Supporting Mix-visual Abilities Musical Ensembles

Luís Miguel Maia da Cruz
Barreira
Instituto Superior Técnico
Lisboa, Portugal
luis.c.barreira@tecnico.ulisboa.pt
October 2022

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.

1. INTRODUCTION

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.

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**.

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 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.

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. 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, and 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.

This extended summary begins by providing insight regarding relevant background information and previous studies, followed by a discussion of our conclusions of the literature collected. Then, we describe the previous work we performed before developing our solution. Next, we describe the development stages of the Haptic Conductor. Lastly, we describe our user study and discuss the results, finishing with the conclusions and a discussion of future work possibilities.

2. BACKGROUND AND RELATED WORK

2.1 Background

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. Music has three central notions, which are harmony, melody and rhythm [13]. Rhythm is the pattern of movement resulting from the placement of notes and silences throughout a musical piece. There are several important notions worth describing, such as: a beat is a pulse that defines the rhythmic pattern of a song; the tempo is the number of beats per minute; the time signature is the number of beats per measure; the meter indicates the pattern of strong and weak beats. The strong beats are called downbeats, and the weak beats are called offbeats.

A measure or bar is defined as the space between the strongest downbeats [14]. The most common measure 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. The other relevant meters are 3/4 and 2/4.

An orchestra is a musical ensemble of different performers, of which the leader is the orchestra conductor. 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]. 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 1 [1].

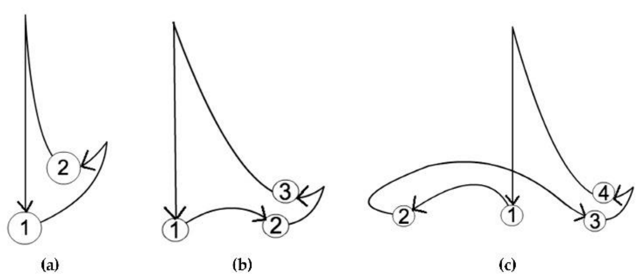

Figure 1. Hand signals for simple time signatures: (a) 2/4, (b) 3/4, (c) 4/4 [1]

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.

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

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. This problem may be countered using 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], which 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 system does not affect or obstruct sighted musicians in any way. The testing showed that blind musicians had difficulties 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. 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.

D. Baker et al. [4] developed a microcontroller board, 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 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]. 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 [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.

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.

Based on the literature gathered, we realise that there is plenty of different haptic feedback systems, although few have been applied to a musical ensemble setting. Therefore, we can assume that it is possible and necessary to fill the gap and adapt the technological advances found in the literature collected 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

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.

3.1 User-centred Design Approach

User-centred design 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 user-centred design methods by involving users in the process results in more functional, intuitive and inclusive systems.

3.2 Interview

In the beginning of our thesis work we conducted a semi-structured interview with conductor Dr Rui Magno Pinto, the main conductor of the Filarmónica Enarmonia. 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. 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.

One of the most common themes of the interview 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. For a teacher and conductor, the tempo is the key to holding the performance of a musical group together. 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, such as clapping and shouting, which is tiring for the teachers. Rui insisted that the priority for the development of a solution was counting the tempo, since that is the basis of a musical performance.

For conductors, 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 be advantageous to use a system that minimizes the disruption of the musical output, so we should preferably aim for a quiet solution. Therefore, haptic feedback is a good mechanism to transmit the information. A mainstream device should be used to minimize the efforts of the performers to use this technology. Most students already use smartphones daily, and it can be used as a vibration receptor, so that no user must acquire any device to make a system work. For that to work, the smartphones must be attachable to the body of the musician.

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.

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.

3.3 Rehearsal Observation

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 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 first stage of the rehearsal was an individual warm-up, where every musician would tune their instrument and after 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.

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, keeping the tempo by clapping loudly.

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. 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.

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. 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.

3.4 Discussion

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.

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 user-centred design to develop the best possible solution to the existing problems. 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.

4. THE HAPTIC CONDUCTOR

The Haptic Conductor was developed in stages, as an iterative process with a user-centred design approach. Each stage covered the development of a prototype, as well as its testing and validation by the members and instructors of the Filarmónica Enarmonia.

4.1 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*, which served as the foundation for the future iterations of our solution.

4.1.1 Development

The features of the prototype are: (1) **Intercommunication** – the prototype must be able to establish a connection between the two Android smartphones, and they must be able to communicate in real-time when in the same network; (2) **Network State Access** – to assure proper functioning of the first feature, the application must be able to access the network state of the Android smartphones; and (3) **Vibration** – the prototype must guarantee that the receptor device vibrates when a message is received, and it should support different vibration durations.

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 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 language.

The prototype consists of only one application for both conductors and musicians, with three activities, which are the windows displayed when running the application. The Main Activity is the default window displayed when the user starts the application. It gives the user the option to select the “Conductor” window or the “Performer” window. 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 devices, we had to choose a communication protocol that allows us to establish a one-to-one network. We had to choose between TCP and UDP, and although UDP offers faster data transmission, it does not offer a reliable data stream unlike the TCP protocol. Therefore, we chose to implement the TCP protocol.

To implement this feature, we created a ServerSocket on the Conductor Activity that waits for a request of the client. We also implemented a feature that displays the IP address of the conductor on the Conductor window. On the Performer Activity, we created a Socket that connects to the Conductor Activity when the IP address of the respective device is inputted. To input the address, the Performer Activity window displays an input box for the user to write the address given by the conductor.

Then, we created a data stream to exchange the messages between the two devices. Once the verification messages were exchanged, we had to develop the tapping 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 Conductor 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. 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. When an option is selected, it will remain the duration until the user changes it again or the application is restarted. The default vibration is 120 milliseconds.

Along the development of the application, we had to add the required permissions to the Manifest file of the application so the features would work on the Android devices.

4.1.2 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.

4.1.2.1 Procedure

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.

Before the test, we connected the two Android smartphones on the same network and inputted the IP address of the device assigned to the conductor on the device assigned to the

We began by asking a student to sit on a chair and attaching a smartphone to their arm using a nylon strap. We asked a conductor to send signals to the student to test their sensibility to the vibration. If they did not feel the vibration with enough strength, we would change the placement of the device to another body part until they felt the vibration correctly.

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. 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 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.

4.1.2.2 Findings

The user-centred design approach we took allowed us to validate every step of the development until we reached the best possible solution we could develop in the time we had.

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. 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.

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. Plus, the distance between the conductor and the musician did not influence the communication between the devices.

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, they agreed that with enough repetition the students might be able to feel the vibrations better. An example of the positioning of the device can be found in Figure 2.

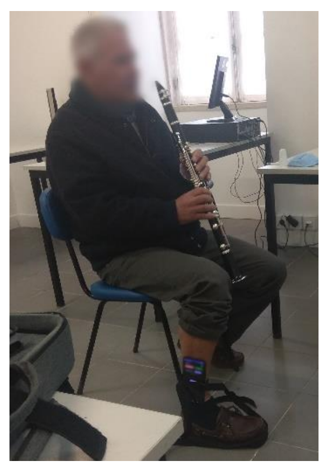

Figure 2. Participant performing the test with the smartphone attached near his ankle.

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.

When asked if they had any suggestions, the users mentioned that the priority should be increasing the power of the vibration.

4.1.2.3 Discussion

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. Plus, 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 prototype.

4.2 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*. It served as the final prototype.

4.2.1 Development

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.

The features of the prototype are: (1) **Intercommunication** – the prototype must be able to establish a connection between more than two Android smartphones, and they must be able to communicate in real-time when in the same network; (2) **Vibration** – the prototype must guarantee that the receptor device vibrates when a message is received, and it should support different vibration durations; and (3) **Time Synchronization** – the prototype must be able to perform a time synchronization between all the smartphones and get the clocks with as little difference as possible, for the communication to function properly.

The architecture for this prototype consists of multiple 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. There was a need to add a Wi-Fi router to the system, which established a local network that all the devices connect to.

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 Activity; and (3) the Performer Activity. The Main Activity remains intact.

The communication method was changed because we needed to implement a one-to-many network, which invalidates the use of TCP. Therefore, we had to implement UDP, which does not guarantee a reliable data stream. While Broadcast networks are easier to implement, we established a Multicast network because it does not send packets to all the devices connected to the network, only sending them to the devices who are explicitly accepting packets from a given sender. For that, we created a multicast group and assigned it to a specific IP address, which the conductor and the performers will join when their activities are started. All messages are exchanged through that group.

Many impulses were received with large delay, if they were received at all since many packets are lost. This was a consequence of using UDP as the communication method between the devices of the system. Receiving delayed impulses would result in different students playing the musical piece at different tempos, which invalidates the correct functioning of the system. Therefore, the best option would be to filter out the delayed packets and have the application ignore these packets.

Android does not allow users to manipulate the clock without having root access, i.e., without attaining privileged control over the operating system. 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.

When the Conductor presses the “Sync” button, the server sends a “Offset” message to the receivers. Then, the activity enters a cycle where the server sends the current time of the smartphone of the conductor to the smartphones of the performer, and the cycle is repeated 60 times. After the cycle ends, the activity shows a popup on the bottom of the screen containing the message “Sync completed!”.

On the Performer Activity, 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. The client then extracts the timestamp the server sent and gets its own timestamp on the moment the packet was received and calculates the offset by comparing the timestamp received with its own timestamp and calculating the difference. That is done for all the packets received and the average offset is calculated, which cancels out the difference between the clocks. The maximum delay allowed is 200 milliseconds because it is still close enough to the intended real-time that the performer can still follow the correct tempo the instructor is sending.

We also improved the vibration and maximized its strength for every device running on Android 8.0 or above. Below that, the device does not allow users to manipulate is vibration.

4.2.2 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.

4.2.2.1 Procedure

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.

We set up the entire system before starting the test. After that, 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. We then 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 send a faster tempo and have the student follow it. The test was repeated by the other student.

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.

4.2.2.2 Findings

The user-centred design 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.

In terms of comfort, there were not any changes in the way the devices were attached to the body of the users. The nylon straps 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. The participants also fully understood every functionality, letting us know that the system remained accessible to the target users.

However, the intercommunication between the smartphones did not provide a data stream as reliable as the one we had with the first prototype, since many messages were lost throughout the testing, and it had to work in conjunction with a synchronization feature to compensate for the delays. 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 proved to be successful as well. The instructors did not have any difficulty comprehending or using the feature, and it correctly synchronized the devices and allowed the application to filter out packets too delayed.

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.

4.3 Summary and Final Discussion

The Haptic Conductor system was developed in two different stages, resulting in two prototypes developed iteratively using a user-centred design approach: the first prototype *One-To-One Tap Vibration Prototype*; and the second prototype *Broadcasting Information Prototype*.

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. Therefore, it was assigned as our final prototype and the system we were going to use to perform the final user study.

5. USER STUDY

To evaluate and validate the Haptic Conductor system, we designed and conducted a user study that was performed through the course of three different sessions in collaboration with Filarmónica Enarmonia. 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.

5.1 Research Questions

The research questions defined 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

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.

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.

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

Table 1. Information of the participants of the user study.

5.3 Apparatus

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. We also used a Windows laptop to install the application on the smartphones and various USB cables to connect the devices to the laptop. We also used the router to establish the local network.

5.4 Procedure

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.

The 1st session of the user study consisted of installing the application on the personal smartphones of the participants. This session also functioned as the introduction to the user study. We had to access the Developer Options of their device to install the application, and 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.

The 2nd session consisted of the practical tests with the Haptic Conductor. We connected all the devices to the network established by the router and attached the smartphones to the users. We tested the best place to attach the device for each individual until they felt the vibrations correctly and comfortably.

We selected the "Performer" on all the smartphones assigned to the students and asked the instructor to select the option "Conductor". When all the smartphones were on their respective screen, we asked the teacher to synchronize the clocks and try to send some signals to the musicians to verify that the system is set up correctly.

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. 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.

The second test was again individual, and 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. Then, 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 using only the Haptic Conductor, without audible cues.

Finally, for the last test, the conductor instructed a count in through the vibrations of the smartphone for the entire group to try and begin a song at the same time, trying to analyse how well the system works in a group setting.

The 3rd and final session consisted of 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.

The duration of the sessions varied, with the \nth{1} session lasting about an hour, the \nth{2} session lasting about two hours and thirty minutes, and the \nth{3} session lasting an hour and a half.

5.5 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 research questions we defined previously 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. The groups are: (1) **User Experience** – we asked the participants about their overall experience as users, regarding their comfort and whether the system interfered with their playing in a negative way; (2) **Functionality** – we analysed our observations and feedback retrieved during the interview seeking to understand the advantages and disadvantages and the benefits and limitation of our solution from the point of view of the participants; and (3) **Impact of the System** – we asked the participants their view on the impact of the system in its current form and what potential they see in the Haptic Conductor in terms of how much it can impact their rehearsals and concerts as instructors or musicians.

5.6 Findings

5.6.1.1 User Experience

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 first prototype. **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 placement of the phone varied. Some participants wore it attached to their arm, others attached to their leg, and others on their thigh. Most participants ended up attaching the device to their back thigh, which suggests that **the thigh may be a more sensible part of the body for 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**.

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**

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.

5.6.1.2 Functionality

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. To test if the feature was working correctly, we had the instructor press the "SYNC" button and verify if the clocks were synchronized. 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. The UDP connection cannot guarantee that every packet is received in real-time, and the test showed us that many packets were lost during the tests. 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.

However, the missing packets proved to be an issue to the beginners during this user study, particularly 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. 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.

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**.

5.6.1.3 Impact of the System

As outsiders, we 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, and the participants agreed with that observation.

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.

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.

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**. The level of musicianship of the participants did not influence their perception of potential for the system.

5.7 Challenges and Limitations

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.

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. Since we could not find a way to work around this issue, we must note it as a limitation of our system.

5.8 Challenges and Limitations

After the user study, we discussed how we can answer the research questions we defined.

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

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. 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. From the point of view of the performers, the impact they felt the most was the same. However, beginners had more difficulties adapting to the system compared to their more advanced peers. However, all participants felt a positive impact using the system.

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 benefit of the Haptic Conductor. No disadvantages were reported by the participants of the user study. 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.

- **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. It also is comfortable to use with the nylon straps. 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?**

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**.

The instructors suggested that the system would already be useful in a concert setting as well, 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

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.

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.

As for future work, we recommend continuing developing the Haptic Conductor by 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, since many blind musicians use iPhone instead of Android.

We also understood from the user study that the results can be improved if 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. Furthermore, future work could cover the gesture capture feature we proposed that we could not develop in time to include in this thesis work.

An improvement the instructors mentioned that should be considered for future work is the differentiation between the downbeat and the rest of the bar. Also, a potential feature to explore is adding other components to the information a conductor can transmit, such as dynamics and flow.

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.

7. REFERENCES

[1] F. Chin-Shyurng, S.-E. Lee, and M.-L. Wu, "Real-time musical conducting gesture recognition based on a dynamic time warping classifier using a single-depth camera," Applied Sciences, vol. 9, 2019. [Online]. Available: https://www.mdpi.com/2076-3417/9/3/528

[2] Asakawa and N. Kawarazaki, "Transfer of synchronized signal using haptic interface," 2018, pp. 379–384.

[3] J. Bajo, M. A. Sánchez, V. Alonso, R. Berjón, J. A. Fraile, and J. M. Corchado, "A distributed architecture for facilitating the integration of blind musicians in symphonic orchestras," Expert Systems with Applications, vol. 37, pp. 8508–8515, 2010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957417410004367

[4] D. Baker, A. Fomukong-Boden, and S. Edwards, "'don't follow them, look at me!': Contemplating a haptic digital prototype to bridge the conductor and visually impaired

performer," Music Education Research, vol. 21, pp. 295–314, 2019. [Online]. Available: https://doi.org/10.1080/14613808.2019.1605344

[5] D. Baker, "Visually impaired musicians' insights: narratives of childhood, lifelong learning and musical participation," British Journal of Music Education, vol. 31, pp. 113–135, 2014.

[6] D. Baker and L. Green, "Disability arts and visually impaired musicians in the community," 2018.

[7] ——, "Perceptions of schooling, pedagogy and notation in the lives of visually-impaired musicians," Research Studies in Music Education, vol. 38, pp. 193–219, 2016. [Online]. Available: https://doi.org/10.1177/1321103X16656990

[8] J. L., S. Miguel, S.-A. J. M., S. M. A., B. J. D. J. E., and Márquez, "Diami: Distributed intelligent environment for blind musicians," M. P., B. José, F. Florentino, C. Emilio, B. Andrés, C. J. M. O. Sigeru, and Rocha, Eds. Springer Berlin Heidelberg, 2009, pp. 475–482.Forman, G. 2003. An extensive empirical study of feature selection metrics for text classification. *J. Mach. Learn. Res.* 3 (Mar. 2003), 1289-1305.

[9] T. Asakawa and N. Kawarazaki, "An electric music baton system using a haptic interface for visually disabled persons," 2012, pp. 602–607.

[10] ——, "Communication method of time synchronization and strength using haptic interface," Journal of Robotics and Mechatronics, vol. 26, pp. 772–779, 12 2014.

[11] D. A. Norman and S. W. Draper, "User centered system design: New perspectives on humancomputer interaction," 1986.

[12] C. Abras, D. Maloney-Krichmar, J. Preece et al., "User-centered design," Bainbridge, W. Encyclopedia of Human-Computer Interaction. Thousand Oaks: Sage Publications, vol. 37, pp. 445–456, 2004.

[13] J. Martineau, Elements of Music. eBook Partnership, 2021.

[14] L. Minguéz, Elementos de Theoria Musical, ser. A Melodia. Bevilacqua.

[15] C. Seaman, Inside conducting. University Rochester Press, 2013.

[16] R. M, "Review on motion capture technology," Global Journal of Computer Science and Technology, 2018. [Online]. Available: https://computerresearch.org/index.php/computer/article/view/1851

[17] D. Vlasic, R. Adelsberger, G. Vannucci, J. Barnwell, M. Gross, W. Matusik, and J. Popovi´c, "Practical motion capture in everyday surroundings," ACM Trans. Graph., vol. 26, p. 35–es, 7 2007. [Online]. Available: https://doi.org/10.1145/1276377.1276421

[18] S. Liu, J. Zhang, Y. Zhang, and R. Zhu, "A wearable motion capture device able to detect dynamic motion of human limbs," Nature Communications, vol. 11, p. 5615, 11 2020.

[19] Gabriel, J. Amparo, C. Amparo, Z. Carolina, R. Sara, B. Ignasi, R. Edgar, V. Eva, R. Carlos, C. J. A., S. Joaquín, S. Jesús, B. Javier, C. J. M. S. Alejandro, and Villarrubia, "Menu navigation in mobile devices using the accelerometer," Rosella, M. Ivana, de la Prieta Fernando, R. J. M. C. V. Pierpaolo, and Gennari, Eds. Springer Berlin Heidelberg, 2012, pp. 133–140.

[20] H. Lahiani, M. Elleuch, and M. Kherallah, "Real time hand gesture recognition system for android devices," 2015, pp. 591–596.

[21] T. Pascu, M. White, and Z. Patoli, "Motion capture and activity tracking using smartphone-driven body sensor networks," 2013, pp. 456–462.

[22] Wenteng, C. Chunlei, B. Liang, Z. Y. Z. Huixiang, and Xu, "Your knock is my command: Binary hand gesture recognition on smartphone with accelerometer," Mobile Information Systems, vol. 2020, p. 8864627, 7 2020. [Online]. Available: https://doi.org/10.1155/2020/8864627

[23] A. Albarbar, A. Badri, J. K. Sinha, and A. Starr, "Performance evaluation of mems accelerometers," Measurement, vol. 42, pp. 790–795, 2009. [Online]. Available: https: //www.sciencedirect.com/science/article/pii/S0263224108002091

[24] C. Dobrian and F. Bevilacqua, "Gestural control of music: using the vicon 8 motion capture system," 2003, pp. 161–163.

[25] L. L. P.-Y. K. H.-C. C. F.-L. Chao, "Implement wireless and distributed vibrator for enhancing physical activity of visually impaired children," Advances in Science, Technology and Engineering Systems Journal, vol. 5, pp. 100–105, 2020.

[26] O. Metatla and C. Cullen, ""bursting the assistance bubble": Designing inclusive technology with children with mixed visual abilities," pp. 1–14, 2018. [Online]. Available: https: //doi.org/10.1145/3173574.3173920

[27] P. L. Emiliani and C. Stephanidis, "Universal access to ambient intelligence environments: Opportunities and challenges for people with disabilities," IBM Systems Journal, vol. 44, pp. 605–619, 2005.

[28] Vivian, B. Javier, C. J. M. P. Cristian, and L´opez, "Improving the language active learning with multiagent systems," H. C. Emilio and Yin, Eds. Springer Berlin Heidelberg, 2009, pp. 719–726.

[29] Alberto, F. J. A. M. Antonia, and Pedrero, "Multiagent-based educational environment for dependents," Francisco, P. Alberto, C. J. M. C. Joan, and Sandoval, Eds. Springer Berlin Heidelberg, 2009, pp. 602–609.

[30] J. Cárdenas and E. Inga, "Methodological experience in the teaching-learning of the english language for students with visual impairment," Education Sciences, vol. 11, 2021. [Online]. Available: https://www.mdpi.com/2227-7102/11/9/515

[31] K. E. MacLean, "Designing with haptic feedback," vol. 1, 2000, pp. 783–788 vol.1.

[32] A. Chang, S. O'Modhrain, R. Jacob, E. Gunther, and H. Ishii, "Comtouch: Design of a vibrotactile communication device." Association for Computing Machinery, 2002, pp. 312–320. [Online]. Available: https://doi.org/10.1145/778712.778755

[33] C. Narayanaswami and M. T. Raghunath, "Designing a new form factor for wearable computing," IEEE Pervasive Computing, vol. 1, pp. 42–48, 2002.

[34] L. Gonz´alez-Delgado, L. Serpa-Andrade, K. Calle-Urgil ´ ez, A. Guzh˜nay-Lucero, V. Robles-Bykbaev, and M. Mena-Salcedo, “A low-cost wearable support system for visually disabled people,” 2016, pp. 1–5.

[35] S. Kammoun, C. Jouffrais, T. Guerreiro, H. Nicolau, and J. Jorge, “Guiding blind people with haptic feedback,” Frontiers in Accessibility for Pervasive Computing (Pervasive 2012), vol. 3, 2012.

[36] M. Plaisier and A. Kappers, “Social haptic communication mimicked with vibrotactile patterns - an evaluation by users with deafblindness.” Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3441852.3476528

[37] H. Nicolau, J. Guerreiro, T. Guerreiro, and L. Carric¸o, “Ubibraille: Designing and evaluating a vibrotactile braille-reading device.” Association for Computing Machinery, 2013. [Online]. Available: https://doi.org/10.1145/2513383.2513437

[38] J. G. J. Vuijk, J. Gay, M. A. Plaisier, A. M. L. Kappers, and A. Theil, “Patrec: A mobile game for learning social haptic communication.” Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3441852.3476563

[39] M. Karam, F. A. Russo, and D. I. Fels, “Designing the model human cochlea: An ambient crossmodal audio-tactile display,” IEEE Transactions on Haptics, vol. 2, pp. 160–169, 2009.

[40] L. Turchet, D. Baker, and T. Stockman, “Musical haptic wearables for synchronisation of visuallyimpaired performers: a co-design approach,” 2021.

[41] J. Peerce, Y. Rogers, and H. Sharp, “Interaction design: Beyond human-computer interaction,” 2002.

[42] M. I. Alhojailan, “Thematic analysis: A critical review of its process and evaluation,” West east journal of social sciences, vol. 1, pp. 39–47, 2012.

[43] A. Lucero, “Using affinity diagrams to evaluate interactive prototypes,” Simone, F. Mirko, G. Tom, P. Philippe, W. M. A. Julio, and Barbosa, Eds. Springer International Publishing, 2015, pp. 231– 248.