 vibrations on the middle motor
Middle-frequency band, text	553.0, content selected, edit text	3 vibrations on the middle motor
Middle frequency band, text	614.0, content selected, edit text	3 vibrations on the middle motor
High-frequency band, text	11470.0, content selected, edit text	3 vibrations on the right motor
High-frequency band, text	8825.0, content selected, edit text	3 vibrations on the right motor
High-frequency band, text	7375.0, content selected, edit text	3 vibrations on the right motor
High-frequency band, text	12760.0, content selected, edit text	3 vibrations on the right motor
High-frequency band, text	9400.0, content selected, edit text	3 vibrations on the right motor
Low-frequency band, slider	95.0, band frequency, slider	2 vibrations on the left motor
Low-frequency band, slider	154.0, band frequency, slider	2 vibrations on the left motor

Information	Screen Reader stimuli	Haptic stimuli
Low-frequency band, slider	191.0, band frequency, slider	2 vibrations on the left motor
Low-frequency band, slider	76.0, band frequency, slider	2 vibrations on the left motor
Low-frequency band, slider	82.0, band frequency, slider	2 vibrations on the left motor
Middle-frequency band, slider	1343.0, band frequency, slider	2 vibrations on the middle motor
Middle-frequency band, slider	4677.0, band frequency, slider	2 vibrations on the middle motor
Middle-frequency band, slider	928.0, band frequency, slider	2 vibrations on the middle motor
Middle-frequency band, slider	553.0, band frequency, slider	2 vibrations on the middle motor
Middle-frequency band, slider	614.0, band frequency, slider	2 vibrations on the middle motor
High-frequency band, slider	11470.0, band frequency, slider	2 vibrations on the right motor
High-frequency band, slider	8825.0, band frequency, slider	2 vibrations on the right motor
High-frequency band, slider	7375.0, band frequency, slider	2 vibrations on the right motor
High-frequency band, slider	12760.0, band frequency, slider	2 vibrations on the right motor
High-frequency band, slider	9400.0, band frequency, slider	2 vibrations on the right motor

Table D.1: Structure of tasks

D.3 MAX8 patches

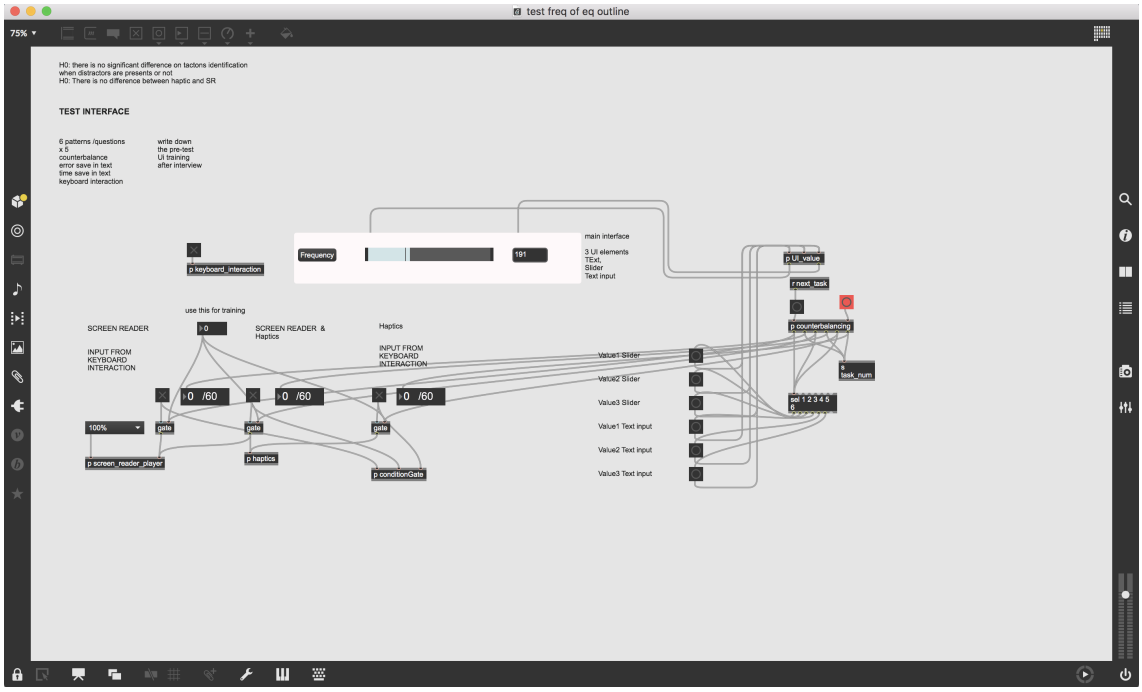


Figure D.1: General patch - Test interface- controlling conditions and showing the number of tasks currently active as well as the stimuli

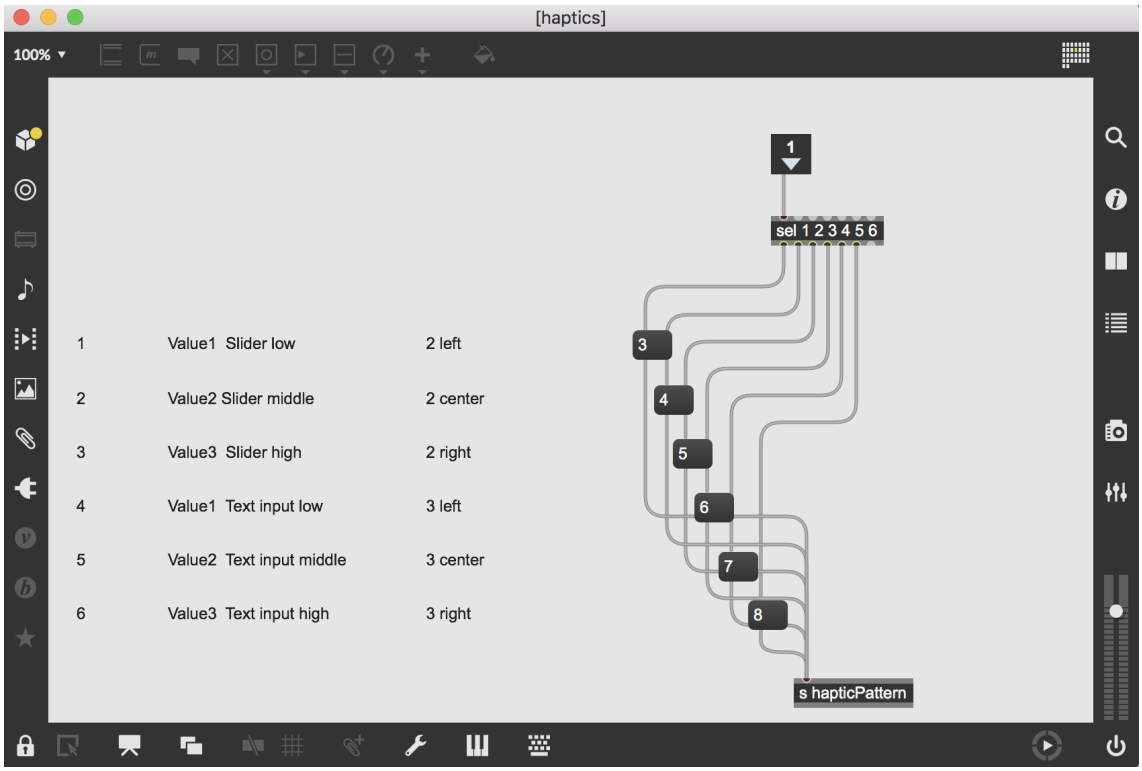


Figure D.2: Subpatch trigger the vibration patterns

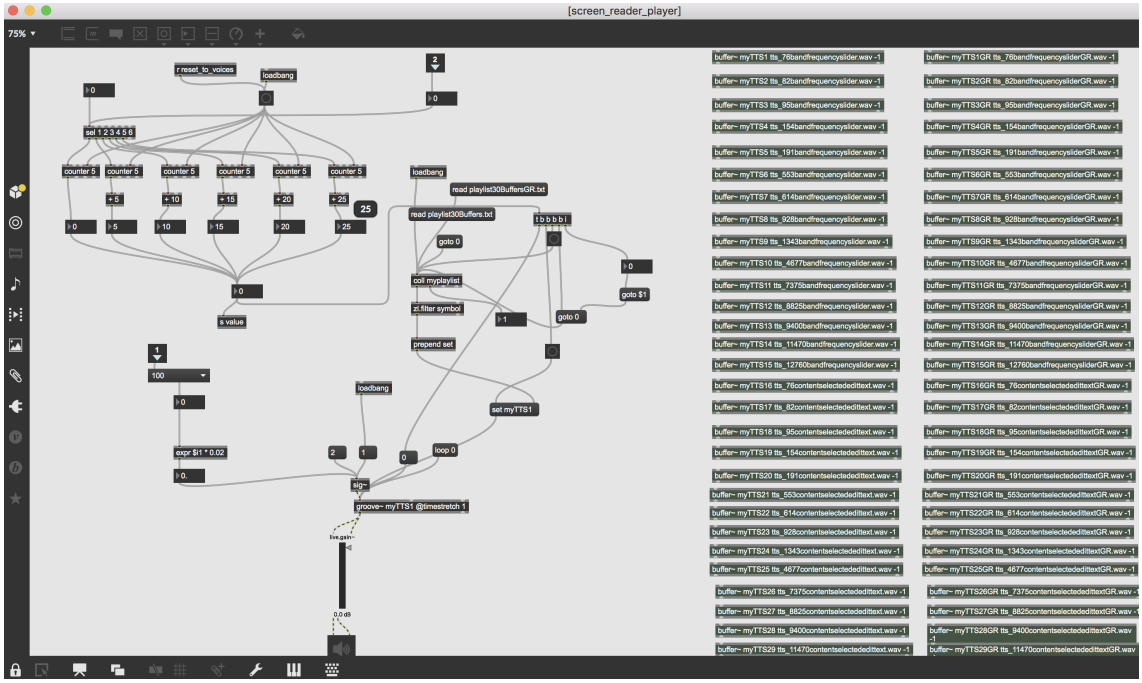


Figure D.3: maxpatch that players all the screen reader simulated feedback

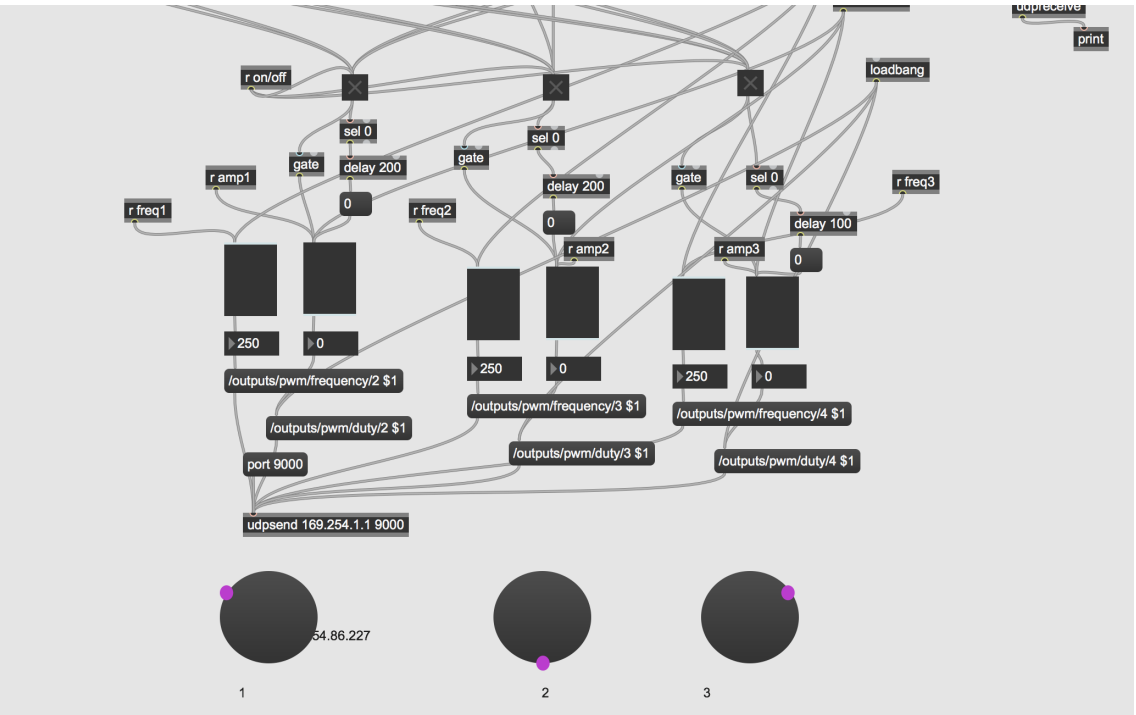


Figure D.4: maxpatch sending OSC messages to device - universal patch that is used in all studies, including the evaluation of the device

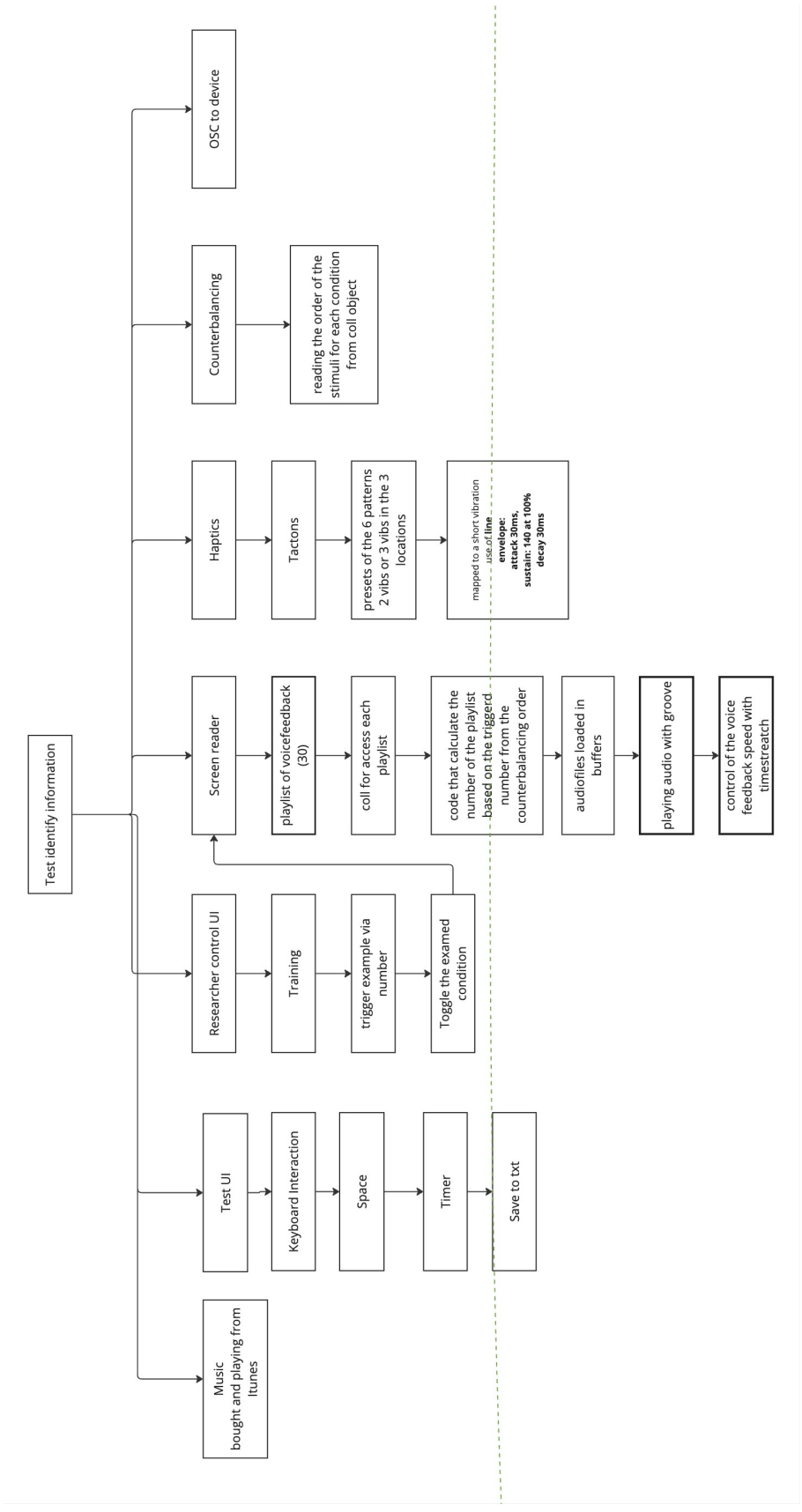


Figure D.5: Workflow of study 2

Appendix E

Chapter 7: Study 2: Interaction task: comparison of three vibrotactile feedback mappings to the Volume Fader.

E.1 MAX8 patches



Figure E.1: Test interface used by the researcher (presentation mode)

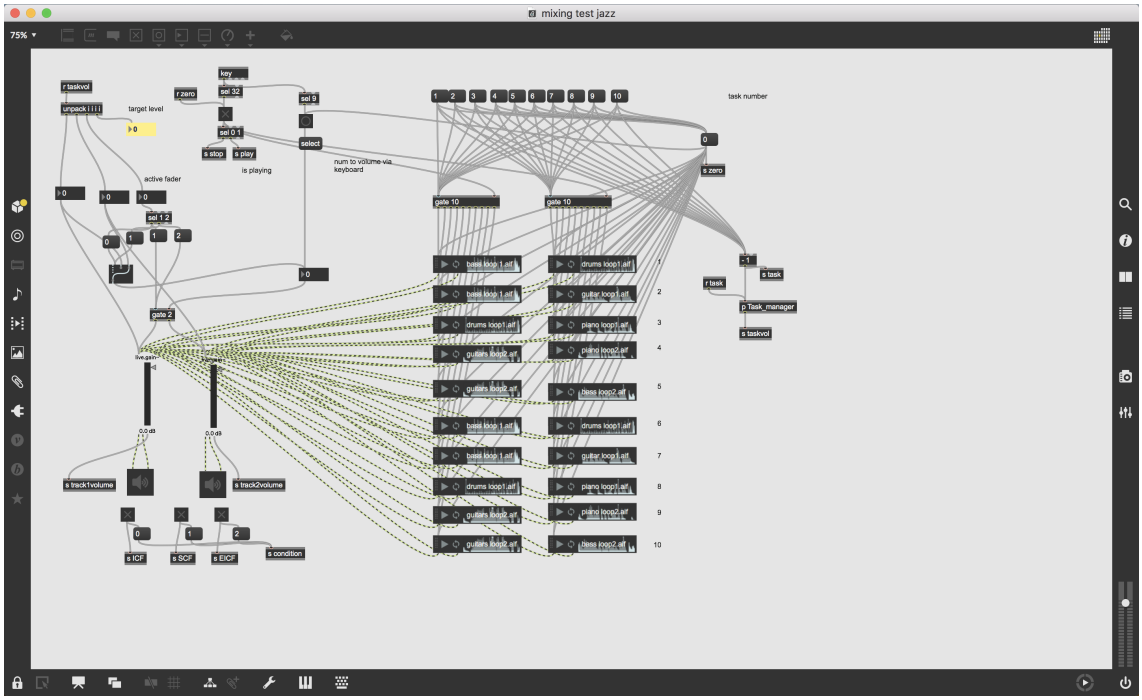


Figure E.2: Test interface used by research

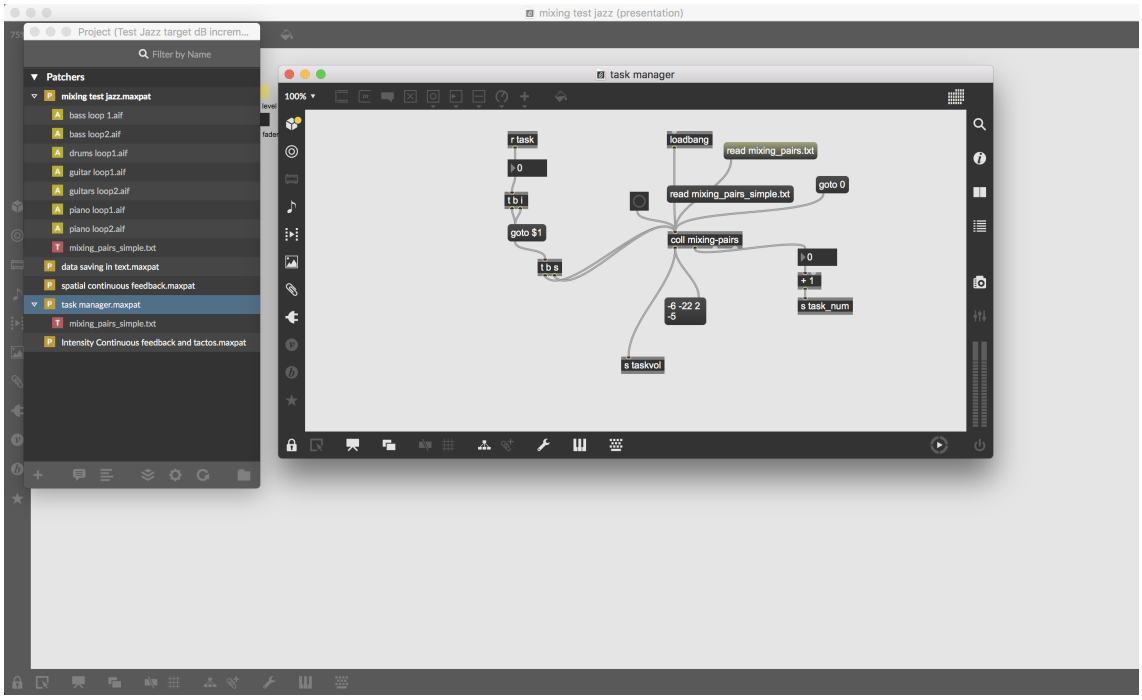


Figure E.3: Max patch that hosts the list of setup numbers for the volume of each instrument of each pair.

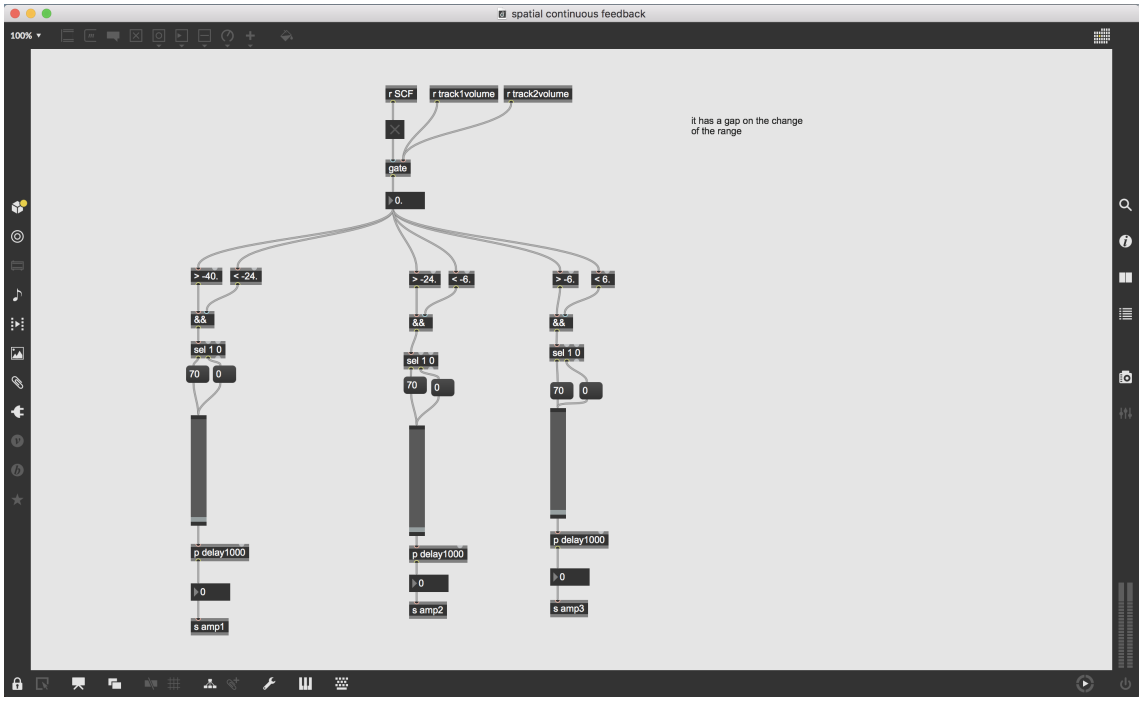


Figure E.4: Max patch mapping of fader milestones to vibrations (Spatial)

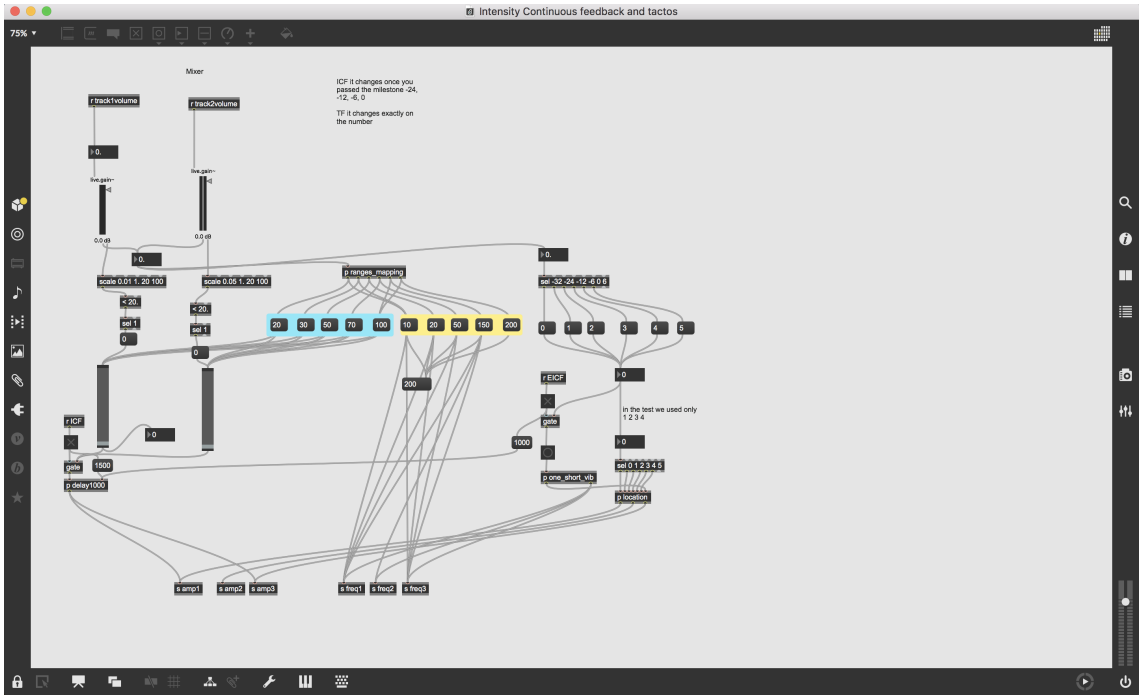


Figure E.5: Max patch mapping of fader milestones to vibrations (Intensity and Tactons)

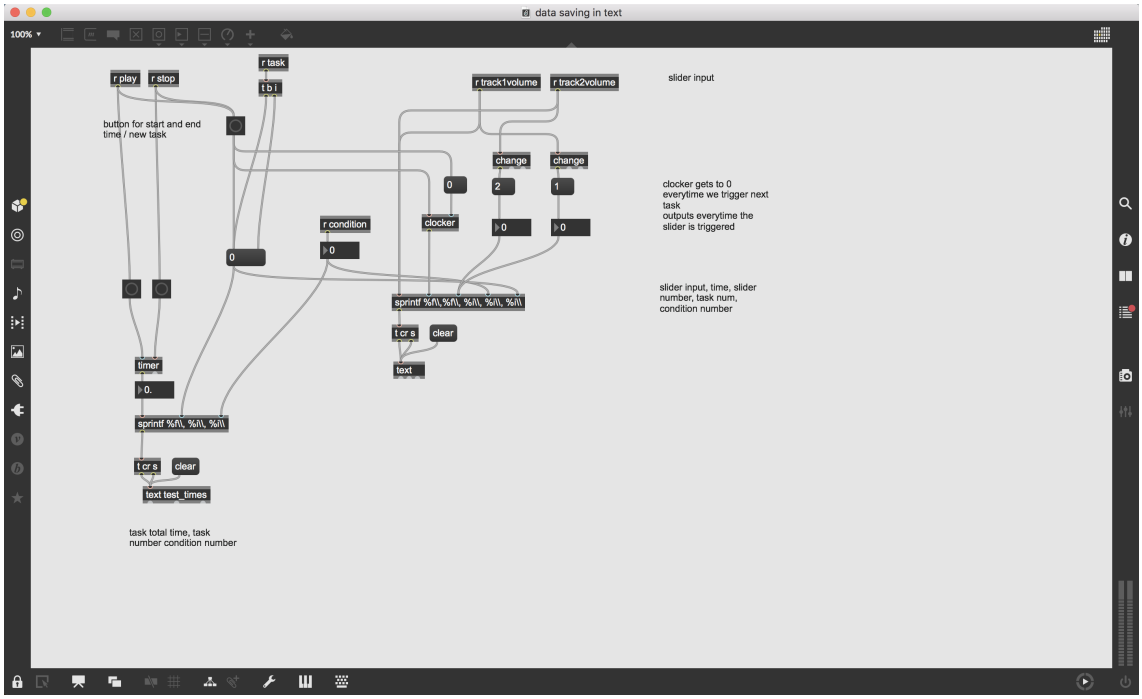


Figure E.6: Max patch saving user interaction to text file

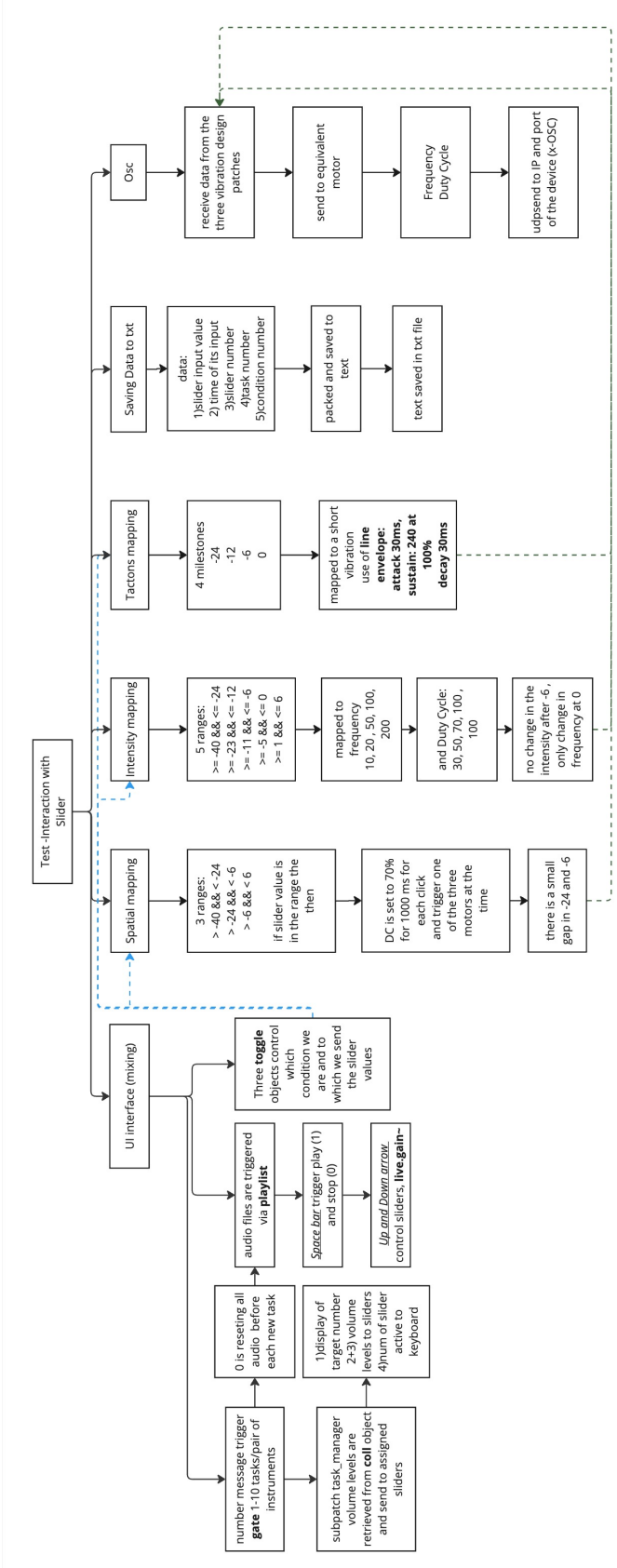


Figure E.7: Workflow of study 2