TÉCNICO LISBOA

Supporting Mix-visual Abilities Musical Ensembles

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Abstract

Mixed-visual ability musical ensembles often serve as an excellent musical output for the skills of their performers and as a natural social environment for both sighted and visually impaired musicians. However, visually impaired musicians face multiple inclusivity challenges in their musical path. That is also the case for conducted musical ensembles, where the instructions of a conductor are central to the group's performance but are primarily visual, leading to the exclusion of low vision and blind musicians. Previous research has shown that it is possible to increase a visually impaired person's access to information via technology using haptic feedback, though most solutions involve expensive and custom hardware. In this work, we propose the Haptic Conductor, an inexpensive and inclusive support system for visually impaired musicians in mixed-visual ability musical ensembles. We conducted interviews with members of a mixed-visual ability musical ensemble, Filarmónica Enarmonia, and an observation of their rehearsal process. Then, we describe our user-centred design approach and the development process of the Haptic Conductor. The user study was performed through three different sessions with members of the Filarmónica Enarmonia, assessing the user experience, functionality and potential of the Haptic Conductor. Although findings revealed challenges and limitations of the Haptic Conductor, the participants confirmed that our approach resulted in an accessible, functional and inclusive system that can help their rehearsal process in its current form, facilitating the communication between conductor and musician. There is also an opportunity to continue the development of the Haptic Conductor in the future, adding functionalities to cover more needs of the users and bridge its limitations.

Keywords

Visually Impaired; Musical Ensembles; Haptic Feedback; Smartphones.

Resumo

Conjuntos musicais de habilidades visuais mistas muitas vezes servem como um excelente veículo para a produção musical dos seus membros, tal como um ambiente social natural para músicos normovisuais e com deficiências visuais. Todavia, músicos com deficiências visuais enfrentam vários obstáculos à inclusão no seu percurso musical. É esse o caso em conjuntos musicais dirigidos, onde as instruções do maestro são essenciais para o desempenho do grupo, mas são maioritariamente visuais, levando à exclusão de músicos com cegueira ou baixa visão. Investigações anteriores mostram ser possível aumentar o acesso de alguém com deficiências visuais a informação através de tecnologias com feedback háptico, apesar da maioria das soluções envolverem equipamento personalizado e dispendioso. Neste trabalho, propomos o Haptic Conductor, um sistema acessível e inclusivo de suporte para músicos com deficiências visuais em conjuntos musicais de habilidades visuais mistas. Fizemos entrevistas com membros de um conjunto musical de habilidades visuais mistas, a Filarmónica Enarmonia, e uma observação do seu processo de ensaio. Descrevemos a nossa abordagem de desenho centrada no utilizador e o desenvolvimento do Haptic Conductor. O estudo final decorreu em três sessões com membros da Filarmónica Enarmonia, onde avaliámos a experiência dos utilizadores, a funcionalidade e o potencial do sistema. Apesar dos resultados terem revelado limitações do sistema, os participantes confirmaram que a nossa abordagem resultou numa solução acessível, funcional e inclusiva que ajuda no processo de ensaio na sua forma atual, facilitando a comunicação entre maestro e músico. Também existe a oportunidade de continuar o desenvolvimento do Haptic Conductor no futuro, adicionando funcionalidades para abranger mais necessidades dos utilizadores e colmatar as suas limitações.

Palavras Chave

Deficiências Visuais; Conjuntos Musicais; Feedback Háptico; Smartphones.

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Acronyms

API	Application Programming Interface
BLSTM	Bidirectional Long Short-Term Memory
BPM	Beats Per Minute
DTW	Dynamic Time Warping
IDE	Integrated Development Environment
IP	Internet Protocol
IPv4	Internet Protocol Version 4
JAWS	Job Access With Speech
LED	Light-Emitting Diode
MCM	Motion Capture Music
MEMS	Micro-Electro-Mechanical System
NVDA	Non-Visual Desktop Access
RQ	Research Questions
SHC	Social Haptic Communication
SVM	Support Vector Machine
TCP	Transport Control Protocol
UCD	User-Centred Design
UDP	User Datagram Protocol
USB	Universal Serial Bus
XML	Extensible Markup Language

1

Introduction

Contents

Musical participation for both children and adults has long been considered beneficial [5]. However, blind and visually impaired people are often at risk of exclusion from musical participation when learning and playing in group settings with their sighted counterparts [5–7]. One of the main reasons for exclusion is the inherently visual nature of the communication during conducted ensembles. Conductors communicate with musicians through a set of gestures (and their characteristics) that convey tempo, pulse, rhythm, and dynamics. Visually impaired musicians do not have access to the conductor's gestures, preventing them from fully participating in music ensembles. Ensuring that children and adults can participate alongside sighted peers is a matter of inclusive practice.

1.1 Problem

Visually impaired musicians often face problems in a mixed-visual ability musical ensemble that do not exist in a sighted setting [5–7]. One of the great fundamental inclusion challenges they face is the need to follow a conductor in a group ensemble, which constitutes a problem since the indications of a conductor are primarily visual [3, 4]. As a performer, a visually impaired musician must learn the compositions without having access to the gestures and the inherently visual instructions of the conductor, playing according to their memory, and based on their own judgment and pace, in isolation from the rest of the ensemble, which leaves them in an uneven position when compared to their sighted peers.

When we consider all these issues, we can state that visually impaired musicians are unable to fully participate in a group musical activity, not being able to have access to the same instructions in real-time as their sighted counterparts do. Therefore, **there is a lack of inclusion of visually impaired musicians in conducted musical ensembles**.

1.2 Goals

The main objective of the development of our solution was to support mixed-visual ability musical ensembles by making the instructions of the conductor accessible to the visually impaired musicians, stimulating an inclusive environment and preventing the exclusion of visually impaired musicians in such a setting. The goal was to promote inclusion considering that the system will be used in a mixed-visual ability environment; Therefore, we had to ponder that the solution cannot disturb the normal functioning of the ensemble.

The aim of this thesis work was to bridge the gap between the visually impaired musicians and their sighted counterparts, converting the instructions of the conductor into a medium that can be recognized by the performers. With such a solution, visually impaired musicians would be able to follow the same instructions in real-time the same way their sighted peers do.

Another goal was to collaborate with a mixed-visual ability musical ensemble throughout this dissertation, in order to have their perspective for the whole of this thesis work and better understand the accessibility problems they face.

1.3 Approach

To accomplish the goals proposed, we had to analyse the existing approaches and systems and study the literature dedicated to supporting visually impaired musicians in an ensemble. We had to study how the conductor's movements are captured in the previous solutions, how they are transmitted to the users, and how the musicians interpret them.

Although previous work has addressed the mentioned problem with approaches such as the DIAMI architecture [3, 8] or other systems that transmit vibration signals to the receptor of the users [2, 4, 9, 10], the existing solutions all demand the development of system-specific hardware, which is often an expensive process, and most involve cumbersome components that cause discomfort to the users. Developing specific hardware also means that there can be malfunctions that have to be corrected for the system to fully function, and also means that each component has to be customisable to make a component as comfortable as possible for each user.

As far as we know, there is a lack of fully functioning inclusive systems that successfully incorporate visually impaired musicians into a mixed-visual ability musical ensemble setting using only mainstream technology. Therefore, we proposed a solution that captured the gestures of a conductor when instructing the performers and transmits them to the users using only a mainstream technology that is the smartphone. To develop such a solution, we integrated design ideas from the previous literature and complemented them using our own approach.

To better design the system we proposed, we used a user-centred design approach, involving members of a mixed-visual ability musical ensemble in the design process in every step of this thesis work by taking into consideration their feedback and experiences [11, 12]. Using this technique, we designed a solution that better suited the needs of the target users.

1.4 Contributions

In this thesis, we provide three main contributions: (1) a study of the fundamental challenges and current practices of mixed-visual ability conducted ensembles; (2) the design and development of a functional prototype of a peer-to-peer system that can transmit the instructions of the conductor and convey vibrotactile feedback through mainstream smartphones; and (3) an evaluation of the proposed solution through testing with users in a real-world scenario, from the perspective of the conductor and the musicians.

1.5 Organization of the Document

This thesis is is organized as follows: In Section section 2.1, we will explain the fundamentals of music theory and the focus points of conducting a musical orchestra, for instance, what different gestures mean for the musicians or what instructions are the most important for the conductors to give. Also, we will describe the experiences of visually impaired musicians from their education to their music careers. We will also analyse different systems relevant to this thesis in Section section 2.2. We will focus on motion recognition technology, vibrotactile haptic feedback, and systems to support musical ensembles, drawing our conclusions from the literature collected. Section chapter 3 will consist of work done before the development of our solution, describing interviews and observations we conducted. Then, Section chapter 4 will encompass all the development of the Haptic Conductor system prototypes and their respective user tests. In Section chapter 5, we will report the final User Study, describing its procedure and analysing their results. Finally, in chapter 6 we will present the overall conclusions of this document and discuss future work possibilities.

2

Background and Related Work

Contents

2.1 Background

In this section, we introduce essential background concepts to understand better the problem proposed. Firstly, we present some music theory fundamentals, followed by some information regarding conducting an orchestra. Finally, we analyse the experiences of visually impaired musicians throughout their life and career.

2.1.1 Music Theory Fundamentals

Knowing how music works can be an essential step to designing a better-suited solution for a problem like supporting mixed-visual ability musical ensembles. In order to properly understand some concepts discussed in the research done in this field, it is necessary to know some of the fundamentals of music theory. This section explains the essential notions needed to comprehend some terms used in past solutions and some concepts that will be used moving forward.

Music theory is a vast and complex subject. When of interest, it can serve as a purposeful and powerful resource given how many different theories and studies there are in each of the fields it contains. Although that is the case and there are different advanced music theory fields, there are three central basic notions one should know, which is Harmony, Melody and Rhythm [13].

Harmony is a combination of sounds produced by the notes played simultaneously by the instruments. It usually serves as a support for the melody in a musical composition. Each note complements the other to form a new sound. An excellent example of a harmonic mechanism are chords, which by definition consists of three or more notes played simultaneously.

Melody is a musical phrase consisting of a sequence of two or more notes created by an instrument. It usually is the most recognisable part of a musical composition, and therefore it is sometimes seen as the main ingredient of a piece. The melody is primarily defined by the pitch and the duration. A pitch is the actual frequency of a note, it is what determines the sound of a note, and the rhythm in a melody is the duration of each note. The merging of these two notions forms a melody.

The most critical building block, in this case, is the rhythm, which sometimes can seem like a confusing notion because it can mean different things, but the most common definition is the pattern of movement resulting from the placement of notes and silences throughout a song [13]. It contains relevant elements that define the rhythm of a composition, like the notion of beat, meter, time signature and tempo. A beat is a pulse that defines the rhythmic pattern of a song; the tempo is the number of beats per minute (Beats Per Minute (BPM)) that indicates how fast the song is; the time signature is the number of beats per measure and is represented by a fraction; the meter indicates the pattern of strong and weak beats. The strong beats are usually called downbeats, and the weak beats are called offbeats.

A measure or bar is defined as the space between the strongest downbeats [14]. The meter of a measure can be simple or compound. The numerator of a time signature defines the number of beats in a measure, and we have a simple meter when most beats can be broken into two equal parts. The simple meter usually contains in the numerator the numbers 2, 3 or 4. An example of a simple meter is the standard 4/4 time signature found in most modern popular music, which means that there are four (4) quarter notes (1/4) in a measure. Another good example is the 3/4 time signature, commonly known as the waltz time signature, and it represents a measure with three (3) quarter notes (1/4). Compound meters are time signatures that usually contain as the numerator the numbers 6, 9 and 12. For the purpose of this research, we will focus solely on simple time signatures to stick to the basic concepts.

It is also important to note that a musical piece does not consist only of notes but also of their intensity and how they are connected. The dynamic of the notes played define how intense the playing is in that section. A phrase that must be played loudly is called *Forte*, and a phrase that must be played softly is called *Piano*. The way the notes connect to each other also defines the overall sound of a musical section. For that, there are two musical performance techniques: *Legato*, which produces a continuous connection between the notes, which means that each note is directly connected to the following note, blending the sound; and *Staccato*, which means that each note must be played separately from the next one, leaving a space between all the notes.

From this section, we can see that music theory is full of nuances. However, the fundamentals discussed here are important to understand every system proposed and the options made by their respective authors when it came to testing those systems with musicians.

2.1.2 Conducting An Orchestra

An orchestra is a musical ensemble of different performers, of which the leader is the orchestra conductor. An orchestral conductor is one of the most respected positions in the music world and is viewed as the silent leader of a musical ensemble, the one member that all the musicians in the ensemble follow, as they are the ones that control the entire performance of the group. A conductor thoroughly studies the musical piece they want the group to play and usually knows all the parts for each instrument as to control the performance completely [15].

Although it looks like a conductor is only there to mark the tempo to someone unfamiliar with the structure of an orchestra, the conductor may be the most crucial piece of such a group. A conductor indicates when to start the performance, marks the tempo, and indicates each section's intensity among other instructions using only their hands and body gestures in real-time.

During performances, the conductor instructs the group what time signature the measure is in by drawing a shape in the air with their hand or with their baton, using a pattern marking each one of the bar's beats. The representation of each pattern performed by the conductor for the three simple meters is shown in Figure 2.1 [1].

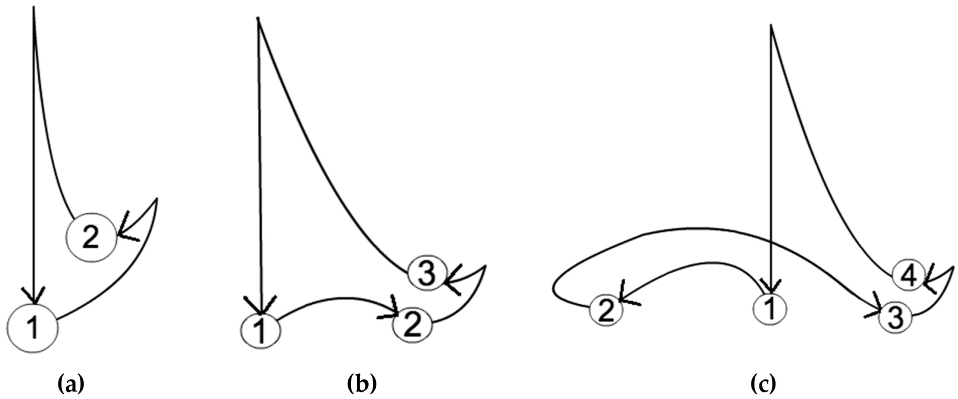


Figure 2.1: Hand signals for simple time signatures: (a) 2/4, (b) 3/4, (c) 4/4 [1]

The amplitude of movements of the conductor when they are performing these patterns indicate the dynamic and intensity of a particular musical phrase. When the movement is broad, the musicians know they need to increase the volume at which they are playing because it indicates that the conductor wants that section played loudly, or *Forte*. However, when the movement is narrow, it indicates a softer section, or *Piano*. It indicates to the musicians that they should play that phrase softly [15].

Another information transmitted in the counting movement is how connected the notes are in a section of the composition. While performing the patterns, the conductor uses the wrist to signal how connected notes are supposed to be by how they flow between beats of the measure [15]. If the beats are marked independently from each other, the musicians interpret that the conductor wants them to perform the notes in *Staccato*, each one separated from the next. If the movement is fluid and each beat connects to the next, the conductor is asking the musicians to play the section in *Legato*, connecting the notes.

A fundamental point of focus when analysing the conductor's work is instructing the musicians on when to finish the performance. Usually, most conductors perform these patterns with their dominant hand and use the non-dominant hand to point to different sections of an orchestra to signal them to come in or out of a particular phrase. To finish the performance, the dominant hand continues the measure motion to keep musicians all in the same tempo and with the non-dominant hand makes a closing motion, raising the hand to signal that the performance is ending and closing it when the musicians are supposed to stop playing.

As shown in this section, conductors send a tremendous amount of information to the musicians of an orchestra just by gesturing their hands [15]. However, given that this information is exclusively transmitted visually, it prevents visually impaired musicians from performing alongside their peers in such a setting.

2.1.3 Experience of Blind Musicians

As stated in Section 2.1.2, participating in musical ensembles such as an orchestra requires the musicians to follow instructions of a conductor, which are mainly transmitted by gestures in a performance [15]. Since visually impaired musicians cannot follow instructions the same way their sighted peers can, their life and professional experiences are much different and particularly challenging.

From childhood, many visually impaired persons are encouraged to learn musical instruments by their parents in order to stimulate social interaction and inclusion, since that is one activity where the visual impairment of the children is not perceived as an impediment [5]. Also, some studies show evidence of low vision and blind children having higher auditory capacities when compared to their sighted peers, which may be due to a variation in their neural development [5].

Although that is the case, the education of visually impaired musicians presents its challenges, starting with the notation. Whereas a sighted music student can learn and accompany musical pieces by reading a music sheet, a visually impaired student needs to have an alternative platform, such as Braille music. However, often there is a lack of competent teachers with grounding in Braille music in mainstream schools, which leaves the visually impaired students in a difficult position to be on the same footing in terms of education as their sighted counterparts [5–7].

Socially speaking, taking part in group musical activities is seen by visually impaired musicians as a positive way to socialise with sighted peers and a good way to feel included in a social group, both as kids and as adults. Nonetheless, they have to deal with the prejudice of being a blind musician, which often is considered part of their musical identities, and some visually impaired musicians embrace it. In contrast, others find it disturbing to be known as a ”blind musician” rather than just a ”musician” [5, 6] when talking about their musical skills since they feel that it can be a way to differentiate them from their sighted peers.

To be part of a musical ensemble, visually impaired musicians often find it challenging to have the self-confidence to face the barriers that this challenge presents. One of the more significant challenges was memorising musical pieces and the extra time required for a low vision or blind musician to participate in an ensemble rehearsal where their sighted peers do not have to memorise the piece since they can play it following the music sheet. A visually impaired musician cannot do that because Braille music requires touching to read it, which is impossible to do while playing an instrument, and for low vision musicians, enlarged music sheets are often unpractical.

The issue of learning pieces is tackled by each musician differently, in the way they find best suited for them. Some visually impaired musicians rely heavily on learning the pieces using Braille music notation, while others use audio and ear-playing. With experience and experimenting with different combinations of these methods, the musicians develop an approach that suits them the best and often find that with time it is easier to pick a musical score by ear and play along with a group [5].

Overall, visually impaired musicians do not sense that musical opportunities are currently adequate compared to their sighted counterparts [5–7]. Although they note that there is a lack of consideration for visually impaired children in schools when learning an instrument, they also state that technological advancements have been increasingly helpful and even revolutionary [5].

2.2 Related Work

As has been shown in Section 2.1.3, the life of a visually impaired musician has many accessibility issues that have yet to be entirely resolved. Although there have been advances in this field throughout the years, it is still necessary to address and work towards a universal solution to avoid continuing neglecting visually impaired musicians. To understand what is needed, we must explore current systems used for this purpose and what has been done to advance the research in this area. For our purpose, we gather the literature regarding the input of such systems, their outputs and their application in a musical ensemble context. By gathering the main contributions of these scientific papers, it will become possible to develop a new approach to address this issue.

2.2.1 Recognizing 3D Gestures

The technology on recognition of 3D Gestures and motion capture has been advanced considerably in the last few years, from what were elementary systems to now more complex, complete ones [16].

By analysing the literature, we see that there are many ways to record a motion gesture, from miniature sensors on the body of a person [17, 18] to the use of more convenient technology such as smartphones [19–22]. The most commonly used gesture recognition systems nowadays, however, are accelerometers, and gyroscopes [23], which we will realise is present in most solutions researched in the literature. Nevertheless, as time passed and the technology advanced, we can see that so did the sensors chosen to implement these systems.

An accelerometer [23] is a device that measures the acceleration, which allows building a system around it based on interaction with the movement of the users. It is considered a Micro-Electro-Mechanical System (MEMS). It measures the static gravity and the dynamic acceleration, which will obtain the angle of the device and then the movement compared to its original angle. Most modern smartphones have this sensor implemented, and it also is present in systems such as the airbag system for automobiles, for example.

One example of an architecture marked by the innovation of its time is the DIAMI system [3, 8]. This system was based on the utilisation of the Wii console remote by Nintendo, called WiiMote, a micro-electro-mechanical system (MEMS). The WiiMote captures the gestures by reading the infrared signal sent by the Light-Emitting Diode (LED) on the tip of the baton. The data is then sent through a Bluetooth chip connection into the control board, which proved to be fast enough to handle every device in a real-time scenario. The data exchange between the WiiMote and the Wii system is instantaneous. The proposed baton's infrared capabilities transmit the user's movement to the receiver of the Wii system, which will interpret and encode the signal in the system's central computer. This architecture was proven to be functional and viable, although there is always a need to customise the baton of the conductor with the infrared sensor and the battery.

Another more recent approach proposed a different motion capture system [4]. At first, the authors designed a watch-like device the user would wear to capture the right arm's movements. However, after discussing the solution with conductors, they decided to abandon the idea and invest in designing a ring-like device that could capture a more intricate range of movements, and that was the device used to develop this investigation. The ring was developed and tested with conductors and musicians using an accelerometer and a miniature Arduino with Bluetooth communication capabilities. The tests conducted revealed that the gestural model created had limited use and that in no way it could contain the entire range of movements needed, plus it proved to be a complicated system to learn.

There have been other authors who developed theoretically similar gesture recognition solutions [2, 9, 10]. They call it an "electric music baton system", and like the other papers gathered so far, it features specific hardware built to support the solution. The built-in accelerometer transmitter records the movements of the baton, and the data is sent to the receivers. The movements are translated by the triaxial accelerometers, which indicate if the movement is back and forth, up and down or left and right. The transmitter system of the solution presented is displayed in Figure 2.2.

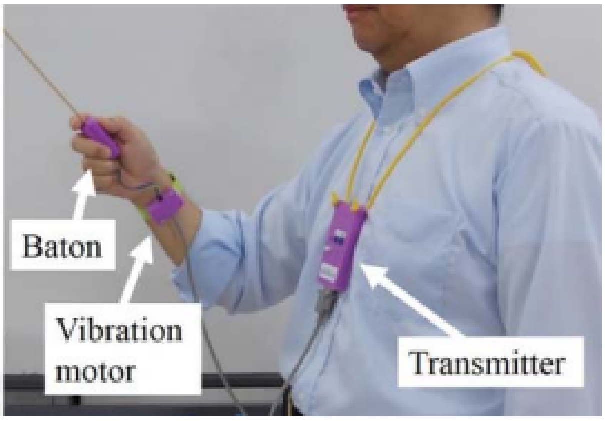


Figure 2.2: External view of the transmitter system. [2]

Other 3D gesture recognition systems of interest have been developed, for example, a wearable motion capture system to use in everyday situations [17]. This system consists of eighteen sensors attached to the body of the user and eight ultrasonic sources, and the data is recorded by a central laptop, which is connected to the driver box using a Universal Serial Bus (USB) interface. The ultrasonic operation consists of a pulse used to calculate the distance measurements, while the inertial subsystem will measure the acceleration and rotation. The laptop will translate the combination of these two independent subsystems. The system proved to be a successful solution since the testing showed that the system acquired motions visually similar to the original ones, and the ultrasonic component proved to be helpful to prevent potential errors in the capture. Although the cost of such a solution may be attractive for how precise it is, it still would cost around 3,000 dollars to implement, not counting with the laptop, since the hardware has to be explicitly recreated to take advantage of the solution, instead of using a more readily-available device such as smartphones.

Another paper presents a similar wearable motion capture device as the previous one [18]. It presents a motion capture method with integral-free velocity detection and proposes an intra-limb coordination model. The authors found that the wearable capture device can capture the correct motion the user is performing, plus they also found that the intra-limb method (on the thigh) simplifies the motion capture system and reduces cost. The testing proved this system works, and the alternative method implemented (the intra-limb method) works as well as the standard method while still reducing complexity and costs. The presented system is one more solution to consider when choosing a method of motion capture for our solution.

Some solutions use already existing systems, such as the Vicon V8 System [24]. This research took place before accelerometers, gyroscopes and other similar components were so readily available as they are today, which helps recognise the exponential technological advances that took place in such a short number of years. The Vicon 8 motion capture system was and still is considered one of the best systems available for motion capture due to its high accuracy, and it produced data that would be saved to disk as a file that would serve as input to animation software. This paper presents yet another application and implementation of a motion capture system. It proposes the development of a software called Motion Capture Music (MCM), on which the motion capture data will be translated into control data for music or other media, such as lighting, digital audio, and video. However, the difficulties it brings in terms of aesthetic and portability reveal how obsolete this solution may be for our problem since it needs specific software and support in order for the solution to be beneficial.

As the smartphone became a more mainstream technology, so did the investigation regarding its power to perceive a user's gestures. There have been solutions developed to support users with visual disabilities who cannot see the screen and therefore cannot select the options they want [19]. It is one example of a simple application utilising the smartphone's accelerometer, which shows us one possibility of what can be done with the same technology used here. The application described uses the integrated accelerometer of the mobile device to detect users' movements and transform them into instructions to navigate through menus. The authors defined a central position around the axis (X, Y and Z), and their movements along the axis define all the selections a user would make. For example, turning the phone at least 45º towards the right selects the option below the one the user is currently selecting, and performing the same motion but to the left selects the previous option.

In another approach [22], the authors propose a solution to control mobile devices without having to look at the device so that the interaction is entirely eyes-free. Due to an identified instability problem in recognising precision in current solutions, this paper proposed a novel scheme using binary motion gestures, where only two simple gestures are required to express bit '0' and bit '1'. It uses five algorithms to recognise the segments of gestures, which are Dynamic Time Warping (DTW)), Naive Bayes, Decision Tree, Support Vector Machine (SVM), and Bidirectional Long Short-Term Memory (BLSTM) Network, and they developed an Android application accordingly. It uses the accelerometer of smartphones to find an improved way to interact with the users' gestures. The new approach recognises a swipe, a flip, a pitch, and a knock and uses them independently, which may be helpful for future approaches if they were to develop a technology using some of these exact mechanisms.

Using a camera to capture the motions of a user has been covered in different fashions by different authors, but not much research has been done regarding using the camera of a smartphone as the motion capture device without having it connected to a central computer. The research presented here, however [20] introduces a new way in which a machine can recognise gestures. The research had the goal to develop a system where a mobile device could fully recognise gestures without the need to connect to the database of the computer, using the frontal camera. It is based on SVM (Support Vector Machine) for recognising various gestures, and the process consists of four steps: hand segmentation, smoothing, feature extraction and classification. In this system, the user only needs to make a gesture in front of the camera for the device to perform an appropriate action. The authors performed tests in five different luminosity levels with five different users, and the tests proved that it is possible for a smartphone to fully recognise some hand gestures without the need to have an entire network behind in the process. That information can be used to further research in this field and could be used to solve a similar problem.

Another possible approach to using smartphones is to use them as wearable sensors to capture the movements of the limbs of a user [21]. The authors present another system of motion capture using smartphones, in which they tried to introduce a modular methodology for amalgamating smartphone sensor data within a centralised repository. The research deals with data synchronisation and remote-control functionality, and it was demonstrated by strapping three devices to the active user's arm to record the motion. The authors also demonstrated and tested continuous sensing with two devices linked by a network to show the differences between the sedentary users and the active ones. The solution took advantage of the Motion Cloud, a centralised repository for all motion capture mediums that can accommodate thousands of devices working simultaneously, to record these motions and utilise the smartphone to recognise the motion.

The technology in this field evolved considerably in the past years, and so did the solutions presented [16]. Although that is the case, there is still more to be accomplished and developed using smartphones to communicate motion capture data, depending on the type of solution one wants to research.

2.2.2 Perceiving Haptic Feedback

As the world of inclusive technology grew, researchers had to find a way to communicate effectively with those with visual disabilities. As stated in Section 2.1.3, those who cannot receive visual stimuli often tend to isolate themselves from a young age due to lack of contact with other people [25] and due to being in an assistive bubble throughout their childhood and education stage [26]. Researchers have had to think about solutions to counteract these tendencies, and one way to do that is by developing haptic feedback systems.

Ambient intelligence is a computing model characterized by embedded computation in everyday devices in order to match the modern demand for ubiquitous access to information [27]. Ambient intelligent services have been developed as a new way to provide universal access to information technologies, incorporating accessibility solutions aimed towards elderly people and people with impairments. Although many ambient intelligent solutions have been developed to try and incorporate people with impairments in a more inclusive educational environment [28, 29], there is research performed using principles of ambient intelligence and including vibrotactile feedback technology, which is featured in the literature assembled. There have also been proposals of systems aimed at visually disabled people using technology such as Non-Visual Desktop Access (NVDA) and Job Access With Speech (JAWS), to facilitate the interaction of the users with the devices from which they would take an educational course [30]. These proposals facilitate the use of information technology to support the ability of the system to counteract the lack of access that impaired people have to them.

Haptic feedback is a communication method using touch. Although most electronic devices are used to communicate visually or by sound, vibration is becoming a communication method just as crucial as the others in the smartphone era we are living in today. It is an essential element in interactive applications [31], more now than it ever was. It is just a different way to transmit information by controlled vibration, on which much investigation has been done, and many solutions have been developed.

Angela Chang et al. designed a vibrotactile system called ComTouch [32], which is a device that complements traditional remote voice communication with touch. It converts the pressure of the user's hand into vibrational intensity between users in a real-time context so that the communication between multi-ability people would be richer in conjunction with the audio exchange. An evident strength of this paper was the advancement it brought to the development in the field of haptic interpersonal communication. The proposed solution showed that users developed an encoding system in their communications, such as emphasis, mimicry, and turn-talking. The tests also proved this system as a very intuitive solution when paired with the audio channel. However, it is a very old-fashioned system that is now considered obsolete given the technology we have available today to develop similar but better and more efficient solutions.

There are plenty of different approaches possible to design a vibrating receiver system, one of them is smart clothing or devices with vibrating motors [33]. Another, more common approach featured in many papers in the literature is a wearable device connected to the sender through a wireless network, in many cases through a Bluetooth connection [3, 8]. In the case of this solution, the authors developed a Bluetooth vibrating bracelet, which provides a real-time data exchange scenario between the sender and the receiver. Each bracelet would be capable of connecting via Bluetooth to the system and contains four vibration motors. The bracelet is pictured in Figure 2.3, which displays one of the vibrators and the bracelet itself. The vibration of the motor signals an instruction to the user. The information transmitted by the conductor's baton is received in the form of vibrations, and the users of this bracelet interpret each vibration and therefore can follow the conductor's instructions. This solution was tested, and the results showed how promising it was to apply to a real-world scenario since the bracelet is light, small, and consumes very little power, which makes it an attractive solution to consider in many different applications, mainly to help people with hearing and visual disabilities.

Whereas the previous solution used a Bluetooth bracelet on the arms of the user as a haptic interface, D. Baker et al. [4] used a slightly different approach while taking advantage of the same communication method. A microcontroller board was developed, consisting of a 20-by-20 matrix of 10mm vibrators and an Arduino Uno microcontroller with ethernet, Wi-Fi and Bluetooth connectivity, and it was meant to be worn on the chest of the performer. This way, the authors guaranteed that the data sent via Bluetooth by the conductor was analysed and processed by the Arduino, which translates the data into the haptic signal the user will receive. The controller is shown in Figure 2.4.

There have been more complex systems developed with multiple different functionalities in the field of inclusive technology for visually impaired people [34]. The purpose of this research was to improve their quality of life by developing a wearable glove with different modules, such as facial recognition, obstacle detection, e-mail reading, drugs reminder and MP3 music player. The authors decided to incorporate vibration feedback in the obstacle detection module by using ultrasonic sensors to send and receive wave signals that will then be processed and generate a vibration for the user to feel, indicating how close they are to an obstacle. There are five different levels of vibration configured, depending on the distance. The surveys found that the proposed solution was positively received since it was deemed lightweight, easy to handle, and comfortable to use. The authors also promoted ideas for further development of this kind of technology, such as a module based on an accelerometer to use gestures to activate certain functions or a module to pair the bracelet with a mobile device, which in conjunction with the wearable

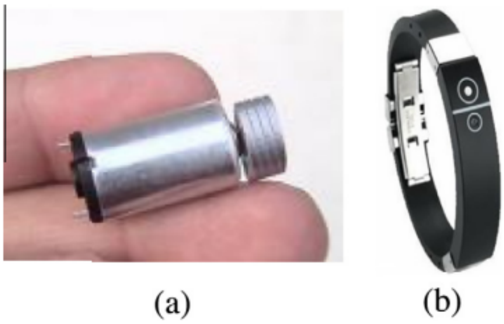


Figure 2.3: (a) Vibration motor; (b) LM957 Bluetooth vibrating bracelet. [3]

Figure 2.4: Vibration controller. [4]

could become a helpful tool.

Other solutions propose approaches to assist visually impaired pedestrians during navigation with the help of a vibration bracelet device on the wrist of the user [35]. This experiment aims to facilitate the mobility of blind people when in a crowded, overloaded environment taking advantage of haptic feedback given by the bracelet. The wearable prototype consisted of two wrist bracelets and an Arduino module with a vibration actuator. It contains a simple design of another wearable Bluetooth haptic receiver.

Plaisier and Kappers [36] investigate whether deaf-blind users of Social Haptic Communication (SHC) - a tactile communication medium for deaf-blind people - would recognise the mimicked vibrotactile patterns. It claimed that a pattern could be displayed by switching vibration motors on and off, making it possible to trace a shape on another person's back. So, it intended to conclude whether SHC users would recognise what was being communicated with the vibrotactile patterns instead. The testing performed by the authors showed that the participants could quickly identify the mimicked signal, which further proves that vibrotactile stimulation can be helpful for this type of communication. It also showed how easily the participants could learn the patterns. Therefore the solution used for the group was generally approved.

Haptic feedback can also be a valid alternative to systems dedicated to visually impaired people that rely on audio feedback, for instance, when accessing the information on electronic devices when such an output is not convenient. UbiBraille [37] is a vibrotactile Braille reading device that actuates on the fingers of users based on mainstream Braille typewriters, allowing the users to access the information from their electronic devices privately. The vibration actuators are positioned on the index, middle and ring fingers of both hands, and each letter is transmitted as a vibration on the respective finger combination used to write the said letter on Braille typewriters. The testing was performed with eleven blind participants, and the authors obtained an average of 92.86% accuracy on word recognition tasks [37], showing that the UbiBraille system is feasible and that haptic feedback is indeed a promising way to convey information such as textual messages to visually impaired users.

Another approach was taken in H. Chu et al., which aimed at helping visually impaired children regarding physical activity both physically and psychologically through a distributed vibration [25]. There was a development of assistive devices (tiny, distributed vibrators), which would help the children move for a specific position. The tests concluded that the physical capacity of the participants (and consequently their social ability) was drastically improved using this technology. It also pointed out that the students were willing to withstand the vibrations, which is important to consider while developing a haptic feedback solution.

Almost every one of these solutions requires Social Haptic Communication (SHC) training. To make this process more engaging, the authors propose a mobile game for learning this mode of communication called PatRec [38] which avoids the use of the usual interpreter executing hand signs on the back of the person with multi-sensory disabilities. It is a multiple-choice quiz on which the player is asked to correctly identify the SHC signal emulated by the vibration motors attached to the backrest of a chair. The vibration patterns are encoded as JSON files. Other solutions have also developed a chair with vibrating motors as their respective haptic receiver [39].

With the literature analysed, we can see that the more used design of a haptic feedback receiver is a bracelet that connects to the information sender via Bluetooth to exchange the data in real-time, which implies that hardware must be developed specifically for each solution and depending on the needs of the users it must be customisable. However, little research has been done using smartphones as haptic receivers, which would efficiently remove that problem.

2.2.3 Supporting Music Ensembles

As seen in Section 2.1.2 and Section 2.1.3, conducting an orchestra demands performing many instructions that the musicians must follow for the musical performance to flow the way it is supposed to, but the traditional methods do not work the same way when conducting a mixed-ability orchestra with blind and visually impaired musicians, since most of the instructions given by the conductor are done with hand and arm gestures. As seen in Sections 2.2.1 and 2.2.2, this problem may be countered using motion capture and haptic feedback technology. However, the applications of these technologies to mixed-ability musical ensembles are scarce and scientific research and testing done on this specific topic with proper testing is slim as seen by the literature retrieved.

J. Bajo et al. proposed a solution called DIAMI [3, 8], described previously in Section 2.2.1 and Section 2.2.2, and it was meant to provide a way for visually impaired musicians to receive instructions from the orchestra conductor in an unobtrusive manner via haptic receptors, with the instructions being captured by a WiiMote through the infrared LED of the baton. The case study the authors established involved five blind musicians and two conductors, and the testing consisted of five stages with each user individually, not in a group setting [3]. The authors also state that sighted musicians gave this solution a 100% acceptance rate because the system does not affect or obstruct them in any way. The testing showed that blind musicians had a lower success rate in the beginning stages, but as they got more familiar with the system the learning rate increased, and so did the satisfaction degree, which greatly increased after the third test. The satisfaction rate was at around 15% in the first test due to problems with the system, but as the problems were fixed and the suggestions of the users were incorporated, the satisfaction degree went up. At the end of the testing phase, the acceptance rate of the blind users was 98%. However, the acceptance rate among conductors was only at 87%, mainly due to the training necessary to correctly use this system and they showed reluctance as to having hardware elements in the baton [3]. The tests also showed that some blind users found the wearable to be somewhat invasive or uncomfortable, even if they approved the system overall.

The solution proposed in D. Baker et al. [4] was also previously described in Section 2.2.1 and Section 2.2.2. The testing was done by having the visually impaired musicians perform a musical piece while receiving the haptic signal of the tempo, which varies multiple times throughout the piece [4]. The quantitative research consisted of statistically analysing the difference in response time between blind musicians, plus the qualitative research was conducted through interviews with the participants where they shared ideas on how to improve the solution. Two haptic patterns were tested: a metronomic haptic signal consisting of a single pulsation per beat to mark the tempo; and a two-dimension pattern recreating the hand movement of the conductor marking the tempo in a 4/4 time signature. The testing showed that the pulsation signal returned far better results than the 4/4 pattern did, particularly in the "finishing together" field, where the score of the pulsation was 5.46 (out of 10) and the score for the 4/4 pattern was only 0.91 [4]. The difference between the two haptic signals is very significant, proving that mirroring the gestures as a haptic signal has limited use and a pulsating signal is more intuitive. Once again, the testing of the system was performed individually by only visually impaired musicians.

Other proposals have been more interactive in their development, proposing to conduct a study with visually impaired music performers, which involved a participatory approach to the design of accessible technologies for musical communication among the group while playing [40]. These tests involved prototypes of musical haptic wearables, which were co-designed and evaluated by the participants of this experiment. The testing consisted of three separate workshops: the first one for brainstorming and the next two to design, test and gather feedback for both choir singing and instrument playing. The test group consisted of nine visually impaired musicians from different musical genres and instruments, but only three took part in all the activities. Again, there was no ensemble mixed-visual ability testing performed and the sample size was short. The authors also found that the solution contained various technical issues that prevented them from accurately developing the system. Despite this, they also concluded that the preliminary results were promising, justifying the further development of this solution.

In another research [2, 9, 10], the testing was performed with ten subjects. The receiver system contains the traditional vibration motors and is to be used on the wrist by the subjects. Different tests were conducted, from a reaction response evaluation to intensity response, but the testing was also done individually with 10 sighted participants, so there was no participation from actual visually impaired persons. In addition to that, the testing was performed solely from a quantitative research perspective with no musical incorporation whatsoever.

There has not been much research performed in a musical ensemble setting when developing inclusive technology. Most of the testing of these technologies are either performed with users individually or with no musicians at all. So, although systems are being developed to improve the inclusion of a mixed-visual ability musical ensemble, they are not being tested in a real-world environment required to understand how viable and practical they really are.

2.2.4 Discussion

Based on the literature gathered in Section 2.2, we realise that there is plenty of different gesture recognition and haptic feedback systems, although not many have been applied to a musical ensemble setting. We compared the different systems regarding the tools they used and the testing performed in Table 2.1. The papers analysed are ordered in the table by their main contributions, be it in the field of motion capture, haptic feedback or supporting mixed-visual ability musical ensembles. Also, the Users columns are separated into Sighted and Visually impaired (VI). Plus, in the Musicians columns, we differentiate between testing with Performers and Conductors and if the testing was done in a musical ensemble setting with more than one musician using the system simultaneously.

Table 2.1: Summary of the analysis of literature.

	Gesture Recognition				**Haptic Feedback**			**Users**		**Musicians**		
Paper	Wearable	Camera	Smartphone	Other	Wearable	Smartphone	Other	Sighted	VI	Performers	Conductor	Ensemble
[17]	✓	X	X	-	N.A.			✓	X	N.A.		
[18]	✓	X	X	Sensors	N.A.			✓	X	N.A.		
[24]	✓	✓	X	Sensors	N.A.			✓	X	N.A.		
[19]	X	X	✓	-	N.A.			N.A.		N.A.		
[22]	X	X	✓	-	N.A.			✓	X	N.A.		
[20]	X	✓	✓	-	N.A.			✓	X	N.A.		
[21]	✓	X	✓	-	N.A.			✓	X	N.A.		
[32]	X	X	X	Sensors	X	X	Pad	✓	X	N.A.		
[34]	✓	X	X	Sensors	✓	X	-	X	✓	N.A.		
[35]	N.A.				✓	X	-	X	✓	N.A.		
[36]	N.A.				X	X	Backrest	X	✓	N.A.		
[37]	N.A.				✓	X	-	X	✓	N.A.		
[25]	N.A.				✓	X	-	X	✓	N.A.		
[39]	N.A.				✓	X	-	✓	X	N.A.		
[3, 8]	X	X	X	WiiMote	✓	X	-	X	✓	✓	✓	X
[4]	✓	X	X	-	✓	X	-	X	✓	✓	✓	X
[2, 9, 10]	X	X	X	Sensors	✓	X	-	✓	X	N.A.		
[40]	N.A.				✓	X	-	X	✓	✓	X	✓(VI only)

As stated in Section 2.2.1 and seen in Table 2.1, there are many systems in the field of gesture recognition, but most of them use wearables or sensors. Not many solutions use the smartphone to communicate gesture recognition data, which ultimately would provide a more portable and convenient solution using mainstream, everyday technology.

Regarding haptic feedback, as stated in Section 2.2.2, the most used technology is a wearable connected to a sender via Bluetooth, exchanging data in real-time. That can also be verified by the contents of Table 2.1, where it again shows how little the smartphone has been used as a haptic feedback receiver, which would prevent the development of specific, customisable hardware for every user for each solution. That would be a more practical, more affordable solution, but not much research has been performed with that end.

Also, whether it was because of lack of access to a musical ensemble or because the authors had different perspectives or priorities, there is little to no testing performed in a musical group setting. All these papers and investigations cited had something helpful to offer regarding possible technologies or solutions to use. However, none performed tests in a real-world scenario with a mixed-visual ability musical ensemble, incorporating both sighted and visually impaired performers points of view. Most of them also did not take particular interest in the perspective of the orchestra's conductor, which can be helpful to determine what is essential to implement in such a solution and how to do it.

Another issue found in these papers is the need to develop specific hardware to support the solutions. That can lead to problems ahead, such as needing to adapt every receptor to the needs and comfort of each user, and that can be a long and expensive process. Also, none of the researchers used a mainstream, existing technology to support their solutions. Therefore, we can state that a gap exists in the literature that can be filled by developing an inexpensive, universal, and accessible solution to further the inclusion of blind or visually impaired musicians in a mixed ability musical ensemble using mainstream technology.

For that effect, we can assume that it is possible and necessary to fill the gap and adapt the technological advances found in the literature collected in order for them to work using a mainstream device such as smartphones and apply them to a real-world, mixed-visual ability musical ensemble setting. In that setting, the testing can be performed in a user-centred way to better accommodate the needs of conductors and visually impaired musicians during a performance. Such a system would increase the accessibility and inclusion of visually impaired musicians in mixed-visual ability musical ensembles without disrupting the activity of the sighted members.

3

Understanding Mixed-Visual Ability Musical Ensembles

Contents

Before starting the development of our first prototype, we sought to better understand the flaws and accessibility issues currently present in a mixed-visual ability musical ensemble setting. In doing so, we collaborated with Associação Bengala Mágica and Filarmónica Enarmonia, which provided us with the opportunity to watch conductors, teachers, and visually impaired musicians rehearse in a real-world scenario. With that, we managed to further assess and note the accessibility and inclusivity problems visually impaired musicians face on a regular basis in the music environment. Therefore, in this chapter, we describe our user research process.

3.1 User-centred Design Approach

As briefly discussed in subsection 2.2.4, we developed the system using a User-Centred Design (UCD) approach. UCD is a development technique that takes into consideration the notes, opinions and experiences of end-users, involving them in the process of designing an object or system [11, 12]. The philosophy behind this approach is to try and increase the usability of an object or system by understanding that the job of a designer is to "facilitate the task for the user and to make sure that the user is able to make use of the product as intended and with a minimum effort to learn how to use it" [12]. Utilizing the UCD methods by involving users in the process results in more functional, intuitive and inclusive systems.

This thesis deals with inclusivity and accessibility issues in mixed-visual ability ensembles, so this approach was the most responsible and effective way to design a system that was simple to use, minimizing the effort of the end-users. Although there are different methods to apply this principle [12, 41], we chose to include end-users in the design process by: (1) Performing background interviews; (2) Performing on-site observations; (3) Performing usability tests.

The background interviews were performed in the pre-design stage, so that we could assess the needs and expectations of the users, while also discussing the different options we had to design the prototypes. The on-site observations were also performed in the pre-design stage, and the goal was to see and experience the current environment of a mixed-visual ability musical ensemble, collecting data from what we observed and projecting what would be needed of our system to improve that same environment. Finally, the usability tests were performed during the design stage by testing the different iterations of prototypes we developed to measure the usability of the system, giving end-users the chance to use the system in their regular environment and soliciting their feedback, which was collected. The information retrieved was used to improve the design of the system until it was as optimized as possible.

Both the background interviews and the on-site observations are described below, while the usability tests were described on the development section of this thesis, since it was only performed in that stage.

For the background interviews, we conducted a semi-structured interview with conductor Dr Rui Magno Pinto, from the mixed-visual ability musical ensemble Filarmónica Enarmonia, where we sought to obtain his point of view as an active participant in these ensembles as a teacher and conductor of visually impaired students and musicians. For the on-site observations, we attended a rehearsal of the Filarmónica Enarmonia, where we could see first-hand the interaction between the educators and the visually impaired musicians, plus we could assess what constitutes a regular rehearsal and the accessibility issues present in such settings.

3.2 Interview

As previously mentioned, in the beginning of our thesis work we conducted a semi-structured interview with conductor Dr Rui Magno Pinto. The goal of the interview was to discuss our collaboration, the project we were developing and most importantly the approach we should take from the point of view of the conductor. For that reason, we examined what were the biggest issues currently when managing a mixed-visual ability musical ensemble and which ones were the most important for a more inclusive and accessible environment in the ensembles to better define the steps we should take in order to reach a solution.

We took notes throughout the interview to gather all the information the conductor was sharing with us, since they are important for the user-centred approach we are taking. Those notes were then analysed using qualitative analysis, a process described in the subsection below.

3.2.1 Analysis

To better interpret the information retrieved from this interview, we gathered all the notes and data obtained to analyse it using affinity diagrams [42, 43]. Therefore, we took the notes and coded them, assigning data to a respective label. Then, by comparing the codes, we define the themes that will encompass the codes, organizing the information in an intuitive way.

3.2.2 Findings

Marking the tempo

During our conversation, one of the most common themes was the discussion regarding the problems conductors and visually impaired musicians face in a work environment. In a group setting, the conductors have difficulty transmitting the information they would otherwise give visually without disturbing or stopping the rehearsal altogether.

The issue of the tempo of a song was highlighted throughout the conversation. For a teacher and conductor, the tempo is the key to holding the performance of a musical group together. Without the conductor counting the tempo, the musicians will not begin and stay at the right tempo throughout a musical piece. Since in a mixed-visual ability musical ensemble many musicians are visually impaired, the gestures usually applied are not an option. So, to face that issue, teachers had to find different ways to communicate that information to the musicians. Rui described the process as such:

> *"We count the tempo by clapping and by shouting, which can be tiring for the teachers. It also creates a more confusing environment for the musicians with a lot of noise that disrupts the music."*

The counting must be transmitted in real-time, because a delay in the reception of the information would mean that a musician would be playing the piece in a different time than the rest of the group.

The pattern the conductor does when counting the tempo always indicates the downbeats of the measures, which is an important frame of reference for the musicians to have. That currently has to be done when counting the tempo with claps by having the first clap of a bar to be louder than the others, or by counting the tempo shouting, which is usually what is done. That same approach is taken when a conductor wants to indicate a *forte* or *piano* section – the counting and clapping is done louder or softer, respectively.

Some pieces do not have a stable tempo, which means that the tempo changes throughout the song and that information is also important to transmit. Most conductors conduct on time, they don't conduct by anticipation, so that information is also important to be transmittable in real-time.

There is also the issue of other, and often more subtle instructions the conductors usually transmit to the musicians with their gestures that they cannot transmit in an efficient way using non-verbal sounds such as claps. If a conductor wants to indicate that a certain section of a musical piece is to be played in *legato* or *staccato*, he must explicitly say that out loud or force the musicians to memorize that cue, which is less reliable than being able to transmit that information in the moment.

Ending a music piece is often done by closing the non-dominant hand, and that is not possible to do in a mixed-visual ability musical ensemble setting, plus it is a hard information to transmit without explicitly saying out loud that the song is ending, damaging the musical output. Also, in loud pieces it might be hard for a musician to hear the cue, even more so when they are focusing on playing the instrument. That is a very important cue that currently is not easy to transmit.

Dr Rui also highlighted that, although all of these are legitimate current issues in these settings, there are instructions that should be seen as more important to maintain the musical ensemble stable during a performance or rehearsal. The priorities are, in order: (1) Counting the tempo; (2) Indicating the dynamics (*legato* or *staccato*); (3) Indicating the flow (*forte* or *piano*).

Using haptic feedback

To face the issues detected, it is important to take into consideration that most teachers and conductors are accustomed to a certain way of conducting, so they instinctively use gestures and visual cues even when dealing with visually impaired musicians. Therefore, we could try to use these natural gestures of the conductors when trying to find a potential solution and take advantage of that.

The educators are open to experiment with different systems and means of communication because they want to teach their students in the best way they can, and they are invested in promoting the most inclusive environment they can for every musician. For them, the way the information gets to the musician is not a concern if we can assure that both the musicians and the teachers themselves are comfortable. It would also be advantageous to use a system that minimizes the disruption of the musical output, so we should preferably aim for a quiet solution.

Most studies point to vibration and haptic feedback as a good mechanism to transmit the information required from a conductor to properly manage the ensemble in a rehearsal or performance setting. Rui mentioned that it may be the best means of communication to use because it is important that the musicians receive the instructions without disturbing the rest of the group. Therefore, we should discard an audio signal as a potential solution so that we can focus on more reliable systems given the setting we are dealing with.

The issue of what platform and technology to use was also brought up in the discussion. Given that we would be using haptic feedback, every musician should receive the instructions in an individual device. Mentioning that there is specific hardware that can be developed and transformed into a vibration receiver, we reached the conclusion that a mainstream device should be used in order to minimize the efforts of the performers to use this technology. Most students already use smartphones on a daily basis, and it can be used as a vibration receptor, so that no user has to acquire any device to make a system work.

The smartphone could capture the movement of the conductor, so that the visual cues are given to a sighted performer while also capturing and transmitting the instructions to the visually impaired performers without additional effort for the conductor. In this situation, the smartphone could be put in a glove to be attached to the hand of the conductor to better interpret the movements.

Since the smartphone would be placed on the dominant hand and considering that the indication of the ending of a musical piece is given with the non-dominant hand, Rui mentioned that it was important to implement a button or a feature that when prompted allows a conductor to instruct the musician that that specific measure is the last bar of the piece, and that the performance is ending. That could be an easy way for a conductor to signal that instruction without an audio cue.

For a smartphone-based solution, the device must be pressed against the body of the performer, but that should not be a problem if we use something comfortable for them to wear.

Adaptability

A system that promotes inclusion and tries to solve the issues present in mixed-visual ability musical ensembles must be adaptable, since every conductor and performer have their own preferences regarding what is comfortable and practical depending on personal likings and responsibilities. Different instruments require different motions and that may influence the position on which the smartphone is placed.

The sensibility is different for every individual. Even if one person feels the vibration the most on the leg for example, another person may feel it the most on their arm. Given that there is no way to predict a universal preference, the system must be flexible enough to be adjusted accordingly for every person.

The ensembles can consist of both children and adults. That means that the size of the wearable where the smartphone will be attached must be completely adaptable. We must take into consideration when devising the system to design a wearable that is comfortable to every user, so it works properly.

The placement of the device on the conductor must also be adaptable. If the system is to capture the motion of the hand of the conductor, the device can be placed in a sort of glove wearable. However, Rui mentioned that for some conductors it can be tiring to conduct an ensemble for an entire session or performance in a regular situation. Wearing a smartphone in their hand would add weight and complicate their movement, potentially reducing the system usability given that the conductor could feel exhausted during a performance. Taking that into account, the system should be as usable as possible, and therefore adaptable as possible so that conductors can use it easily without disturbing their performance.

Rui also mentioned that to properly signal a measure to the musicians it would be important that the downbeat was marked by a stronger vibration than the rest of the bar so that the performer does not get lost trying to figure out which beat is the first of a particular bar. But he also stated that each educator should be able to activate and deactivate the feature depending on what is needed in the moment.

Experimentation

Throughout the interview there were references to how important experimentation is going to be to find the best solution for the issues we are facing. To truly know how such a system would help in a real-world situation, we must test it with real-world users in the appropriate scenario. Only then will we see what works and what does not.

To perform experiments, we must have access to potential users who are interested in testing the system. That is the case of most visually impaired musicians, who know that these technologies diminish the differences in accessibility between them and their sighted peers in mixed-visual abilities musical ensembles. Rui mentioned that all the musicians in his group are receptive to trying new things in their musical environment.

> *"The students would be thrilled to perform these experiments. They realise it is something they need in order to improve their musical environment and they are very appreciative of all the efforts we are taking part in."*

Testing the prototypes with end-users will allow us to receive feedback immediately and improve the design until the performers are comfortable enough and the device is functional for them to use them during rehearsals and performances.

Rui also stated that only by experimenting will we be able to see how much effort is required from the users to take full advantage of the device. And since they are used to a loud environment in their rehearsals due to not only the music but also the instructions of the educators, they might face difficulties to concentrate on the new form of instructions, at least in early stages. However, Rui is confident that they will get used to the system quickly.

3.3 Rehearsal Observation

After we conducted the semi-structured interview with Dr Rui Magno Pinto, we were invited to perform an on-site observation of a rehearsal of his group, Filarmónica Enarmonia. The rehearsal took place at Escola do Largo, in Chiado, Lisboa.

Figure 3.1: Filarmónia Enarmonia rehearsing.

The goal of this observation was to experience the usual environment of a functioning mixed-visual abilities musical ensemble, its challenges and issues, and how the educators face them and adapt to communicate with the performers. Plus, we watched how the group is organized and the different stages that form the rehearsal process.

We took notes throughout the day and paid attention to what was happening in different study groups to try and gather as much information as we could from watching different students and different educators without disturbing them. We took photographs and recorded parts of the rehearsal as well, with the permission of the participants. We also briefly talked to the parents of some of the students and to Rui at the end of the day. The observations we made are valuable to incorporate user-centred design into the development process of our thesis.

3.3.1 Analysis

We explored the notes we took during the day and coded them, labelling the different notes, similarly to the process described in Section 3.2.1. The different codes were then associated with different general themes, creating affinity diagrams [42, 43]. In this case, the notes consist solely of our own observations of the rehearsal.

3.3.2 Findings

Rehearsal process

It is important to acknowledge that every musical ensemble has their own schedule and work stages, regardless of the visual ability of its participants. However, during this observation of an active mixed-visual ability musical ensemble, we noticed some procedures that differ from the typical stages of a sighted-only musical ensemble.

We quickly noticed that the members of the ensemble were very diverse. It consisted of both sighted and visually impaired musicians, and the members ranged from very young children to adults. Certain the children were just old enough to be able to grab and play their instrument. Some of the parents of the children were also part of the ensemble, playing alongside their sons and daughters. Most of the members were still beginners and were still learning the basis of their instruments, but some performers were already experienced, and they helped their colleagues when necessary. A few of the members were both visually and hearing impaired.

The ensemble consisted mainly of brass instruments, such as trumpets, saxophones, and flutes. These instruments are interesting choices because they do not seem to require visual references, since the musicians play them with their fingers always sitting on the valves, which does not require them to search for a button or key that may be hard to locate for a visually impaired beginner. The educators told us that there are also percussion instruments, but the percussion teacher was unable to attend the rehearsal that day. Percussion instruments such as tambourines and tympani also require no visual clues, which again is helpful for beginners.

The first stage of the rehearsal was an individual warm-up, where every musician sat down with their instrument. First, they would tune it and then they would warm up by playing simple notes or scales with a teacher assisting them when needed. Then, they were grouped by the educators according to their instruments and practiced musical pieces they had learned prior to the class.

After that, the musicians would learn another musical piece or passage. This stage of the process showed a disparity between the sighted and visually impaired musicians. When learning the new piece, the sighted musicians had a music sheet available with the notes, some low-vision performers also had a music sheet with a bigger font, and blind musicians did not have access to any sheet. That leaves the blind musicians with no option but to memorize the piece in order to play it correctly with the group in the final stage.

At last, the final stage consisted of a group rehearsal. The ensemble was gathered and sorted by instrument and put in their respective positions. Then, the educators sat beside them to help them with playing the piece they had just learned. The conductor stood in front of the ensemble and quickly assessed how the other stages went for the musicians. After that, he indicated which song they were going to play and conducted them.

To keep the tempo and mark the beats, the conductor clapped loudly so that the performers could hear him over the music that was being played. However, since a few of the performers were both visually and hearing impaired, they could not hear the clapping clearly enough to follow it properly. To solve that problem, one of the assistants had to stand beside them and stomp their feet on the wooden ground, so that they could hear and feel the beat. With that, the hearing impaired performers seemed to keep in time better than before. After that assistance, the rehearsal concluded with the performers practicing the songs they had learned together.

Interaction between conductor and musicians

One of the most fundamental aspects of watching the dynamics between the educators and the musician was seeing how they had to adapt their teaching techniques when dealing with visually impaired students.

When teaching a sighted musician, the educators would show how to play the notes by showing them visually the position of the fingers on the valves, and gesture whatever instruction they wanted to give while the musician was playing, whereas when dealing with a visually impaired musician neither technique is possible. In that case, they would hold the hand of the musician and place the fingers correctly on the valves, and when they wanted to give instructions while the students were playing, they had to say it out loud, which sometimes distracted the student if they could hear it at all.

The process of teaching music appears to be a much more visual endeavour than it seems, since one of the easiest ways to teach someone is to have the student copy what the teacher is doing. That is not possible when dealing with visually impaired students. Still, when dealing with the blind members of the ensemble, the educators gesture the instructions instinctively.

When trying to give instructions when a group is playing, the conductor must order the performers to stop playing and name the visually impaired student they are talking to so that they know they are the one being addressed. However, sometimes educators forget this issue and start talking without saying who they are referring to and the students get confused. This situation happened a few times and is a good example of one of the many adaptations educators must make when in these settings.

Accessibility problems

To prepare for thesis work, we had to gather and analyse different papers regarding the experience of visually impaired musicians, which is described in Section 2.1.3. During this observation, we got to see those problems in a real-world scenario while watching the ensemble rehearse the music pieces and practice their instruments.

As previously stated, to learn a new piece of music, blind musicians must memorize all the notes and rhythm. That is an obvious accessibility issue since their sighted counterparts do not have to do it because they have access to music sheets that contain all that information. Plus, alternatives such as braille music sheets are currently largely unavailable. This prevents the visually impaired musicians to be at the same level as their sighted counterparts, which widens the gap in accessibility between them.

When dealing with a small group of visually impaired students, the teacher must stop the performers from playing whenever they need to give an instruction to a particular player. That can be frustrating for both the educators and the students because sometimes the rehearsal does not flow continuously, and that start-and-stop process tires both parties.

In the final stage, with every musician playing, that problem is intensified. There are many musicians playing at the same time and constantly stopping the practice to give notes clearly left the conductor frustrated for that same reason. However, currently it is the only way the conductor can communicate his instruction to the musicians.

A major problem in the group rehearsal had to do with the counting of the tempo. The conductor had to mark the beats by clapping, which had to be done loudly to stand out throughout the performances. However, even with the clapping some of the hearing impaired students could not hear it properly and had to have someone standing close to them stomping the wooden floor. Although that helped, it showed that sometimes in these settings there is a need for more assistance than expected, which may require more people other than the conductor. Plus, that increases the noise in the room, which disturbs the overall musical output and makes the experience less pleasurable for those who participate.

Another issue regarding the clapping and stomping has to do with how exhausting that can be for the educators. The rehearsal lasted for approximately two hours and having one person clapping strongly and another stomping on the floor during most of that time tires the conductors. It is an impractical method that is presently required but should be abandoned when an alternative surges.

3.4 Discussion

The goal of the interview and the on-site observation was to better understand the issues and the needs of mixed-visual ability musical ensembles and use the information and knowledge retrieved to design the best possible solution using user-centred techniques. Both the interview and the observation showed the disparity in accessibility and inclusion visually impaired musicians experience in an ensemble setting when compared to their sighted peers.

With the problems and experiences recognized, we discussed what steps to take to develop an inclusive system that helps transform a mixed-visual ability musical ensemble in a more accessible environment.

As considered in our semi-structured interview with Dr Rui Magno Pinto, the system must be affordable, which is why it will consist of smartphones as the devices that both send and receive data. Since most musicians have a smartphone they use daily already, it will not require additional investment on their part to successfully use such a system.

The development of the functionalities of the system will also follow the priorities defined by Rui, which means that the first functionality to be implemented is a way to transmit the tempo to the musicians. That can be done by a conductor marking the beats by tapping the screen in early development stages, and later it can be done by using the sensors of the modern smartphones to capture their hand movements.

The system must be adaptable to fit comfortably regardless of who and where one wears it, be it a child or an adult. For that to be possible, the place where the smartphone will be attached has to be chosen with that issue in mind.

Attending the rehearsal also showed how important it is to experience the current environment on-site when trying to understand and tackle an inclusivity problem. It reiterated how important it is to use a mechanism such as UCD to develop the best possible solution to the existing problems. With that said, the prototypes will be developed iteratively, with each iteration being tested with the mixed-visual ability musical ensemble to receive the feedback of both the teachers and the students and take it into consideration when designing the next iteration.

After defining what is needed of this project and how it is going to be approached, we moved on to its development stage, where we defined the mechanisms we were going to be using to reach the best solution possible.

4

The Haptic Conductor

Contents

The development of the Haptic Conductor started by analysing the information retrieved from the interview and rehearsal described in sections 3.2 and 3.3. There, we assessed the needs, difficulties and priorities of a mixed-visual ability musical ensemble and gathered feedback to develop a system that would tackle those issues in an accessible approach.

The Haptic Conductor was developed in stages, as an iterative process with a UCD approach, as explained in section 3.1. Each stage covered the development of a prototype, as well as its testing and validation by the members and instructors of the Filarmónica Enarmonia. The first stage consisted of the development of the first prototype, named "One-To-One Tap Vibration Prototype", and the second stage consisted of the development of the second prototype, named "Broadcasting Information Prototype", plus their tests with the mixed-visual ability musical ensemble. We took into account all the feedback received during each stage before advancing to next, adjusting the system based on the results of the tests.

In this chapter, we detail these iterative stages that lead us to achieve the final system used to perform the final user test further described in section 5.

4.1 1st Stage: One-To-One Tap Vibration Prototype

For the first prototype, we proposed the development of an Android application that could establish a communication between two Android smartphones over a local network, called *One-To-One Tap Vibration Prototype*. This subsection describes its development and the results of the tests performed to validate the application.

4.1.1 Features

Before we began the development process, we sought to first understand what the purpose of the *One-To-One Tap Vibration Prototype* was. The intent of our iterative approach to the development process was to add features to the Haptic Conductor system, starting from an established base and verifying its functionality in every stage of development. Therefore, the structure of each prototype had to be defined, starting with this first prototype, which served as the foundation for the future iterations of our solution.

Having discussed what the priorities should be when developing such a system previously in Section 3.4, we defined the main functionalities that we implemented in this first development stage.

- **Intercommunication**. The *One-To-One Tap Vibration Prototype* must be able to establish a connection between the two Android smartphones, meaning the sender device must be able to communicate with the receptor device when both are connected to the same network. Once established, the communication must be in real-time, leaving as little delay as possible between the moment data is sent and the moment that same data is received. The communication must also only be assured between the two intended devices, preventing other devices from joining the network as to not disturb their communication in this early stage.

- **Network State Access**. To assure the proper functioning of the Intercommunication feature, the application must be able to access the Network State of each Android smartphone in order to retrieve the necessary information.
- **Vibration**. The prototype must guarantee that the receptor device vibrates on cue, meaning when a message is received from the sender device. The application should support different vibration durations and give the option to select those different durations to the user when required.

Once these features were established, we moved on to their implementation and practical development.

4.1.2 Architecture

In order to properly develop the prototype, we had to establish what the architecture would be. Since the prototype is fairly simple, so is its architecture. The architecture proposed for the *One-To-One Tap Vibration Prototype* is displayed in Figure 4.1.

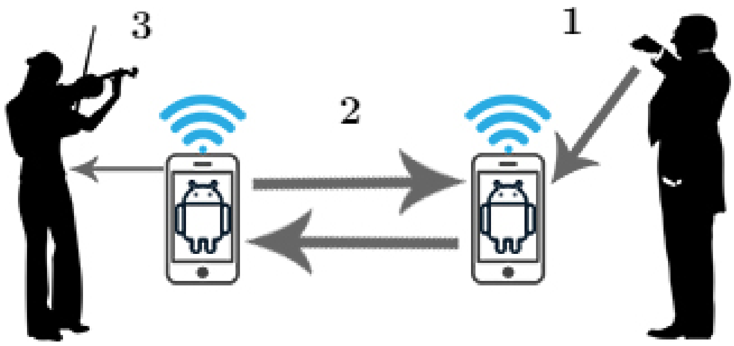


Figure 4.1: Illustrative architecture of the *One-To-One Tap Vibation Prototype*. (1) Conductor tapping the screen to send the signal; (2) Sending information the performer through the local network; (3) Haptic feedback.

The entire system in use for this prototype consists of two Android smartphones, each one equipped with the application and their native sensors. There is no other equipment required in order to use this prototype. Each smartphone must also have the ability to create an access point, on which the other must connect so that both phones are linked on the same local network.

The application was developed using the Kotlin[1] language on the Android Studio Integrated Development Environment (IDE)[2]. While Java[3] is still the standard Android programming language, Kotlin offers

[1] Kotlin (https://kotlinlang.org/)
[2] Android Studio (https://developer.android.com/studio/)
[3] Java (https://www.java.com/)

a faster, more lightweight approach and recently has been more adopted and recommended by Google to program Android applications[4]. Therefore, and since it offers Java compatibility and interoperability, we incorporated this language in our code.

4.1.3 Development

This subsection describes the development of the code of the application, explaining the implementation of each feature and the methods used to do so.

The first step in the development of the prototype was to define whether there should be two different Android applications, one for the conductor and one for the musicians, or if there should be just one application that groups the features from both the conductor and the musician. Although having two separate applications could be a legitimate approach due to each person having only the features they need, that would limit the flexibility of the system. For example, if the smartphone of a student runs out of battery and there is a spare smartphone from a teacher, they would not be able to lend the phone to the student because it would not include the required features. Plus, it is simpler to only have one application instead of separating the features.

Therefore, we opted to have the system contained in only one Android application. In order to do that, we had to develop three different Activities[5], which are the windows displayed to the user when running the application. We took in consideration our previous discussions described in Section 3.4, thus proposing to develop an application as simple and easy to learn as possible.

The first activity developed was the Main Activity, which is the default window that is opened when the user starts the application. The only feature of this activity is giving the user the option to select whether they want to access the "Conductor" window or the "Performer" window. To implement that feature, two buttons with the words mentioned are displayed and the user is asked to choose one of the options. The activity is always listening for a click on each button, and when an option is chosen the main activity starts the respective activity, redirecting the user to the intended window.

To develop the communication between the conductors and the students we had to first study how to program a simple message exchange between the two phones. To do that, we had to choose a communication protocol that allows us to establish a Unicast connection, i.e., a one-to-one network. The two main protocols are Transport Control Protocol (TCP) and User Datagram Protocol (UDP), both of which have their advantages and disadvantages. UDP offers the fastest data transmission of the two, prioritising speed over reliability by not establishing a connection between the parties prior to the data sending, which was not particularly advantageous for the approach we were taking with the *One-To-One Tap Vibration Prototype*. TCP, however, offers a reliable data stream by establishing a connection

[4] Android's Kotlin-first approach (`https://developer.android.com/kotlin/first`)
[5] Android Activity (`https://developer.android.com/reference/android/app/Activity/`)

between the server and the client before data is sent, detecting errors when messages are exchanged. Therefore, we selected TCP as the best protocol to implement on this prototype.

In order to perform any wireless connection, we had to add the respective Permission[6] to the *AndroidManifest.xml* file. The permission required here is "INTERNET", which allows the application to open network sockets. Throughout the development of the Haptic Conductor, other permissions were added to the Manifest file when required.

To implement the TCP connection, we established a server on the Conductor/Server Activity. That was done by creating a ServerSocket[7] on a specific port, which in this case was the port 9999. This function creates a server socket that waits for a request from a client to form the socket. When the request is received, the server accepts it, and the client is connected.

However, for the TCP to work properly, the client must connect to the Internet Protocol (IP) address of the server. Since every smartphone has a different internal default IP address and it is variable depending on which network it is connected to, if any at all, the activity must also display the current IP address of the device. Therefore, we created a function that verifies if the device has any active connection to a Wi-Fi network or a cellular network. If it does not, the message "No connection" is shown and the user knows the device is unreachable because it does not have a connection and thus it does not have an active IP address. If it does, the function displays the current Internet Protocol Version 4 (IPv4) address and the user knows that the device is ready to establish the connection with the client. For this feature to function, we had to assure that the device allows the app to access its network and Wi-Fi state. Therefore, we had to add the respective Permissions to the Manifest file. The two permissions required were: (1) "ACCESS_WIFI_STATE", which allows the application to access the Wi-Fi state of the device; and (2) "ACCESS_NETWORK_STATE", which allows the application to access the Network of the device.

The next step was to create an input and an output data stream, which receives and sends the messages intended between the server and the client. To test the connection, the client sends an "Hello" message when it is accepted, to which the server replies "Hello to you too!" when the message is received. If the messages are exchanged correctly, the connection is accurately established.

On the Performer/Client Activity, we had to program the correct parameters to establish the connection to the server. Therefore, we created a Socket[8] that connects to the IP address of the server on port 9999. To connect to the IP address, it must be inputted by the client. To do that, there is an EditText[9] widget where the user can input the IPv4 address of the server, and a "Confirm" button next to it. If the address is accurately inputted and the connection is established, a message with the IPv4 address is displayed and the device vibrate, letting the user know that the device is connected to the server.

[6]Android Manifest Permission (https://developer.android.com/reference/android/Manifest.permission)
[7]Android ServerSocket (https://developer.android.com/reference/kotlin/java/net/ServerSocket)
[8]Android Socket (https://developer.android.com/reference/kotlin/java/net/Socket)
[9]EditText Widget (https://developer.android.com/reference/android/widget/EditText)

Then, a data stream was created similarly to the one created on the Server Activity. After the connection is established, the client sends “Hello” and awaits the response. When received, the user assures that the client is properly connected.

Once the basic message exchange was performed and verified, we had to develop the tap feature, where when the conductor taps the screen, a message is sent to the receptor, which will then vibrate. To do that, we created a “Tap” button on the Server Activity that occupies most of the screen. The activity then waits for the button to be pressed, and when it is clicked the server sends a message “Test” to the client and flushes the data stream. The activity is constantly listening to this action while the client is connected to the server.

On the Client side, the activity is always listening to the data stream while it is connected to the server, awaiting the reception of the “Test” message from the server. When a message is indeed received, the device is ordered to vibrate. In order for the smartphone to vibrate, we had to add another Permission to the Android Manifest file, this time the permission “VIBRATE”, which allows the application to have access to the vibrator of the device.

Once the vibration is permitted by the device, it will vibrate each time a “Test” message is received by the receptor. To further increase the flexibility and the customization of the system, we also implemented a feature to edit the duration of the vibration so that the user can change it to better suit their preference. The default duration is 120 milliseconds, but when the user clicks the “Duration” button a popup window displays other options that they can select, which are:

- 30 milliseconds;
- 60 milliseconds;
- 90 milliseconds;
- 120 milliseconds;
- 150 milliseconds;
- 200 milliseconds.

We selected 120 milliseconds as the default duration during the development of the prototype because it felt long enough to sense but not too long, meaning the vibrations would not merge with each other in faster tempos. The options have 30 milliseconds intervals between them because we felt that was the right interval for the user to feel the difference between the options. The last two options have a 50 milliseconds interval because we felt that in longer durations that increase was the ideal to sense the difference. All these options were subject to change if the participants so suggested.

When an option is selected, it will remain the duration until the user changes it again or the application is restarted.

Newer Android smartphones do not permit the application to be fully active when the phone is locked, i.e., the screen is off. Therefore, we had to assure that the screen of the phone is always on when the application is running. To do that, we had to introduce that feature on the Extensible Markup Language (XML) files of the three activities. By ordering the smartphone to keep the device always awake with the command *android:keepScreenOn = true*, the screen will never turn off when the application is running. In order to reduce the chances of accidentally press an unwanted button, we also wrote the command *android:screenOrientation="portrait"*, which will maintain the application always running vertically regarding the screen orientation.

4.1.4 Navigation

In this section, we showcase the navigation flow of the Android application *One-To-One Tap Vibration Prototype*.

When the user first opens the application, they are presented with the home screen, which consists of a message asking the user to select an option between “Conductor” and “Performer”, with the respective buttons displayed in the centre of the screen below the message. The opening window is presented below in Figure 4.2.

From this point, the navigation of the user can change depending on if they are a conductor or a performer and they select their respective option.

After selecting the “Conductor” option, the user is redirected to the screen shown below in Figure 4.3. The screen displays a “Server established” message and the instruction “Tap the button to send signal” on the top centre of the screen. The IPv4 address of the device is also displayed on the top right side of the screen, close to the other messages. Below the text is a “Tap” button, on which the instructor will click to transmit the signal to the musicians.

The navigation flow of the Performer Activity is different. There is an “Insert IP” message on an EditText widget where the user must input the IPv4 address of the device of the conductor, and beside it there is a “Confirm” button, which when pressed with the correct IP address, displays a message on the top centre of the screen that reads “Connection successful! Awaiting signal from server”, plus a message right below the widget with the IP address inputted. The screen also contains a “Duration” button, which when pressed opens a popup window with different duration options for the vibration of the device. Finally, when the option is selected, that popup window closes and there is a popup message stating the duration of the vibration selected. An example of this navigation flow is shown below in Figure 4.4.

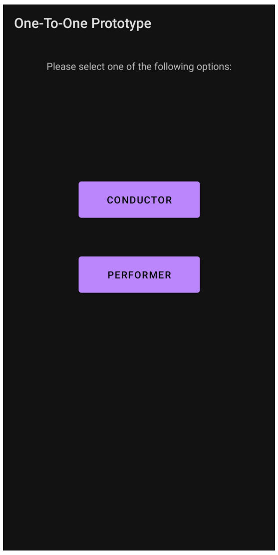


Figure 4.2: Home screen displayed after the application is opened.

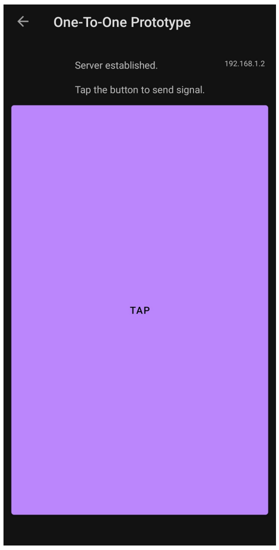
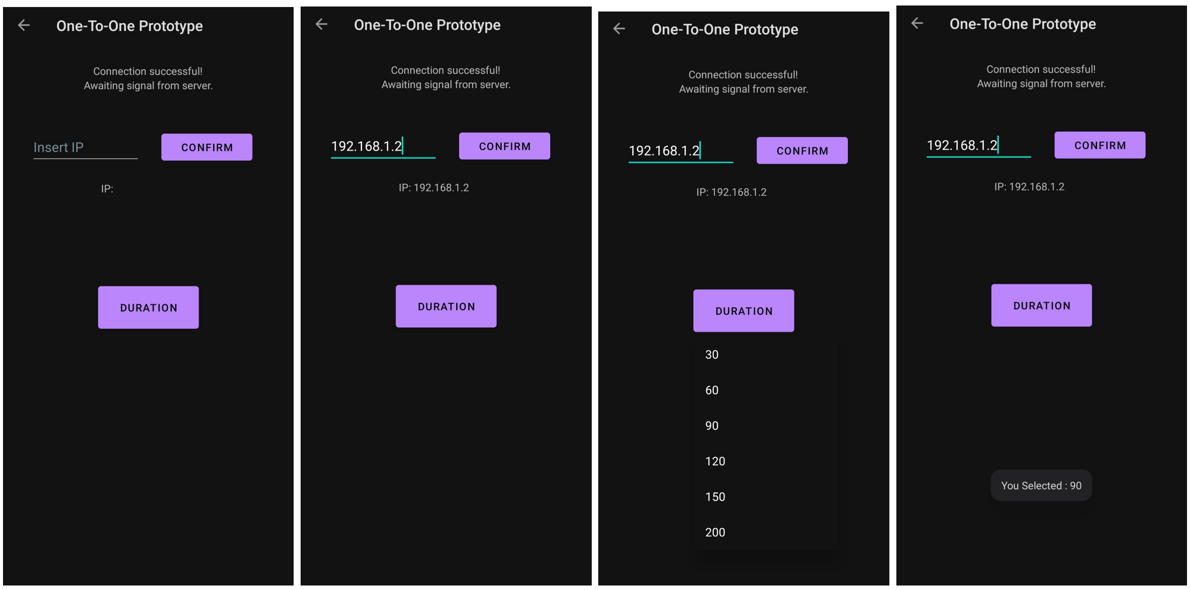


Figure 4.3: Conductor screen displayed after the "Conductor" option is selected.



(a) **(b)** **(c)** **(d)**

Figure 4.4: (a) Performer screen displayed after the "Performer" option is selected; (b) Performer screen after the IP address is inputted; (c) Performer screen while selecting a different vibration duration; (d) Performer screen with popup showing the new vibration duration.

4.1.5 User Test

In order to test the prototype developed, we scheduled a user test with Dr Rui Magno Pinto, the conductor of Filarmónica Enarmonia. The test was then performed on 9th April 2022 at the Junta de Freguesia de São Domingos de Benfica, in Lisbon.

4.1.5.A Participants

For this test, we recruited ten students of the ensemble, six of which were visually impaired and the other four were sighted persons. The ages of the students varied from 7 years old to 66 years old. We also recruited four instructors of the ensemble to perform the test, all of which were sighted adults.

4.1.5.B Procedure

First, we began by asking a student to sit on a chair and attaching a smartphone to their arm using a nylon strap while explaining the test we were going to perform. While doing that, we inputted the IP address of the sender phone in the receptor, establishing the connection between them. At that point, the smartphone assigned to the conductor was already hosting a local network on which the smartphone assigned to the student was already connected. This was all done previously on the test preparation, which was possible since both smartphones used belonged to the investigation team.

Then, with the connection established, the instructor was asked to send the signal to the student to test their sensibility to the vibration. If the vibration was not felt enough for it to be possible to play music while following the vibration pattern, the student was asked to share that information and to ask us to switch the placement of the smartphone from the arm to the leg or any other place where it was felt properly and comfortably.

After the student confirmed they could feel the vibration, the test proceeded by having the teacher send a rhythmic pattern to the student by tapping on the phone without counting the time out loud, who was asked to clap or stomp their feet on time. For the sighted musicians, the test was performed back-to-back with their instructor as to not let them use their sight to follow the tapping movement of the instructor instead of the vibration. After that, the instructor told the student to try and start a song on time without a vocal count-in. The teacher would then send four vibrations, which constitute the usual count-in bar, and the student should start playing the song on the correct time.

After these tests were performed, the student was dismissed to the regular rehearsal and another student would come in to perform the test as well. Throughout the testing process, the instructors would also change among them in order to test the Haptic Conductor with their respective students for the comfort of the students.

While performing the test, we took notes of observations we would make and of what the participants would say while testing the system. After all the testing was done, we grouped all the participants in the main room, and we conducted an informal conversation where we asked for their feedback. The conversation was recorded to further analyse the information retrieved.

4.1.5.C Findings

The test allowed us to observe the Haptic Conductor in practice being used by the target users in their natural, albeit controlled, environment. It contributed to retrieving information observed and constructive feedback regarding the overall usage of the system from the users, both students and instructors.

We analysed our notes taken during the test and coded them, labelling the different notes, similarly to the process described in Section 3.2.1 and Section 3.3.1. The different codes were then associated with different general themes, creating affinity diagrams [42, 43].

Practicality

Since the system must be used when the students are playing their instrument and the instructor is conducting them, the practicality of the usage of the Haptic Conductor is a very important parameter when in the process of testing it. The Haptic Conductor must be a comfortable solution, as to not disturb the musicians when they are playing their instruments, and it must be an accessible, easy to use system.

After the initial explanation, all the users understood the system immediately, letting us know that it is simple and accessible enough to not require any training to use correctly. That is important because it suggests that there is no need to have an instruction period nor an expert present to set up the system, being that the instructors and musicians can use the system independently.

The Android smartphones used were our investigation devices. We chose to not use the personal smartphones of the members of the musical ensemble as to not complicate the procedure, given that there was no real advantage assessed in doing so. Using our own devices, we could establish the hotspot and the connection between the two phones, and input the IP address so that all of that preparation was done before starting tests with the users. That way, there was less time wasted and less interruptions throughout the test.

Regarding the placement of the device on the musicians, the straps were a practical solution because they could tighten regardless of the size of the performer and the part of the body where it was placed. The straps used proved to be malleable, plus they were comfortable to wear wherever the user wanted to wear them. When tight enough, the phone never slipped out of the strap, being attached to the body for the entirety of the test.

Examples of the positioning of the device can be found in Figure 4.5. Additionally, Figure 4.6 depicts a user testing the prototype.

Since the device worn by the musicians only vibrates with the screen on as mentioned previously, that meant that the screen could not be facing towards the body of the user. Every time a user placed

Figure 4.5: Smartphone attached to the leg of a participant with a nylon strap.

Figure 4.6: Participant performing the test with the smartphone attached near his ankle.

the phone screen-down on their body, they would accidentally press the home, or the return button and the system would stop working. On the occasions when that happened, the phone had to be removed from the strap, the application started again and the IP address inputted again. Only after doing that was the smartphone ready to be strapped again, this time with the caution of placing it screen-up on the arm or leg of the user. That proved to be an inconvenience because of the time wasted when such a thing would happen, meaning we had to be extra careful with that every time a new test was being performed.

On the side of the teacher/conductor, the system proved to be very simple to use. Not one user needed any special teaching or instructing, they immediately started using the application correctly, showing us how straightforward it is in a positive way.

Functionality

Perhaps the most important parameter we had to evaluate during this first stage of testing was the functionality of the system as it stood. It was important to assess if the communication was established correctly, if the students could receive and interpret the haptic feedback given by their smartphone, and if the signal was being transmitted in real-time correctly from the phone of the teacher to the phone of the student.

There was also attention to whether the system would work as correctly with the conductor standing right next to the musician as it would with the conductor standing farther way from the musician. That issue was raised by the teachers during the test because they wanted to assure that they could move freely while using the system as they often do during the regular rehearsals of the ensemble.

Many students in the beginning of the test said they did not feel the vibration. After tightening up the smartphone, little changed regarding that issue, as few of them felt the change. That was a problem because if the students do not feel the vibration properly, they cannot use the Haptic Conductor system since it relies exclusively on the haptic feedback given by the phone.

After changing the placement of the smartphone from the arm to the thigh or leg, many started to feel the vibrations better. Other users tested the system on their ankle, and they felt improvements as well.

What we realised from this experiment was that almost every user preferred a different placement of the phone than their peers, which is important because it shows us that the straps must be able to hold the smartphone regardless of where the users want it to be. We had to keep that in mind when moving forward with the development.

We also realised that the students were having some difficulties concentrating on the vibrations because they are not used to practice in a more silent environment than their regular setting. Since every command they receive from their instructors is vocal or audible, they are used to concentrate on their hearing and not on their touch, and that seemed to be a problem at first. As the tests progressed, the users seemed to get more accustomed to the vibration, following the instructions more correctly than they did in the beginning of the test.

In order to better understand what their students were saying, the teachers asked to also try and feel the vibration as if they were the students. While they did mention that the vibration was indeed weak, they were also able to follow the vibration much better than their students. Therefore, we assumed that since the teachers are already expert players of their instrument, they could concentrate on the haptic feedback without detriment to their music playing. That assumption was also shared by the instructors themselves when discussing the possibility during the test.

A positive note was that very little signals were lost during the test, meaning that most if not all the impulses arrived at the phone of the students, making them vibrate in real-time with very little delay. That functionality is imperative to the well-functioning of the Haptic Conductor and the tests proved it worked correctly.

The teachers separated themselves more from the students in the end of the test to prove that the system works regardless of their distance, as long as the device of the musician still reaches the local network shared by the device of the instructor. This also proved to be the case, since the distance did not seem to influence the communication between the devices.

To the students that seemed to have more difficulties getting used to the vibration impulses, a teacher suggested ignoring the system briefly and performing the test by touching the arm or back of the student signalling the time of the song to see if the student could concentrate on that touch better. That was performed with three different students, and neither of them had trouble following those instructions. After doing that, all of them were able to follow the vibrations much better than they did before.

Another way to improve the vibration effect seemed to be to increase the duration of the vibration. Although the intensity of the vibration was the same, increasing the duration of the vibration from the default value of 120 milliseconds to 200 milliseconds had a positive effect, since most users reported feeling the vibrations better. However, increasing the duration means that in musical pieces with faster rhythms, the time marks may not allow the vibration to have space between each other, merging them all together. That spoils the experience of the musician, since almost all he would feel would be one long vibration instead of many shorter vibrations. Therefore, that cannot be a universal solution, although it can work in slower musical numbers.

That showed us that the vibration may require a habituation period where the student must learn to focus and follow the vibrations the same way they do when the instructions are audible or when the teacher is touching them, by being able to concentrate on the impulse without it being their sole focus, allowing them to play their instrument simultaneously.

Feedback

A major advantage of the UCD approach we took was being able to gather feedback instantaneously from the users during the testing process. We took notes of the feedback the users were giving us during the tests, but we also conducted a constructive conversation with all the users after all the tests were performed and recorded it, as to not miss any important information they shared with us.

When asked what they felt using the system, most students mentioned the difficulty to sense the vibration of the device. They argued that the vibration was too weak to follow without having to focus on it so much that they are not able to focus on playing their instrument at the same time. Although all the participants said that they did feel the vibrations, the majority said that it had to be stronger to follow without problem.

However, a teacher intervened saying that they agreed that the vibration was very weak, but that they felt that with practice and repetition the students would be able to follow the instructions given through vibration without issue.

> *"We have to take into account that most of our members are beginners and have yet to master their instruments, plus they are not used to follow quieter instructions. Since our rehearsal is always so noisy, maybe they must have a habituation period where they try to follow only the vibration in silence."*

Although the power of the vibration was the most mentioned point, there was also mention of the placement of the smartphone on the body. Some students said that it may not be viable to have the phone stuck on their arm if the instrument requires a lot of arm movement. That is the case of most percussion instruments, namely the drums, where the arm is in constant movement. However, given that we did not test the system with any student of the drums, there is no way of knowing how much of an impact it would have had. Nevertheless, when assured that the smartphone can be placed wherever the user feels the most comfortable and the most useful, the musicians dismissed the issue.

All the users that performed the test said that the system was comfortable, that it did not harm their musical performance, nor did it feel unpleasant to use. However, there was mentioned that since the vibration is weak and the strap is tight, sometimes the user can confuse the vibration with their own heartbeat. Some users said that they felt the same and that maybe had to do with the amount of pressure the strap was exerting.

The instructors also mentioned that they felt no problem in marking the tempo of a song by taping a screen of a smartphone. They did not experience any fatigue in the process nor did they found it difficult to ignore the minimal delay the system inevitably presents, always being able to correctly send the tempo to the students without any relevant problem.

When asked if they had any suggestions, the users mentioned that the priority should be increasing the power of the vibration. They also said that it would be interesting to have different vibration patterns and test if that helps them feel the vibration better.

After finishing the interview, many members of the musical ensemble, including the instructors, told us how much potential they think this system has and how excited they are to use it in the future. The conductor also told us that they think that this prototype would already be useful in some specific rehearsal settings, such as when they have to focus on only one student to learn a particular part of a musical number.

4.1.6 Discussion

After the *One-To-One Tap Vibration Prototype* was developed and tested with the mixed-visual ability musical ensembles, we had to assess all the information we gathered from every stage of development and from the feedback received in the testing stage and plan how to move forward and improve the work we have done for the next prototype.

The purpose of the iterative and UCD approach we took in developing the Haptic Conductor was to build the foundation of the system and validate every step until we reached the best possible solution we could develop in the time we had. Therefore, and as mentioned previously in this chapter, this first prototype served to validate the different features implemented, such as the intercommunication between two Android smartphones and the haptic feedback.

The intercommunication relied on a TCP socket that the user tests showed worked as planned, establishing a reliable data stream between the server and the client devices. Almost no message was lost in the entirety of the test, which is one of the advantages of the TCP protocol, and the communication was as close to real-time as it was possible, having very little delay every time.

Regarding the vibration, all the tests showed us that most users felt it was very weak. Going forward, we had to try to tackle that issue by increasing the power of the vibration if possible. If that was not feasible, we should explore other vibration patterns, as suggested by the users when we asked them for feedback.

The results of the tapping approach taken for marking the tempo proved to be efficient and easy to perform, from the point of view of the instructors. The movement did not tire the conductors, who told us that it seemed a good solution to maintain on the next prototypes.

The *One-To-One Tap Vibration Prototype* served as the basis for the development of the Haptic Conductor, implementing successfully the vibration feature and the intercommunication in real-time feature. The next prototype maintained the vibration feature but expanded its network capabilities to include more musicians instead of just one. We also tried to improve the vibration feature in order to have the best solution possible.

4.2 2nd Stage: Broadcasting Information Prototype

For the second prototype, we proposed the development of an Android application that could establish a communication between multiple Android smartphones over a local network. The prototype is called *Broadcasting Information Prototype*. This subsection describes the development of the application and the results of the tests performed to validate the solution.

4.2.1 Features

For the second stage of development, we proposed taking the first prototype and implementing more features on top, while correcting the aspects noted on the testing phase of the first prototype, which was the purpose of the iterative approach taken during this thesis work. To develop the application, we had to define the features we wanted to implement.

After a round of tests with the *One-To-One Tap Vibration Prototype*, we gathered enough information and feedback to help us define which features we should implement and which ones had the most importance. The main functionalities of the application that were implemented in the second development stage are listed below.

- **Intercommunication between multiple devices**. In this feature lies the main difference between the first prototype and the *Broadcasting Information Prototype*. This prototype must be able to establish a connection between multiple Android smartphones, meaning the sender device must be able to communicate with multiple receptor devices when all of them are connected to the same network. The communication must be as close to real-time as possible, leaving the less possible delay between the moment data is sent and the moment that same data is received. The communication must also only be assured between the intended devices, not distributing the data to other devices, even if they are connected to the same network as the smartphones running the application.

- **Vibration**. The functioning of the vibration feature is similar to the same feature on the *One-To-One Tap Vibration Prototype*, as described in section 4.1.1. On this prototype though the vibration intensity is optimized to the maximum power allowed by the vibrator motor of each smartphone. Also, it still supports different durations, giving the users the option to choose the duration of each vibration while using the application.

- **Time Synchronization**. This feature was added to the feature list at the development stage in order to tackle the issues we encountered when validating the remaining features. While developing this prototype, we realised that in order to improve the Intercommunication feature we had to implement a feature that would allow us to synchronize the clocks of each device. Therefore, the application must be able to perform a time synchronization between all the smartphones and get the clocks with as little difference as possible.

Once these three features were declared and planned, we advanced to their implementation and practical development.

4.2.2 Architecture

The architecture remains simple, and it stayed similar to the architecture of the previous prototype, described in section 4.1.2. The architecture proposed for the *Broadcasting Information Prototype* is displayed in Figure 4.7.

The architecture for this prototype consists of multiple (more than two) Android smartphones, all of them equipped with the application and their native sensors. A difference from the architecture of the previous prototype is that the smartphones do not need to create an access point to establish the network.

For the system to work properly, there was now the need to add a Wi-Fi router to the architecture of the prototype. The router functions as the access point of all the smartphones. While it is not connected to the internet, the router establishes a local network that all the devices connect to.

The router itself does not need to have a special requirement or features. All that is needed is a simple router that can promote the fast exchange of data between the smartphones. Ultimately, we chose the TP-Link TL-WR840N[10] because it is a fast, simple and inexpensive router that allows a flexible and easy setup.

[10]TP-Link TL-WR840N (https://www.tp-link.com/pt/home-networking/wifi-router/tl-wr840n/)

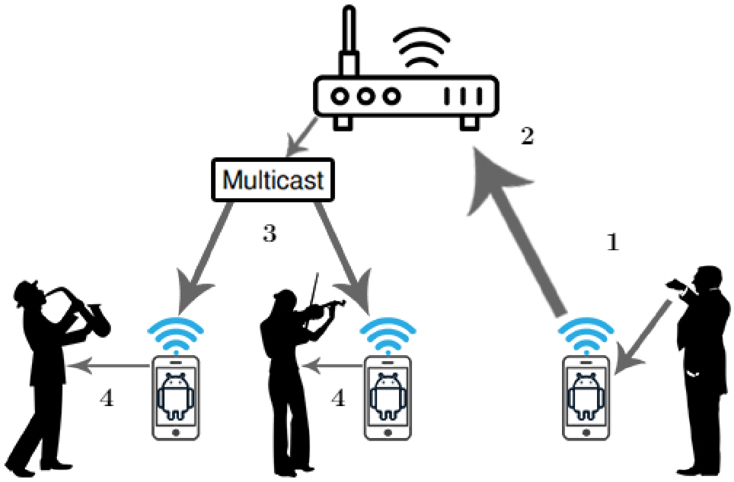


Figure 4.7: Illustrative architecture of the *Broadcasting Information Prototype*. (1) Conductor tapping the screen to send the signal; (2) Sending information to router in local network; (3) Receiving multicast information from router in local network; (4) Haptic feedback.

The application was again developed using the Kotlin language on the Android Studio IDE.

4.2.3 Development

In this subsection, we describe the development of the code of the application. We explain our implementation decisions and the methods used to program the prototype.

The basic structure of the application remains the same from the previous *One-To-One Tap Vibration Prototype*, with the application containing the same three Activities: (1) The Main Activity; (2) the Conductor/Server Activity; and (3) the Performer/Client Activity.

The Main Activity remains intact, not needing any changes from the first prototype besides the translation of all the text to Portuguese. It gives two options to the user to proceed, asking him to select between accessing the “Conductor” window or the “Performer” window. The activity is listening for a click on each of the buttons, and when either option is selected the main activity starts the respective activity and redirects the user to the intended window.

On the previous prototype, we developed the communication between the devices using the TCP protocol, establishing a Unicast network, i.e., a one-to-one transmission approach. TCP offered us a reliable data stream, detecting errors during the process and establishing a connection between the server and the client prior to the exchange of any data.

However, this application had a different goal. Since we had to use multiple clients in our tests, we could not use a Unicast network approach. Instead of a one-to-one system, we had to use a one-to-many system, and that invalidated the use of the TCP protocol. It requires a one-to-one connection between servers and clients, and therefore we did not use TCP on the *Broadcasting Information Proto-*

type. Instead, we opted to use UDP.

The UDP internet protocol offers a faster data transmission while compromising the reliability of the data stream, which may be an issue for the development of the system. That could be a problem because without guarantee that the messages are received there might be the case of the client not receiving all the vibrations they are intended to receive, which could complicate the experience for the musicians.

To accurately develop this network approach, we had to choose between using Multicast or Broadcast, i.e., between one-to-many and one-to-all. While Broadcast networks are simpler to implement, the host sends a message to every device connected to the network, even to the ones that are not intended to receive the messages. Multicast networks, however, function between the Unicast and Broadcast approach, where the same host sends the messages to multiple destinations, but not all the devices of the network. For all these reasons, we chose to implement a Multicast network.

To do that, we had to change our approach on the Conductor/Server Activity. Now, instead of creating a ServerSocket, we created a DatagramSocket[11] because it allows the implementation of Multicast. We then defined an IPv4 address on which there was created a group. That group will contain all the devices who run the application, and it will point to the defined IP address so that the server sends the messages to that address and the clients receive the messages from that address. There is a specific requirement to create Multicast groups in Android, which is to use a class D IP address, which means that the group must be in the range *224.0.0.0* to 239.255.255.255. For that reason, we chose the address *228.5.6.7*.

On the Performer/Client Activity, we also had to apply the changes to correctly establish the Multicast network. Therefore, instead of creating the client with a Socket, we used a MulticastSocket[12], which offers the feature of joining multicast groups like the one we created on the Server Activity. Then, we make the socket join the group on the host address *228.5.6.7*.

For the Multicast approach to work on most Android devices, we had to first give the needed permission on the Manifest file of the application. While maintaining the permissions "ACCESS_WIFI_STATE" and "ACCESS_NETWORK_STATE", we also had to add the permission "CHANGE_WIFI_MULTICAST_STATE", which allows the application to enter Wi-Fi Multicast mode.

Most Android smartphones however filter out all the packets received that are not explicitly addressed to themselves, refusing packets forwarded to any multicast address. To allow the Android smartphones to receive multicast packets, we had to acquire a MulticastLock[13].

In order to do so, after joining the multicast group on the Performer/Client activity, we created a WifiManager[14], which allows us to control all the functionalities of Wi-Fi on the smartphone. Then, we

[11] Android DatagramSocket (`https://developer.android.com/reference/kotlin/java/net/DatagramSocket`)
[12] Android MulticastSocket (`https://developer.android.com/reference/kotlin/java/net/MulticastSocket`)
[13] Android MulticastLock (`https://developer.android.com/reference/kotlin/android/net/wifi/WifiManager.MulticastLock`)
[14] Android WifiManager (`https://developer.android.com/reference/kotlin/android/net/wifi/WifiManager`)

acquire it, and the device is ready to receive the multicast messages sent from the host.

While developing the application and checking its features, we noticed that many impulses were received with large delay, if they were received at all since many packets are lost. This was a consequence of using the UDP protocol as the communication method between the devices of the system. Some aspects of these consequences we cannot control, but we could try to tackle them and get around these issues.

When conversing with the instructors and observing the rehearsal in the previous work stage, described in section 3.2.2, we realised that receiving delayed impulses would result in different students playing the musical piece at different tempos, which invalidates the correct functioning of the system. Therefore, we concluded that between receiving delayed impulses and filtering them out, the best option would be to filter them out and have the application ignore these packets.

As a means to implement that feature, we had to define a delay time range during which the packet should be accepted, and the device should vibrate in response. Any packet that would be received out of that time frame is to be ignored and the device should not vibrate or respond to it. However, that is not trivial to implement since the time of different smartphones runs at slightly different speeds, and although the differences are minimal, they are noticeable in the context of this prototype. For example, if the clock on client device X is 1 second ahead of the clock on server device Y and the delay permitted we defined to filter the packets is 0.5 seconds, the device X would filter out every packet that is sent by the device Y, even if the communication was in literal real-time, with a delay of 0 seconds.

Android does not allow users to manipulate the clock without having root access, i.e., without attaining privileged control over the operating system. As the application was designed to be used by the smartphones of the members of the mixed-visual ability musical ensembles, we cannot demand that every user has to attain root access on their smartphone in order to use the application. Therefore, we had to design a functionality that allows the app to synchronize the time without having to manipulate the clocks of the smartphones.

The approach we took to fix this problem was to calculate the difference (i.e., the offset) between the smartphone of the Conductor and all the smartphones of the Performers. To do that, we had to implement a feature in the Conductor/Server activity that synchronizes the clocks when the Conductor thinks is necessary.

We added a “Sync” button on the top right of the screen, and the Activity is always listening for a click on that button. When the button is tapped, the server sends a “Offset” message to the receivers and waits for 2 seconds before proceeding. That pause gives enough time for all the smartphones of the performers to receive the packet. Then, the activity enters a cycle where the server sends the current time of the smartphone of the conductor to the smartphones of the performers, after which the function sleeps for 0.1 seconds so that the packets all contain different timestamps. That cycle is then repeated

60 times. After the cycle ends, the activity shows a popup on the bottom of the screen containing the message “Sync completed!” to let the user know that the process is finished, and they are free to advance.

On the Performer/Client side, we had to differentiate these packets from the regular packets, and that is why the first message of the server is “Offset”. Every time a message is received, the client activity checks if it is the word “Offset”. If it is not, the device assumes is a regular “Tap” message and vibrates; if it is, the device gets ready to calculate the offset. To do that, we created a MutableList[15] and established that the next 50 packets received contain the timestamps of the conductor. The 10 extra packets sent were meant to prevent the application to be stuck on the offset calculations if some packets are lost in the transmission. Then, when each packet is received, the client extracts the timestamp the server sent and gets its own timestamp on the moment the packet was received, and calculates the offset by following this simple calculation:

$$timeReceived – timeSent = Offset$$

The result of this equation is then stored on the MutableList previously created. This process is done for the 50 packets received, and when it is finished, we have a list of all the offsets. We extract all the values stored and add them to the total Offset, until we end up with the sum of all the offsets calculated. Finally, we had to calculate the average offset by dividing the total Offset value with the number of entries, following the equation $averageOffset = totalOffset/50$.

We now had the average offset for all the performer's smartphones. Therefore, to obtain the real delay of each “Tap” message, we had to calculate it every time such a message is received. That is done by calculating the difference between the time when the packet is received and the average offset, following the expression $difference = timeReceived – Offset$. That calculation cancels out the difference between both clocks and allows us to get the real value of the delay.

To filter out the packets with too much delay, we had to define the maximum delay allowed. Through trial and error, we came up with the value 200 milliseconds for maximum delay, because we felt that a delay of 200 milliseconds is still close enough to the intended real-time that the performer can still follow the correct tempo the instructor is sending. If the delay is greater than 200 milliseconds, the device ignores it; if the delay is less than or equal to 200 milliseconds, the device executes the vibration.

In order to tackle the main problem referred by the members of the ensemble, we had to search for ways to improve the power of the vibration of each smartphone. However, the ability to manipulate the vibration of an Android smartphone was only added in Application Programming Interface (API)[16] level 26 with the resource VibrationEffect[17], which means that we cannot manipulate the power of the

[15] Kotlin MutableList (https://kotlinlang.org/api/latest/jvm/stdlib/kotlin.collections/-mutable-list/)
[16] Android API (https://developer.android.com/guide/topics/manifest/uses-sdk-element.html#ApiLevels)
[17] Android VibrationEffect (https://developer.android.com/reference/kotlin/android/os/VibrationEffect)

vibration for every Android smartphone with an operating system below Android 8.0, also known as Android Oreo[18]. That ended up being a limitation of our solution.

With this information in mind, the vibration feature of the Performer/Client activity has to first verify if the Android version of the smartphone is 8.0 or newer, and if it is, we created a VibrationEffect, which triggers a one-shot vibration. Since it allows to manipulate the strength (i.e., the amplitude) of the vibration by inputting a value between 1 and 255, with 1 being the weakest and 255 being the strongest, we inputted 255 as it is the maximum value permitted. If the Android version is older than 8.0, the device vibrates with the default strength, as it did in the previous prototype.

This prototype maintained the ability to change the duration of the vibration, with still the same options as on the previous prototype, described in section 4.1.3. It also maintained the fixed vertical screen orientation and the screen always on, such as the *One-To-One Tap Vibration Prototype*.

4.2.4 Navigation

In this section, we showcase the navigation flow of the Android application *Broadcasting Information Prototype*. While it may be similar to the navigation flow of the *One-To-One Tap Vibration Prototype*, there are some noteworthy variations that are described here.

Almost all the text was translated from English to Portuguese so that the application is more accessible to all the test users, which are the members of the mixed-visual ability musical ensemble Filarmónica Enarmonia.

When the application is opened by the user, it presents the home screen, still consisting of a message asking the user to select an option between “Teacher” (formerly named “Conductor”) and “Student” (formerly named “Performer”). Both the buttons are displayed in the centre of the screen below the message. The home screen is pictured in Figure 4.8.

After the user selects one of the options, they are redirected to the activity of the respective option they selected.

When selecting the option “Teacher”, the user is redirected to the screen of the Conductor/Server activity. The screen once again displays a “Server established” message along with a “Tap to send signal” message on the top centre of the screen. Still the IPv4 address of the server is displayed on the top right side of the screen, but now its use is only to show the user that the device is connected to the network and the server is correctly established. Occupying the larger part of the screen is the “Tap” button, on which the instructor taps to transmit the signal to the musicians.

Right below the IP address is the “Sync” button, on which the instructor clicks to synchronize the clocks of the devices included in the system. When that button is pressed, the synchronization is performed, and when it has finished a popup notification is presented on the bottom of the activity screen

[18] Android Oreo (https://developer.android.com/about/versions/oreo)

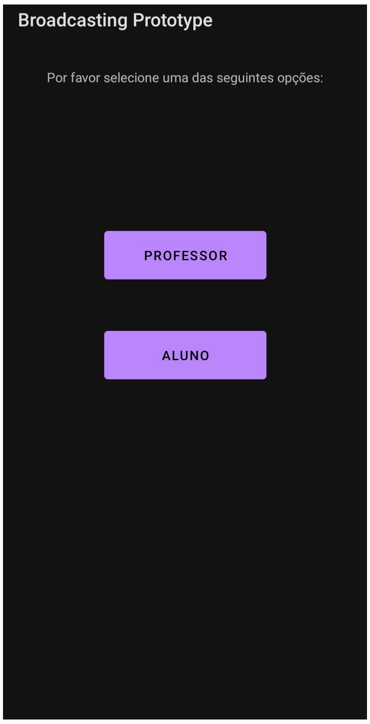


Figure 4.8: Home screen displayed after the application is started.

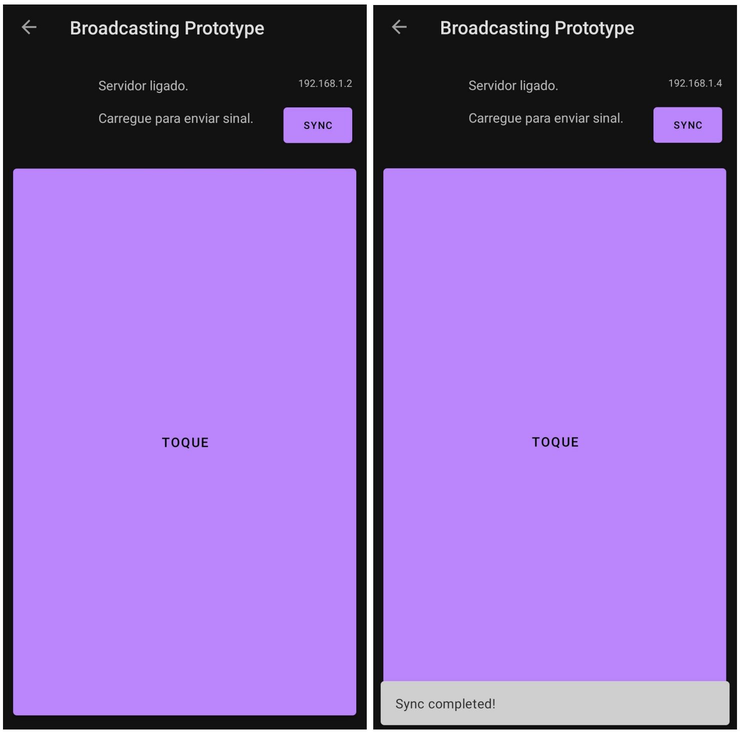
with the message "Sync completed!". The screen is pictured in Figure 4.9, both before the "Sync" button is pressed and after the synchronization is completed.

The navigation flow of the Student Activity differs from the previous prototype, since now there is no need to input any text, whereas in the previous prototype the user had to input the IPv4 address of the server. This leads to a simpler screen displayed. On the top centre of the screen there is a "Connection successful! Awaiting signal from the teacher" message, and below there is now only the "Duration" button, which when clicked still opens a popup window with different duration options for the vibration of the device. Just like with the *One-To-One Tap Vibration Prototype*, the screen of the Student activity of the *Broadcasting Information Prototype* also displays the popup window closing once an option is selected, and shows a popup message stating the duration of the vibration selected.

An example of the described navigation flow is shown below in Figure 4.10.

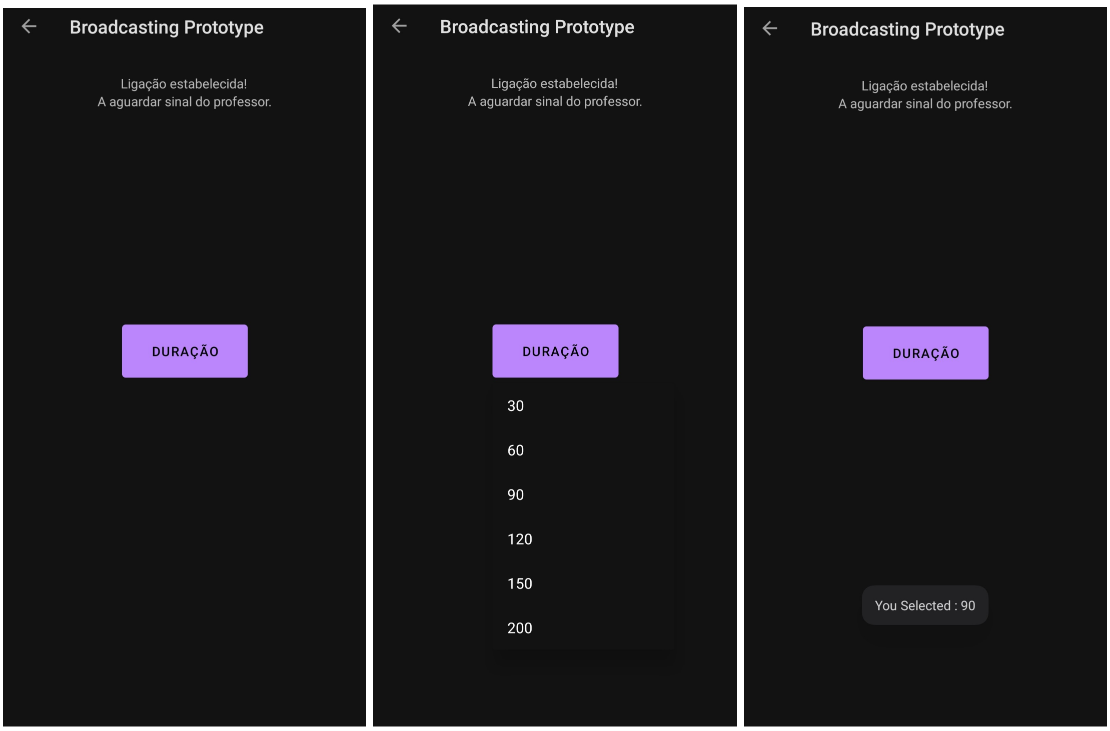
4.2.5 User Test

To conduct the formative testing of the *Broadcasting Information Prototype*, we scheduled a user test with Dr Rui Magno Pinto, the conductor of Filarmónica Enarmonia. The test was performed on 1st August 2022 at the Sociedade de Instrução Guilherme Cossoul, in Lisbon.



(a) **(b)**

Figure 4.9: (a) Teacher screen displayed after the "Teacher" option is selected; (b) Conductor screen displaying the popup message showing the synchronization process is finished.



(a) **(b)** **(c)**

Figure 4.10: (a) Student screen displayed after the “Student” option is selected; (b) Student screen displaying the popup window showing the different duration options; (c) Student screen with popup message showing the new vibration duration.

4.2.5.A Participants

For this test, we recruited four instructors of the Filarmónica Enarmonia musical ensemble, one of which was visually impaired and the other three were sighted persons. All the teachers were adults. Due to lack of availability and summer break, it was not possible to recruit any students to perform this test. However, we asked the instructors to perform the test as both teachers and students.

4.2.5.B Procedure

Before starting the test, we had to prepare the system. We plugged and connected the router, placing it on the centre of the room we were in. Then, we connected the three Android smartphones of our investigation team to the local network created by the router and checked if everything was set up correctly.

After that initial preparation, we asked one instructor to take the roll of the conductor and two instructors to take the roll of the performers. We then attached the two smartphones on the arms of the "students" and sent some signals to check if they could feel the vibration.

To start the test, we asked one of the "students" to follow a simple, slow tempo the conductor was sending by hitting a timpani drum with a drumstick. Then, we asked the conductor to instruct a faster tempo and have the student follow it the same way. When that student was finished, we asked the other student to repeat the same test as their peer.

After both students performed their individual tests, we asked them to try and follow the tempo together. The conductor sent a constant and slow tempo for the students to follow at first, but in the middle of the test the conductor was asked to accelerate the tempo without telling the students to see if they would follow the change.

Finally, the last part of the test consisted of both students getting the count-in for a musical piece and trying to start the performance at the same time. The conductor sent four vibrations, which is the count-in bar, and the students should start playing the song on the fifth vibration, entering at the correct time.

While the test was being performed, we took notes of observations and of immediate feedback the participants would say while testing the system. After the tests were performed, we asked the users for feedback regarding this prototype. We took notes of their feedback to further analyse the information shared.

4.2.5.C Findings

The test allowed us to observe the *Broadcasting Information Prototype* in practice being used by instructors of a mixed-visual ability musical ensemble in a controlled but natural environment. We retrieved important information by observing and conversing with the participants, while also getting constructive feedback regarding the prototype.

We analysed our notes in the same fashion as previously described in the same stage of the previous prototype, in section 4.1.5.C. We coded the notes, associated them with general themes, and created affinity diagrams [42, 43] in order to present the findings in a clear and direct way.

Practicality

The practicality of the Haptic Conductor remained one of our biggest focus points, and one that is very important for the users of the system. The solution must be comfortable, as to not disturb the musicians when they are playing their instruments, and it must be easy to use.

In terms of comfort, there were not any changes in the way the devices were attached to the body of the users. The smartphones were once again placed with nylon straps on the arms of the users, and that proved once again to be a comfortable yet malleable solution to wear where the user wanted to wear it, plus it was a very practical solution because we could manipulate them with ease.

Once again, we chose to use the Android smartphones of our investigation team because we realised that installing the application in the personal smartphones of the volunteers would only complicate an otherwise simple test and there was nothing to gain by doing that at this stage.

After explaining the system and the changes that were made between the first and the second prototype, the participants fully understood every functionality, letting us know that the system remained accessible to the target users. One of the aspects we want to guarantee in these tests is that the prototype is easily understandable and trivial to use, and the tests have been proving it is both.

The main difference between the test of the *Broadcasting Information Prototype* and the test of the previous prototype was the clock synchronization between the device of the conductor and all the devices of the musicians. After explaining what that feature is and what it offers to the system, all the participants found it to be a good feature and easy to use. Clicking the button and waiting until the notification confirming the process completion appears seemed to be a simple process for all of them, since no instructors had difficulties using the feature.

Overall, the results of the tests regarding the practicality of the prototype were promising, remaining on the same vein as the tests of the *One-To-One Tap Vibration Prototype*. No issues were found on this topic.

Functionality

The aim of this test was focusing on the new functionalities of the Haptic Conductor and understanding the functioning of the system on the proper environment with its target users. We had to assess how well the intercommunication between all the devices would work with the new UDP network, with the assistance of the router installed in the room where the test would take place. We had to observe how many packets would be lost during the test and how damaging their absence would be in a rehearsal setting.

Another issue we had to analyse during the test was the synchronization feature and how well it worked. The functionality of the entire prototype is reliant on the correct implementation of this feature. Without it, most of the messages would be lost on most devices due to the different times on each smartphone. Therefore, this was our main observation focus during this process.

First, the participants of this test all felt the vibration much better than they did on the first test, which was an important improvement since this was the main issue reported by the users on the tests for the first prototype. The difference was notorious, and we were able to begin the test right away. Also, no participant asked to change the placement of the smartphone, so every user had the device attached to their arm.

One participant had difficulties concentrating on the vibration in the initial stage. However, as the test went along, they overcame those difficulties and were able to follow every vibration without any noteworthy problems.

A positive note was that the time synchronization feature worked correctly. Before the conductor pressed the “SYNC” button, one of the receptor smartphones was not vibrating, meaning that all the packets it was receiving were being filtered out and ignored. When we inspected the issue, we noticed that that particular device was 1 minute ahead of the device of the conductor, creating a situation that presented itself as a good opportunity to test the synchronization feature to try and fix that issue.

When the conductor pressed the “SYNC” button, the time synchronization was performed, and they sent multiple packets to see if the problem was corrected. The receptor that was 1 minute ahead did in fact start to receive all the packets, correctly fixing the system and proving that the synchronization works and is essential to the correct performance of the Haptic Conductor.

A negative note was that multiple packets were lost during the tests. In any given stage of the test, we noticed that multiple vibrations were either not being received or being ignored, compromising the communication between the server phone and the client phones. We could not recognise a pattern of missing vibrations, since it seemed to happen arbitrarily. However, the number of missing impulses was not enough to prevent the participants from following the tempo the conductor was sending.

Both “students” were able to mark the tempo individually and to mark the tempo together. When it came to the final testing stage, the participants took longer to correctly begin their performance on time simultaneously. The silent count-in proved to require the participants to adapt their focus, plus it showed us that sometimes the first packet may be missing, which can lead to one student receiving the first vibration on the first beat and another student receiving the first vibration on the second beat. That is a problem because in the described case the second student will always begin the song one beat late.

However, after the first three tries the “students” were able to begin the song on time simultaneously. To prove its effectiveness, that test was repeated three other times and the students began the music piece correctly on all those repetitions.

Feedback

The UCD approach we took with this thesis work allowed us to have direct access to the feedback of the target users of the Haptic Conductor during the testing process. We took notes of the feedback received and we conducted a constructive conversation with the four instructors that tested the system. The notes were taken as to keep all important information that was shared.

The participants mentioned how much easier it was to feel the vibrations when compared to the tests of the *One-To-One Tap Vibration Prototype*. Although they still did not describe the vibration as powerful, they felt it had just the right strength to feel it properly when the strap is as tight as possible. When the strap was a little looser than that, they said the difference is immense and the vibration feels softer because it is not pressuring the arm enough.

Although the vibration was stronger and the instructors that participated in the test claimed that they could feel the impulses much better, they also argued that for the students it may be harder to feel the signals because many of them are still beginners and are not as comfortable playing their instrument as they are. That has an impact because it means that the students would be concentrating more on their performance rather than the vibrations they should be interpreting at the same time.

> *"For the students and especially the kids, it may be harder to respond to the vibrations because they have other things to focus on at the same time. Not that it is impossible, but I am sure that many of the children will have to adapt to the system before being able to use it fully."*

There was also mention of the issue of the missing impulses, which the instructors saw as a potential but surmountable issue for the students. While the tests proved that someone with the proficiency level of the instructors is able to correctly maintain the tempo that was being instructed while some vibrations are missing, they feared that some students might not be able to comprehend how to do so at an early stage. They did however believe that with some practice the students can overcome that fault.

When asked if they had any suggestions, the users mentioned that it would be a good addition to have a stronger vibration on the downbeat, i.e., the first beat of the measure. Given that the vibration was already at the maximum strength it could be, the instructors mentioned that maybe it would be a good alternative to send a different vibration pattern instead of a stronger vibration on the downbeat, so that the students would know every time a measure begins.

All the instructors told us that the found the *Broadcasting Information Prototype* to be significantly superior to the first prototype for various reasons. Unlike the *One-To-One Tap Vibration Prototype*, this one allows multiple students at a time instead of just one, plus the vibration is sensed much better, which is a major advantage. The main conductor of the mixed-visual ability musical ensemble, Dr Rui Magno

Pinto, also told us how much he thinks this version of the Haptic Conductor would help in a rehearsal setting and how useful he thinks it already is.

> *"This system already helps us teachers so much because we will not have to scream our instructions anymore in a rehearsal. We just proved it. I would conduct an orchestra with this system tomorrow, honestly."*

One of the instructors did mention that in an ensemble performance such as a concert setting, a conductor does not count the time during an entire musical piece because what drives the rhythm of the piece is the percussion section of the ensemble. Thus, it would also be helpful to use the Haptic Conductor only on the drummer in a concert setting so that the rest of the musicians can focus only on their playing, since many of them are beginners as previously stated. The instructor also said that it is possible because the pieces played by the ensemble are still very basic and they don't require any tempo changes mid song or other complex dynamics.

The participants reiterated the potential they see in this solution and how much they want to try it with their students in the final test to see how they react and behave when rehearsing with the Haptic Conductor.

4.2.6 Discussion

After the development and testing of the *Broadcasting Information Prototype* with a mixed-visual ability musical ensemble, we assessed all the information we received during every stage of the process. The observation and feedback received allowed us to plan and prepare the final user study in the best way possible.

The UCD approach once again proved to be valuable. Using all the feedback we received during the tests of the first prototype, we were able to improve the Haptic Conductor and develop a better overall solution, as stated by the instructors who were involved in the testing process.

This time, the intercommunication between the smartphones relied on a UDP multicast approach. The tests showed us that it did not provide a data stream as reliable as the one we had with the *One-To-One Tap Vibration Prototype*, since many messages were lost throughout the testing and it had to work in conjunction with a synchronization feature to compensate for some of the delays this approach inevitably brings. However, the participants approved the functionality as it was, given that still most of the vibrations were received in as close to real-time as it was possible, and the ones that were not, should not jeopardize the correct utilization of the Haptic Conductor.

Regarding the vibration feature, the tests proved that the increase in strength was noticeable and that all the instructors had little to no problem feeling them correctly. This was a major improvement from the first prototype where many participants reported they struggled to feel the vibrations.

The time synchronisation feature was key to the good functioning of the Haptic Conductor at this stage, and it when tested it proved to be successful as well. The instructors did not have any difficulty comprehending or using the feature, immediately understanding its purpose and when to use it without any assistance other than our introductory explanation. That is important because it shows us that the conductors will have no trouble remembering to use this feature in a real-world, uncontrolled environment.

As was the case with the previous prototype, the tapping feature was efficient and easy to perform. It did not tire the conductors, nor did it present them with any issues.

The *Broadcasting Information Prototype* served as the natural development of the *One-To-One Tap Vibration Prototype*, improving its functionalities and correcting some of the issues that were reported, resulting in the best solution we developed.

4.3 Summary and Final Discussion

In this section, we discuss the development of the Haptic Conductor, summarising the process and describing the final prototype that we used for the User Study.

The Haptic Conductor system was developed in two different stages, resulting in two prototypes developed iteratively using an UCD approach: the first prototype *One-To-One Tap Vibration Prototype*; and the second prototype *Broadcasting Information Prototype*. The features of each prototype were described in this section, along with the user tests performed to validate each one of the prototypes and their results.

From the beginning of this thesis work, we emphasized how important it was for us to develop the Haptic Conductor using the UCD approach. This technique allowed us to get notes and opinions from the target users of the system in each stage of the development process. After each prototype was developed, we conducted formative user tests to obtain their feedback. With the members of the mixed-visual ability musical ensemble involved in the design process of the Haptic Conductor, we were able to achieve a more functional and inclusive system than we would have been able to achieve without their feedback.

After the last formative tests, we validated the features of the *Broadcasting Information Prototype* with our observation and the feedback of the users. It proved to be a functional, intuitive and practical system.

The *Broadcasting Information Prototype* was therefore assigned as our final prototype and the system we were going to use to perform the final user study.

The architecture of the final prototype of the Haptic Conductor consisted of one smartphone for the conductor and multiple smartphones for the performers, one for each. All the smartphones are connected through a local network, established by a router. All the devices exchange data through an UDP multicast network, which assures that one device can send messages that will be received by multiple receivers, which in our case means that the instructor can send the same message in real-time for all the students simultaneously.

In order to avoid the reception of delayed packets, we had to implement a functionality that filtered out all the packets that were not received within an acceptable time interval. However, most smartphones have clocks that run at slightly different speeds, which prevents us to filter the packets without having to coordinate the time of all the devices prior to the utilization of the system. Therefore, the Haptic Conductor features a time synchronization functionality, which allows the conductor to synchronize all the clocks before the ensemble starts a musical piece.

Using the synchronization button, the instructor sends multiple packets containing the current timestamp of the sender to the receptors. After receiving each packet, the smartphones of the students will calculate the difference between the timestamp received and their own time, which is the offset. When the host stops sending synchronization packets, the receptors then calculate the average offset. Having that value, the device can obtain the real delay, which will be used to filter out all the packets received with excessive delay.

When the packets are received within the allowed time range, the receptors vibrate, with each vibration representing a beat marked by the conductor. The vibration was set to the maximum strength allowed by each device, while its duration can be changed by the user to better suit their preference.

Finally, with the development process summarized and the final prototype describe, we advanced to the final user study to test the system in a real-world mixed-visual ability music ensemble setting.

5

User Study

Contents

To properly evaluate and validate the Haptic Conductor system, we designed and conducted a user study that was performed through the course of three different sessions. These sessions were proposed to evaluate the practicality and the effectiveness of the system in a real-world scenario, with members of a mixed-visual ability musical ensemble as participants, both conductors and performers. The user study was also important to explore different utilizations of the Haptic Conductor and identify its benefits and limitations in a real-world environment.

In this section, we expose the research question we aimed at answering during the user study and explain the study process, detailing the participants of the test, its apparatus and procedure. We then explain how the data retrieved was analysed and assess all the findings we obtained from the performance of the test. Lastly, we discuss the results and the answers to our questions, concluding the user study process.

5.1 Research Questions

The main objective of this study is to test whether the Haptic Conductor can help incorporating visually impaired musicians into a mixed-visual ability musical ensemble setting. In order to do that, we had to define the Research Questions (RQ) that should be answered by the findings obtained in this study. The questions are:

- **RQ1:** What is the impact of the Haptic Conductor on the rehearsal practices, both for the conductor and the musicians?
- **RQ2:** What are the advantages and disadvantages of the Haptic Conductor? What are its benefits and limitations?
- **RQ3:** How is the user experience using the Haptic Conductor?
- **RQ4:** What is the potential of the Haptic Conductor?

5.2 Participants

The Haptic Conductor is a system designed to be used by visually impaired members of mixed-visual ability musical ensembles and their instructors. We collaborated with Associação Bengala Mágica[1] and Filarmónica Enarmonia[2] throughout this thesis work, and with their help we managed to recruit members of the musical ensemble to participate in our final user study.

[1] Bengala Mágica (https://bengalamagica.pt/)
[2] Filarmónica Enarmonia (https://gulbenkian.pt/projects/filarmonica-enarmonia/)

Since Filarmónica Enarmonia consists of approximately 20 musicians, we had to select which musicians would participate in the study, and for that we asked for the assistance of the instructors to help us select which musicians they thought would be best suited to perform the test. We ended up selecting musicians that played different instruments from each other with different levels of skill. Although most students that participated were beginners still learning the fundamentals of their instrument, two of the participants recruited were at a higher level of expertise.

In total, we recruited 6 visually impaired musicians and 2 instructors to perform the tests. All the relevant information of all the participants is displayed in the table below.

Table 5.1: Information of the participants of the user study.

Role ID	Participant ID	Demographics			Musicianship	
		Age	Gender	Visual Ability	Instrument	Playing Level
C	1	42	Female	Sighted	-	
C	2	32	Female	Sighted		
P	1	11	Female	Low vision	Clarinet	Beginner
P	2	10	Male	Low vision	Percussion	Beginner
P	3	27	Male	Blind	Percussion	Advanced
P	4	10	Male	Low vision	Trumpet	Beginner
P	5	44	Male	Blind	Tenor Saxophone	Intermediate
P	6	32	Female	Blind	Soprano Saxophone	Beginner

The ID of the participants is composed by their Role ID and their Participant ID. For example, to refer the first conductor participant we used C1; and, to refer the second performer participant we used P2. From this point on, all the participants were referenced by their assigned ID to maintain their confidentiality.

Three of the musicians were young children between the ages of 10 and 11 years-old (P1, P2, P4), while the other three were adults (P3, P5, P6). All instructors were sighted adults (C1, C2).

The instructors were present for all the sessions and all the performers were present for the two first sessions of the study. However, the only performer present for the final session was P6, along with both instructors. The work of the third session was done remotely with the performers who were absent.

5.3 Apparatus

To perform the user study, we had to assess what materials were needed and how they were going to be used. This section described these materials and their usage in the user study.

For this study, we needed one Android smartphone for each participant with the Haptic Conductor application installed. We asked the participants who had smartphones with the Android operating system for permission to install the application on their devices, and the participants who do not have an Android smartphone were provided with one of our investigation devices. A separate smartphone was used to photograph record both the audio and video of the participants testing the system at different stages. To attach the devices to the body of the performers, we used a nylon strap per musician.

To install the application on the smartphones and to make changes to the application when/if necessary, we used a Windows 10 laptop with the Android Studio program. The application was installed by connecting the devices to the laptop via USB, which means we needed two USB cables: one micro USB cable that is generally used in older Android smartphones; and one USB-C cable, which is used in more recent devices. An extra USB-C cable was used to simultaneously connect two devices to the laptop along with a USB power adapter to charge the battery of any smartphone that needs it.

To establish the local network and connect all the devices, we used a TP-Link TL-WR840N router, along with an ethernet cable to connect it to the laptop if we had needed to make any changes to its configuration.

Besides the interviews recorded on location, we had to conduct interviews remotely with the participants that were unable to be present for the last session of the user study. Those conversations were conducted through e-mail, WhatsApp[3] and Zoom[4].

5.4 Procedure

In this section, we report the procedure of the user study, describing the goals and course of action for each session.

The user study was conducted in three different sessions, performed on separate days. The 1st session was conducted on 24th September 2022; the 2nd session was conducted on 8th October 2022; and the 3rd session was conducted on 15th October 2022. All three sessions were conducted at the Junta de Freguesia de São Domingos de Benfica, in Lisbon. Each session took place in a room with only our research team and the participants, while the other members of the musical ensemble were having their regular rehearsal on different divisions of the building. It was important for the participants to not get distracted by their peers rehearsing so that they would be fully concentrated on their test tasks.

The duration of the sessions varied, with the 1st session lasting about an hour, the 2nd session lasting about two hours and thirty minutes, and the 3rd session lasting an hour and a half. That was the case because every session had different goals and procedures. The procedure of each of the sessions is described below.

1st Session

Unlike the previous formative tests performed, on the final user study we proposed to install the Haptic Conductor application on the Android smartphones of each participant. Since that can be a long process that reveals noteworthy problems, we assigned the 1st session of the user study to perform the

[3] WhatsApp (https://www.whatsapp.com/)
[4] Zoom (https://zoom.us/)

installation of the application on the devices of the participants. This session also functioned as the introduction to the user study.

Since the participants were already familiarised with this thesis work from the previous observations and formative tests, there was no need to introduce ourselves or the goals of the system. However, we explained to them the final system we designed and the tests we intended to perform with them, so that every participant is aware of what is expected of them and agrees to ultimately participate in the study.

We then asked all the participants who had an Android smartphone if they allowed us to install the application on their smartphone, which all agreed to do. However, many of the members of the ensemble had iPhone[5] smartphones, and since our application only runs on Android devices, their personal smartphone could not be used. Nevertheless, they were assured that even if their personal device could not be used, we would provide them with an Android device so they would still be able to participate in the study.

To install the application on an Android device, we had to first enable the access to the developer options[6] by opening the Settings app, selecting “About Phone” and tapping the “Build Number” option seven times. When that is done, a popup notification shows up on the bottom of the screen signalling that the developer options are now available. To access them, we choose the option “System” and “Advanced”, and there we select “Developer Options”. For Android 8.0.0 and Android 8.1.0 the “Developer Options” menu is available after “System”.

To allow an application to be installed via computer, we must enable USB debugging on the “Developer Options” menu. After toggling the USB debugging option, a warning message appears cautioning the user to not install any application from an unverified device. After that option is activated, the device is ready to install the application. The procedure described varies depending on the brand of the smartphone and the Android version.

This procedure was performed for each personal smartphone of the participants with them present so that they were informed of what is happening in real-time on every step of the way. When the application was successfully installed in a smartphone, we tested if it vibrated when another smartphone sent a “Tap” through the Haptic Conductor to be sure that it was working properly.

During the session, we informed the participants that we needed their permission to install the application on their personal phones and to record them and take photographs of them. For that reason, we gave them a consent form with detailed information about the study and asking them for their consent to conduct the tests. Since most participants were visually impaired, all the users chose to consent through voice, audibly agreeing to the terms of the test while being recorded. Nevertheless, the consent form was given to all the sighted participants. We also told them to reach out to us if they had any questions regarding the tests.

[5] iPhone (https://www.apple.com/iphone/)

[6] Android Developer Options (https://developer.android.com/studio/debug/dev-options)

After the session was finished, we explained the tests we planned to conduct during the next session and asked them to bring their smartphones charged if possible.

2nd Session

After installing the application on the personal Android smartphones of the participants in the 1st session, we were ready to advance to the proper tests of the user study. Those began in the 2nd session of the user study.

We began by preparing the system, setting up the laptop and the router and verifying if it is configured correctly. Since we did not make any changes to the application, there was no need to reinstall it on the devices. With the logistics all set up, we discussed with the instructors which students should participate in the study, trying to balance experienced participants with beginners and adult participants with children. We also wanted to include both low vision and blind participants to measure if the experience was different for different visual impairments. Finally, we also discussed having students from different instruments to verify if the instrument of the musician impacts the system effectiveness.

We ended up selecting the 6 performers mentioned in section 5.2. We grouped 3 children (P1, P2, P4) with three adults (P3, P5, P6). All children were beginners; one adult was a beginner (P6) while the other two were more advanced (P3, P5). P1, P2 and P4 are all low vision persons, while P3, P5 and P6 are blind persons. The group of students selected covers different instruments: P1 plays the clarinet; P2 and P3 play percussion; P4 plays the trumpet; and P5 and P6 play saxophone, tenor and soprano respectively. This information is reported in Table 5.1

When the performers were selected with the help of the instructors, we gathered all the participants on the room where the tests were going to be conducted. Even though they all were already familiar with the goals and operation of the Haptic Conductor, we recapped what the system does and what we believed it would achieve before starting the test. While talking to them, we connected all the smartphones to the wireless network named “Enarmonia”, which was the local network established by our router. That assured that all the smartphones were connected to the same local network and allowed the system to work correctly. Then, we asked them if they had any questions and once those were all answered we began attaching the smartphones to the participants.

We started by asking them if they wanted the device attached to their arm and they all agreed. We then started fastening the device to their arm with the nylon straps until it was tight enough for the smartphone to be secure and pressured enough against the arm of the participant without ever hurting them. We made sure no strap was too tight by asking the participants if they were comfortable throughout this process.

After a participant had the smartphone attached to their arm, we sent a test signal to their device to test if they were feeling the vibrations correctly. If they told us they could not feel the vibrations, we would try and tighten the strap even more. If after that they still could not feel the vibrations, we would ask

Figure 5.1: Participants during the preparation of the test.

them where they think they would feel it correctly and propose switching the place where the smartphone was attached, proposing for example the thigh or the ankle, since both of those were reported as more sensitive body parts for some participants on the formative test of the first prototype, as described in section 4.1.5.C. After that, we tested once again if they felt the vibration correctly. This process was repeated until we found a place for each individual where they felt the vibrations effortlessly.

When all the participants reported they felt the vibrations without issue, we started the testing process. We selected the “Student” on all the smartphones assigned to the students and asked the instructor to select the option “Teacher”. When all the smartphones were on their respective screen, we asked the teacher to try to send some signals to the musicians. When they did, most musicians did not receive the vibrations due to the clocks of the devices being out of synchronization. The reason we asked them to do this was for them understand why it is imperative to synchronize all the devices before beginning using the system.

Once they realised how crucial it is to synchronize all the clocks of the devices, they were asked to press the “SYNC” button and wait until the screen showed a popup saying the synchronization was completed. After that happened, we asked the instructor to try once again sending the signals and verifying if all the students received them. Once that is assured, we move on with the test.

The first test was to ask the students individually to try and follow a simple rhythm that is sent by the conductor by smacking the table on each beat of the tempo. The goal of this test is to assure that every student can follow a simple rhythm before increasing its complexity. Each participant was asked to smack the table to mark the tempo they were receiving, and if they failed, they got to try again until they were able to do it correctly, getting used to the vibrations in the process. When all the students were able to correctly perform that first test, we once again asked them one at a time to follow a rhythm sent by the instructor, this time at a faster tempo.

When that first test was concluded, we again asked the performers to individually mark the tempo the instructor was sending them. This time however, the instructor started with a slower tempo and midway through would accelerate without warning the participants, to verify if they were able to follow the tempo modifications without any audible notice. The participants were allowed to repeat the process until they were able to perform it correctly, like on the previous test.

The next test was individual once more. Each performer was asked to play the musical piece they know best or feel the most comfortable playing after a count in from the conductor. A count in is the cue a conductor gives the musicians, so they all start playing at the same time, usually consisting of one or two bars. Usually, the count in is visual or audible, but for the sake of our system we asked the conductor to perform it silently, using only the vibrations of the Haptic Conductor. Each student performed that test individually.

Finally, the last test was similar to the previous one, where the conductor instructed a count in through the vibrations of the smartphones, without any audible cues. However, for the final test we wanted to fully test the ability of the Haptic Conductor in a group setting. Therefore, we asked all the performers to try and begin the song they felt most comfortable playing as a group at the same time. Since this is a new way to play and rehearse and they are not fully accustomed to focus on the sensation of the vibrations on their body, we had no issue allowing them to repeat this test as much as they wanted until they were more comfortable with the system and were happy with the result.

When the rehearsal of the ensemble ended, our test session ended as well. We thanked all the participants for their time and availability and explained to them what we were planning to do on the third and final user test session.

3rd Session

With all the tests performed, we wanted to better understand the experience of the users while using the Haptic Conductor. With that goal in sight, we designed a 3rd session of the user study where we performed the last test of the 2nd session again, in order to have the utilisation of the system fresh in the minds of the participants. After that, we conducted a semi-structured interview with the participants to gather their feedback and notes they wanted to share regarding their experience with the Haptic Conductor and its impact in their playing and rehearsal environment.

We aimed to conduct the interview collectively, with every participant present in the room simultaneously. However, due to personal reasons, only one performer that participated in the two sessions of the user study was present to be interviewed and all the other students were absent. On the other hand, all the instructors were present as well. In order to obtain the feedback from the other participants that were unable to attend this last session of the user study, we managed to speak with them through WhatsApp.

Our interviews with the participants present were recorded in audio format and the interviews with the

Figure 5.2: Participants using the Haptic Conductor while performing a test.

participants that were absent were recorded in text format to further analyse the information retrieved.

5.5 Data Collection and Analysis

In this section, we present our methods of data collection and analysis.

In the 2nd session of this user study, we recorded video of parts of the test, and in the 3rd session we recorded the audio of the interviews we conducted. The remote interviews were recorded via text. Plus, we took notes of noteworthy data and feedback the participants gave us throughout the entire user study process.

The data collected from this user study went through a qualitative analysis, where we sought to answer the RQ we defined previously in section 5.1 by analysing our observations and interviews with the participants.

To better analyse the qualitative data we retrieved from both our observations and the interviews we conducted with the participants, we gathered all the data we obtained and analysed it using affinity diagrams [42, 43]. We then coded the data and assign each code to a respective label. Then, by comparing codes, we defined the groups that will encompass all the data. This way, the information is organized in an intuitive manner.

We ended up dividing the data we retrieved into three different groups: (1) User Experience; (2)

Functionality; and (3) Impact of the System. The three groups are explained below.

User Experience. In order to evaluate the comfort and practicality of the Haptic Conductor, we collected feedback from the participants in the interviews by asking them questions about their overall experience as users. These interviews included question regarding their comfort and if whether using the system interfered with their instrument playing in a negative way. We also analysed our notes of our observations throughout the tests to obtain more information regarding this topic.

Functionality. To evaluate the overall effectiveness and functionality of the Haptic Conductor, we analysed our previous observations of the system being used and the feedback we received during the practical tests in informal conversation with both the instructors and the students. To complement these notes, we also included questions on the semi-structured interview with the participants regarding the functionality of the Haptic Conductor, seeking to understand the advantages and disadvantages and the benefits and limitations of our solution from the point of view of an instructor and of a visually impaired musician.

Impact of the System. It is important for the validation of our solution to expand our analysis and try to understand the current impact of the system as well as its future potential. Since we had the opportunity to test the system with members of a mixed-visual ability musical ensemble, we had access to the point of view of the target users of the Haptic Conductor. To make use of that privilege, we questioned the participants during the interviews regarding their view of the impact the system had in the tests we performed with them. We also asked them their opinion on how much potential they see in the Haptic Conductor and how much such a system can impact their rehearsals and concerts as instructors or as visually impaired musicians.

5.6 Findings

The qualitative data we retrieved from the user study was analysed. In this section, we showcase the findings of our user study. The findings are organised by groups, as described in the previous section 5.5.

5.6.1 User Experience

Throughout the entire development process of the Haptic Conductor, one of our main focuses was on the practicality, intuitiveness and convenience of the Haptic Conductor. As such, the user experience has always been important to us since the moment we began this thesis work. The Haptic Conductor must be easy to use and comfortable, as to not disturb the musicians when they are playing their instruments. It also must not disturb the conductor while instructing the ensemble in a rehearsal or live performance.

The installation of the application itself was challenging because of the many different brands of Android smartphones there are and the many different versions of Android. To install the application, the method varies from brand to brand and Android version to Android version, which complicated the process. An issue was that many of the young participants that had personal smartphones of their own had parental control active on their device, which prevented us from installing the application. To correct this issue, we had to ask their parents to disable the parental control so that we could access Developer Options and install the application.

Other issue, particularly on Xiaomi[7] smartphones, was that to toggle the option "USB Debugging", the user had to be logged in to their Mi account. The users that did not know their Mi account had to retrieve it or create a new one so that the application could be installed. Overall, the installation process was more complicated that we could have predicted, and showed us that in the future we should approach the installation of the application differently.

All the smartphones were attached to the body of the student participants the same way they have been since the first formative test of the *One-To-One Tap Vibration Prototype*, described in section 4.1.5.C. **The nylon straps we used proved again to be a flexible and practical solution** because they could tighten regardless of the size of the performer or the part of the body where it was placed. Since we had both children and adults as participants on our user study, we had to guarantee that we could attach the smartphones on every participant, and the nylon straps were malleable enough and comfortable for every musician regardless of where it was placed. The percussionist P3 detailed his experience:

> *"The straps were very comfortable, they did not hurt my arm whatsoever. I felt that the phone was secure the entire time because the strap was tight, but not tight enough to bother me." - P3*

The placement of the smartphone proved once again to be a matter of personal preference. While we began the test by placing the device on the left arm of all the participants, we were capable of changing the placement of the device very quickly whenever it was needed.

Four of the students (P1, P4, P5, and P6) did not feel the vibration on their arm and asked us to change the placement of the smartphone. When we changed it to the leg, one of the participants (P6) claimed to feel the vibration much better. However, it did not help the other three. The performer P5, who also was in that situation, suggested placing the smartphone on the back thigh, almost sitting on top of the device. When we tried his suggestion on him, he reported that he could feel the vibrations perfectly.

We then suggested to participants P1 and P4, who did not feel the vibrations properly on neither their arm nor their leg, to follow the suggestion of their peer and placing the device on their back thigh. Both P1 and P4 reported the same as their peer, saying they could feel the vibrations correctly with that placement. This situation suggests that the **thigh may be a more sensible part of the body for**

[7] Xiaomi (https://www.mi.com/global/)

some people and that the added pressure of the weight of the body along with the pressure of the nylon strap helps the users feel the vibrations of the device.

Another factor that influenced the placement of the device was the members each performer used to play their instrument. The system cannot disturb the playing of the instrument, it must assure that the musician is capable of both using the system to its full potential and play their instrument without issues. P6, a soprano saxophone student, explained that phenomenon during our post-test interview as quoted below.

> *"Since my instrument [the saxophone] has to be projected to the air, which means that I must have my arms raised, placing the phone on my leg does not bother me at all. I only use my arms and neck when playing, and since my legs do not move, there is no problem placing the phone on my leg." - P6*

All the participants understood every functionality of the Haptic Conductor without any issue and told us that they found the system easy to comprehend and use. While the students only needed to connect the phone to the correct network and press the option "Student", the instructor had more functionalities to understand, but **all the instructors claimed that the system was intuitive and that they did not have any difficulty understanding what to do**.

The most challenging feature was the clock synchronization because on most tries the instructor forgot to press the "SYNC" button before beginning the test, which resulted in many students not receiving the vibrations and not realising why that was. However, as the study went on, the instructors began remembering to synchronize the clocks more often and claimed that with enough practice and usage they will remember to synchronize the clocks of the devices every time.

The feature itself was easy to understand and perform, since all the participants realised that after the button is pressed, they had to wait for the notification confirming the process completion. That seemed to be a good method to let the instructor know that the synchronization is complete, and they can proceed with the exercise.

Overall, the results of the tests regarding user experience were a success for the most part, proving **the Haptic Conductor is an easy system to learn and use**, and that it is not complicated to set up. That means that it is an accessible solution, which was a priority of ours since the beginning of this thesis work.

5.6.2 Functionality

The final user study helped us not only analysing the user experience but also assess the functionality of the Haptic Conductor. The system must be able to function properly in its entirety to be useful for a mixed-visual ability musical ensemble. So, we had to assess if every feature was working properly.

During the installation process, we verified if the application was working correctly on each smartphone right after installing the application. On most Android smartphones it worked without any issues. However, the application did not work properly on Huawei[8] devices. The two Huawei devices on which we installed the Haptic Conductor application could send impulses to other phones, which would vibrate as expected, but the opposite was not possible, i.e., the Huawei smartphones would not vibrate when receiving the multicast packets as the other devices do. However, we could not fix this issue and we have to address this issue as a limitation of our system.

A feature we had to analyse was the clock synchronization between the smartphone of the conductor and all the smartphones of the musicians. This feature is key to a good system performance because without it many of the smartphones will not be able to receive the intended signals and will not vibrate due to the different times on each smartphone. Therefore, this was a major topic during our user study.

By having the instructors send the signals without synchronizing the clocks in advance, we and the other participants realised that most of the smartphones did not receive the intended signals. That was due to the clocks being out of synchronization. To test if the feature was working correctly, all there was to do was to have the instructor press the “SYNC” button and verify if the issue was corrected or not. Fortunately, after pressing the button and the message saying the synchronization was completed appeared, the instructor sent the signals and all the performers received the impulses, proving that the feature works as expected.

Regarding the intercommunication between the devices, the issue of missing packets persisted, even after the synchronization was completed. Since the communication between devices is established in a UDP network and the packets are exchanged via multicast, we cannot guarantee that every packet is received in real-time, and the test showed us that many packets were lost during the tests. That was the case as well on the formative tests of the *Broadcasting Information Prototype*, described in section 4.2.5.C. In that test, the missing packets proved to not be a problem because the participants could easily follow the tempo even with missing vibrations because they were at a higher expertise level than all the musicians of the ensemble.

A difference from that test was that in this user study we had multiple participants that were beginners and were not used to follow the vibrations as their tempo cues. The children had the most trouble following the vibrations because they found it hard to concentrate on both the vibrations and playing their instrument at first. Nevertheless, they were able to improve as the test went by, reinforcing that this issue may be surpassed with enough practice.

> *“It is a matter of habituation. That is, instead of being focused on a clap or a snap, we have to learn to be focused on a vibration on the body, which is a much more subtle cue.” - P6*

However, the missing packets proved to be an issue to the beginners during this user study, partic-

[8] Huawei (https://consumer.huawei.com/pt/)

ularly during the count in. When the vibrations failed in the middle of a musical piece, the students did not stop, nor did they spoil the correct tempo. They continued playing in the correct tempo throughout. The real issue is when the vibrations fail during the count in and the first couple of bars of the song. Since they are beginners and, in most cases, inexperienced when it comes to playing an instrument, they are not capable to obtain the correct tempo if some beats are missing from their cues, unlike their more experienced peers. A beginner participant explains this issue with the quote below.

> *"When the vibration fails it is very difficult to use the system. Maybe it is a matter of habituation as well, but since we are still learning it is hard for us to follow a rhythm if some vibrations are missing, particularly in the beginning." - P5*

On the tests where few if any of the vibrations were missing, all the participants were able to follow the tempo the instructor was giving them, proving that if there is a way to ensure that all the vibrations are received the system will be easier to use.

An instructor suggested cueing the first and second beats of the count in out loud along with the vibrations, helping the performers assess the rhythm with an audible cue and following the vibrations more accurately after that. They also ensured that cueing the first two beats audibly would not be an issue for them. When we tested their suggestion, we concluded that it did help, because there seemed to be a higher tempo accuracy than there was without the audible cue. However, the improvement was not significant enough to be considered a definite solution to the missing packets issue.

Another suggestion was regarding a potential use of the Haptic Conductor on a concert setting. An instructor told us that in a concert setting, the entire ensemble follows the lead of the percussionist to maintain the rhythm of a piece, therefore we could ponder only having the percussionists use the Haptic Conductor in a concert setting, leaving the students to be more focused on their instruments instead of having to concentrate on vibrations as well. We did not test this suggestion, but it was noted as a potential future test.

Regarding its functionality, the Haptic Conductor is not perfect. Although there is the issue of some packets not being received by the students, that did not seem to be an impediment to the usage of the system. Both the instructors and the students share the opinion that that issue can be overcome by enough practice using the system and perhaps by an audible count in. But, besides that issue, **the Haptic Conductor functions correctly and is already a solution the participants would like to use in their rehearsals or concerts**.

5.6.3 Impact of the System

Collaborating with the Filarmónica Enarmonia on the user study, we were able to obtain feedback on our system directly from members of a mixed-visual ability musical ensemble, both from instructors and students. That feedback is especially valuable when discussing the impact of the system or its potential in the future, since only they experience what it is like to participate in such an ensemble.

We, as outsiders, can observe the differences between a typical rehearsal of the ensemble and a rehearsal in a controlled environment, such as the one we had on our user study, with the utilization of the Haptic Conductor. However, we cannot fully understand the difference a system like this makes on the functioning of the ensemble because we are not members of the ensemble, nor do we know what is like to be a visually impaired musician. Therefore, on this topic the feedback of the participants is especially great.

From the point of view of an outsider, the rehearsal seemed to become less confusing with the Haptic Conductor than what we witnessed in the previous rehearsals we attended, described in section 3.3. The instructors seemed to agree with our observation.

> *"During this tests we shouted a lot less than we are used to do. That does not mean that we can conduct an entire rehearsal in silence, but if the system can help us transmit information without having to shout that is already good. We can have a quieter environment that way." - C2*

> *"It is a relief to not have to be shouting all the time. At least we can end the rehearsal without losing our voice." - C1*

The instructors also reported that they did not feel fatigue using the system, since the tapping of the screen did not feel difficult or tiresome to them. That is an important note because the system would not be completely accessible if it demanded the instructors to perform complex or tiring motions. This way, it remains simple to use.

The participants affirmed that they see a potential positive impact of the current version of the Haptic Conductor on their musical ensemble. They claim that although it is not perfect, if they were to use the Haptic Conductor in a rehearsal or in a concert it would already be useful, particularly in the part of the rehearsal where the students are grouped by instruments because the groups are smaller.

> *"The system would already help us rehearse in the instrument groups, with less noise distracting the other groups. We would not be disturbing the instructors of the other groups and we would be able to control our own group better. - C2"*

During the interviews, we also asked the participants if they see potential on the system and if it should continue being developed in the future, to which all the participants answered positively without exception.

All participants, both instructors and students, stated that the system would already help their situation, therefore the potential of the Haptic Conductor in the future is great. An instructor shared her point of view during their interview.

> *"The system has a lot of potential, without a shadow of a doubt. There is still a lot to explore, and maybe with more time the system could have other features, but what we have is already helpful. It has potential and we should continue investing in this system." - C1*

From the point of view of a novice student, the potential they see is the same as the one shared by the instructor in the quote above.

> *"It should be improved, particularly the issue of the missing vibrations, but even with that it is already helpful and it should be continued because it has potential to change our group for the best." - P6*

With all this feedback, we realise that every participant agrees that they see great potential for the Haptic Conductor. Although they all concur that it can be better, they **unanimously say that the current system is already helpful to their group environment and that it should be continued**.

5.7 Challenges and Limitations

As described in the previous section, the user study revealed limitations of the system that must be noted in this thesis work.

As stated by the various visually impaired participants, most blind individuals use iPhone smartphones rather than Android smartphones since the screen reader functionality is considerably better on iPhone devices. That means that most of the members of the mixed-visual ability musical ensemble cannot use the Haptic Conductor on their own smartphone because the application is only supported by Android devices.

Installing the application on the devices of the users directly from our research laptop also proved to be a challenge because it required the users to change the settings of their device, which should not be a case in an accessible system.

While testing the system, we also realised that Huawei smartphones do not receive the vibrations as intended. While they could send the vibrations, they could not receive the impulses the other phones sent. While we know that is a security feature of the Huawei devices, we could not find a way to fix this issue, which is why it is a limitation of the Haptic Conductor. Another limitation of the system is not being able to manipulate the strength of the vibrations for every Android smartphone with an operating system below Android 8.0.

Finally, another limitation is the system not being able to prevent losing packets during its utilization. Even when synchronized, the system does not guarantee a continuous data stream and many vibrations are not received, either because the packet arrived too late or because it did not arrive at all. Even though the instructors reported that the number of packets lost was not impeditive of the correct usage of the system, it still is an issue to many beginners at an early stage. Since we could not find a way to work around this issue, we must note it as a limitation of our system.

5.8 Discussion

In this section, we took into account the findings described in the previous section and discussed how we can answer the RQ we defined in section 5.1.

RQ1: What is the impact of the Haptic Conductor on the rehearsal practices, both for the conductor and the musicians?

The information we analysed in the previous section allowed us to better understand what impact the participants felt while using the system. From the point of view of the conductors, they found that the Haptic Conductor impacted the rehearsal by transforming it in a quieter and more controlled environment, explaining that with the system they do not feel the need to shout continuously the instructions, nor do they feel the need to clap to mark the tempo, which is tiresome for them. With the Haptic Conductor, the instructions are sent silently through vibration to the musicians, which is an improvement when compared to their current environment.

From the point of view of the performers, the impact they felt the most was the same as the one mentioned by the instructors. The performers felt they did not have as many distractions as they do usually in their typical rehearsal setting.

The instrument played by the participants of our user study did not influence the impact of the Haptic Conductor, since it was positive for all the participants, regardless of their instrument. What did influence the impact of the system was the musical level of the participants, since it was more difficult for the novice students to adapt to the vibrations. However, the impact was still positive and all the members agree that with enough practice the novice students will take advantage of the system the same way their more advanced counterparts do.

Overall, all the participants stated how impactful the system already is, while stating that they feel the Haptic Conductor can be even more effective in the future if it is continued.

RQ2: What are the advantages and disadvantages of the Haptic Conductor? What are its benefits and limitations?

Overall, our results show that **the advantages of the Haptic Conductor far outweigh its disadvantages**. Our system successfully allowed the instructors to mark the tempo by tapping their screen and sending vibrations to the students, and they unanimously agreed that that feature is a major advantage of the Haptic Conductor. No disadvantages were reported by the participants of the user study, as they agreed the system only improved their experience, not worsening it in any sense.

The benefits of the Haptic Conductor according to the participants of the user study consist of **being**

able to communicate the tempo of a musical piece silently, allowing the instructors to conduct the group of musicians in a more controlled manner, having a better overall environment. A limitation of the system is the inability to guarantee that every signal is received in real-time on the receptor devices, limiting the usage of beginners in an early stage. Although all the participants agree that it may be due to lack of practice and a matter of habituation, for now that is a limitation of the system.

RQ3: How is the user experience using the Haptic Conductor?

Overall, **the user experience using the Haptic Conductor is overwhelmingly positive**. The results of the user study showed us that the Haptic Conductor is a universally easy system to understand fully and to use. No functionality was too hard for any of the participants, regardless of their age or expertise level.

The system is also comfortable to use. Every participant reported that the nylon straps we used were pleasant to use and did not cause any pain or discomfort. It also is easy to place and to change its placement, allowing the user to select freely the best place where the device should be attached. Every participant agreed that the system **promotes an overall positive user experience, being the accessible solution we proposed since the beginning of this thesis work**.

RQ4: What is the potential of the Haptic Conductor?

The user study demonstrated with the feedback gathered from the participants that every user sees great potential in this solution. Although most of the participants agree that the solution can be improved, all of them agree that the system **would already help their mixed-visual ability musical ensemble in its current form**. The potential they see in this system is immense, and they believe it can improve extraordinarily the rehearsal process of their ensemble if it is to be continued.

Since we were not able to test the Haptic Conductor in a concert, we could not verify its usability in that setting. However, the instructors suggested that the system would already be useful in that context, allowing them to conduct the ensemble in a more organized way. They see enough potential in the system to state that if it is continued it can vastly change the way they approach their concerts.

The participants see the system having more features in the future that can help them even more than it already does, and **they all suggest the project is continued to fulfil its full potential**.

6

Conclusion and Future Work

Visually impaired persons have faced multiple challenges in their everyday lives, both as children and adults [5–7]. From a young age, their visual impairment can be a source of disconnect and isolation from their sighted peers, and that isolation can persist throughout their adult lives [25, 26]. As seen in Section 2.1.3, music can be a way for visually impaired persons to feel stimulated and be part of a social group. However, they face multiple inclusion challenges, such as the lack of alternatives to traditional music teaching methods, such as music sheets. Those problems are only more explicit when they are part of a conducted musical ensemble since the instructions of a conductor are primarily visual, as seen in Section 2.1.2. Plus, as discussed in Section 2.2.4, there is a lack of accessible and inclusive solutions to this problem using inexpensive, mainstream technologies.

Therefore, this thesis work focused on developing a system that mitigated the exclusion of visually impaired musicians from mixed-visual ability musical ensembles while using mainstream technology, which in our case was the smartphone. The Haptic Conductor was designed with a user-centred approach and tested in a mixed-visual ability musical ensemble setting. We assessed the performance of the Haptic Conductor in a group environment and retrieved feedback from the conductors and musicians in every stage of development to improve the solution.

After the development stage, and to validate our approach and the Haptic Conductor, we conducted an extensive final user study, where we proposed to answer our research questions by analysing the qualitative data retrieved from the tests performed. Our findings show that the system successfully facilitates the communication between the instructors and the students in a rehearsal setting, contributing to a calmer and more organized environment. The instructions sent were clear and were interpreted correctly by the participants of the user study. However, the user study showed that the Haptic Conductor also has its issues, in particular the signals that are lost on the communication between the devices. We could not guarantee a continuous data stream where every packet was received in real-time, so the Haptic Conductor ignores packets received with excessive delay, which would confuse the students who would be receiving an inconsistent tempo. That results in missing vibrations, which is the lesser evil according to the instructors. Nonetheless, the participants agree that that limitation can be overcome by having more practice sessions, also agreeing that the system has use in its current state and can help their musical ensemble, while also stating that they see great potential in this system if it continues to be developed.

At the end of this thesis work, we were able to have a functioning, accessible and inclusive system that supports visually impaired musicians and that can be used in every mixed-visual ability musical ensemble.

We would recommend future work in order to improve the system we have developed. As many participants of the user study noted, most visually impaired persons have iPhone smartphones and not Android smartphones. That is due to the screen reader of the iPhone being more effective and effortless. Since the Haptic Conductor is only supported on Android, future work could involve investing in the development of an iPhone application that mirrors the already developed Android application, allowing the Haptic Conductor to cover more devices and hopefully more personal smartphones of the target users.

Additionally, the results of the user study suggest that the system can be better evaluated after the students are more accustomed to the vibrations. Therefore, we would suggest in the future conducting more testing sessions with the members of the mixed-visual ability musical ensemble to allow them enough time to get used to the system to get the best and most useful results possible. Furthermore, future work could cover the gesture capture feature we proposed that we could not develop in time to include in this thesis work. Although no conductor mentioned this feature or that it would be good to have, it may be interesting to invest in developing an effective gesture capture that allows the smartphone to capture the gestures of the conductor and sends their instructions to the students.

An improvement the instructors mentioned that should be considered for future work is the differentiation between the downbeat and the rest of the bar. Throughout the process, it was stated by the members of the musical ensemble that it would be interesting to test such a feature as it may help the students recognize better where they are in a musical piece. Also, a potential feature to explore is adding other components to the information a conductor can transmit, such as dynamics (*Forte* or *Piano*) and flow (*Legato* or *Staccato*).

Finally, it is important to correct the issue of the missing packets as much as possible. That was the main limitation of the system referred in the interviews with the participants and they agree that without that issue, the Haptic Conductor would be a more complete and overall better solution.

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