A Guitar Controller for People with Cerebral Palsy

Marcel Schmidt

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Supervisors:
Zacharias Vamvakousis & Rafael Ramírez

Department:
Department of Information and Communications Technologies

Universitat Pompeu Fabra
Barcelona

Abstract

It has been proven that playing a musical instrument brings with it several benefits such as increased intelligence and improvements in fine motor skills. Unfortunately, people with motor disabilities are often excluded from these benefits. This thesis aims to improve this situation by proposing a guitar controller which gives people with Cerebral Palsy the possibility of creating music, hence enabling them to access the aforementioned benefits.
For the design of the interface, the movement abilities of a person with Cerebral Palsy were analysed and, based on the findings, a tangible user interface was implemented. Besides this individual tangible user interface, universal software was designed and implemented.
The interface was given to a patient with Cerebral Palsy and was tested by using different evaluation methods. Firstly, the patient's playing accuracy was measured and analysed over a period of nine weeks. Secondly, a usability and user experience test were conducted. Next the patient's supervisor was interviewed to see how the interface influenced the user's life. Finally, the interface was reviewed by a music therapist to evaluate its potential in the field of music therapy.
The results indicate a slight improvement in the user's technical (fretting) ability. An improvement in the patient's strumming performance, however, could not yet be seen. Nevertheless, the interviews indicate that the interface had a positive effect on the patient due to increased self-confidence and identification with the instrument. Even though the results look promising, we should bear in mind that the results gained are from a single patient and therefore cannot be generalised.

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Chapter 1

INTRODUCTION

1.1 Motivation

Most people who have played a musical instrument or have seen people playing one would agree that playing an instrument has a positive impact on the musician. Within the last two decades, many studies have aimed to research the benefits of playing music, for instance the relationship between musical training and intelligence[38]. Others have focused on the influences of musical training on cognitive tasks, such as reading, mathematical, verbal, and spatial abilities [37]. A comprehensive review of the benefits of playing music was done by Hallam and MacDonald in 2013 [21].

This, amongst other factors make music particularly appropriate for therapeutic use. Music therapy is well established for the treatment of illnesses like Alzheimer's disease[43], schizophrenia[32], depression[28], autism[24]. Despite its usefulness in the field of neurological disorders, music therapy has been proven to be applicable in other fields of treatment. For instance, Schneider et. al. have successfully demonstrated that using musical instruments can improve motor skill recovery after a stroke[39].

However, many people with motor disabilities are excluded from the above mentioned benefits, as they are not able to hold or play an instrument due to their limited range of movement. Traditional instruments are often designed to be controlled by extensive movement or specific posture, which often makes them inaccessible to people with motor disabilities.

We believe that the advancement in technology enables the design new interfaces which make traditional instruments accessible to people with motor disabilities and therefore gives them access to the benefits of playing musical instruments.

Figure 1.1 illustrates the exclusion problem and how it could be solved with the aid of an interface.

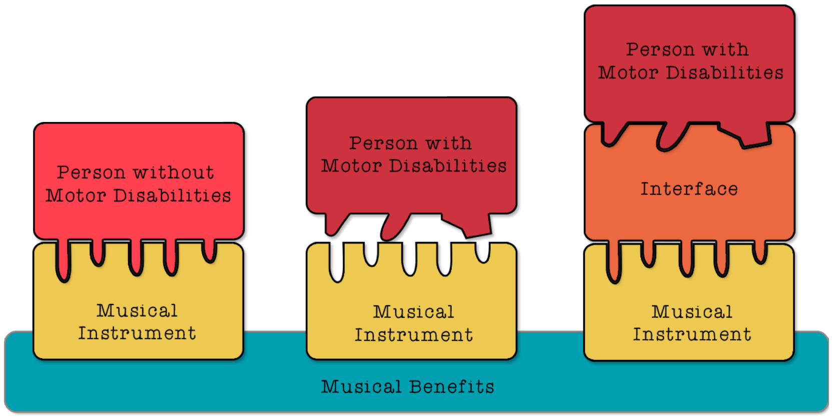


Figure 1.1: Illustration of the exclusion problem

The next section will explain the goals of this research followed by a short overview of the thesis structure.

1.2 Goals

This study aims to map the limited movement of a person with Cerebral Palsy to the input of a traditional musical instrument and therefore let this person access the musical benefits. To achieve this goal the following sub goals were chosen:

- State of the art review
- Movement analyses of a subject with Cerebral Palsy
- Design and implementation of a software application including a graphical user interface
- Design and implementation of a physical user interface based on the movement abilities of the analysed subject
- Evaluation of the interface based on qualitative and quantitative measures

1.3 Thesis Outline

In chapter two we will have a short introduction to the guitar, followed by a brief section on what Cerebral Palsy is and how it can be categorized. The chapter will finish with a review of the state of the art. The third chapter will explain how the interface was designed and the following chapter will describe how the interface was implemented. Chapter five will show the evaluation procedures and the results. These results will be discussed in chapter six. The thesis will conclude with chapter seven and propose future work in chapter eight.

Chapter 2

BACKGROUND

As the final interface aims to control a guitar synthesizer it is essential to have a look at what a guitar is and how it is played, which can be found in the first section of this chapter. The second section will analyse Cerebral Palsy in general and later focus on a case study of a person Cerebral Palsy. Furthermore, we will have a look at what has been done in the area of assistive technology.

2.1 Guitar

2.1.1 What is a guitar?

A guitar is a musical instrument which produces sound by means of vibration of several strings stretched between two fixed points, which dates back to the 12th century [51]. Guitars can be categorized into acoustic guitars, where the vibrations of the strings are acoustically amplified by the body, and electric guitars, where the string-vibrations are picked up and and then electrically amplified. Figure 2.1 shows an acoustic guitar and its components.

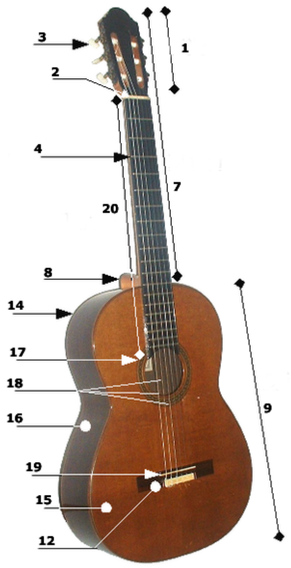


Figure 2.1: Acoustic guitar with its parts: (1)Headstock, (2)Nut, (3)Machineheads, (4)Frets, (7)Neck, (8)Heel, (9)Body, (12)Bridge, (14)Bottom deck, (15)Soundboard, (16)Body sides, (17)Sound hole, (18)Strings, (19)Saddle and (20) Fretboard

We will not further describe the functionality of the guitar, but rather focus on how to interact with a guitar, which is described in the next section.

2.1.2 Playing the guitar

Traditional guitars are played by a combination of two distinct actions: fretting the notes and strumming. These two actions can be assigned to each hand. For right handed people the fretting is usually done by the left hand and the strumming is done by the right hand.
The left hand presses the strings to the fretboard and hence shortens their available lengths to vibrate. This changes the string's frequency of vibration and therefore the produced pitch. The left hand can fret single notes or a combination of notes to form a chord. Furthermore, there are some advanced techniques the left hand can do such as hammering-on, string-bending, slides and vibratos.
The right hand strikes the fretted strings at the desired time, and is therefore responsible for the rhythm. This is done by either strumming or finger-picking the strings.
We can conclude that playing a guitar is a combination of note selection and note execution, where both actions can be done separately but have to be

done together to play a note. The fretting requires high spatial accuracy whereas the the note execution requires a high temporal accuracy.

2.2 Cerebral Palsy

As cerebral palsy is not a single condition but rather an umbrella term used to describe a group of conditions, we will in this section define what is meant by Cerebral Palsy and how it can be classified. Afterwards we will have a look at one specific case of Cerebral Palsy.

2.2.1 Definition and Classification

Bax defined Cerebral Palsy (CP) in 1964 as a group of disorders of movement and posture due to a defect or lesion of the immature brain [16]. Until recent years this was the most common definition, but due to modern brain imaging techniques and better understanding of CP an International Workshop on Definition and Classification of Cerebral Palsy was held to reconsider this definition. The new definition is the following: *"Cerebral palsy (CP) describes a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, perception, cognition, communication, and behaviour, by epilepsy, and by secondary musculoskeletal problems"* [36]. Even though CP is the most common physical disability in childhood, with rates between 2.0 and 2.5 per 1000 live births, in many cases the cause remains unknown [35].
CP can be classified based on severity level, topographical distribution, motor function or in regards to the gross motor function classification system (GMFCS).
The severity level classifies CP into mild, moderate, severe or no CP. However, this system provides little specific information and lacks a specific set of criteria. The topographical distribution classification describes which part of the body is affected. For instance Monoplegia means that only one limb is affected, Triplegia if three limbs are affected or Quadriplegia if all four limbs are affected. The motor function classification separates CP into two main groups, spastic and non-spastic. Spastic cerebral palsy is characterized by increased muscle tone, whereas non-spastic cerebral palsy is indicated by decreased or fluctuating muscle tone. Both groups contain sub groups with different symptoms. A full classification overview with all sub categories can

be found at cerebralpalsy.org [3]. The Gross Motor Function Classification System, which was originally developed in 1997, classifies CP based on the degree of severity, where 1 is the lowest and 5 the highest severity [34].
In the next section we will focus on one case and describe how CP impacts upon his daily life.

2.2.2 Case Study

As seen in the previous section, CP can have a variety of effects on the body and different types of CP can be mixed such as spastic and non-spastic CP. In this section we will have a deeper look on one case to get a better understanding of CP.
To find a suitable subject for this thesis, several nursing homes for people with motor impairment and sheltered workshops throughout Spain and Germany were contacted. It was important to find somebody who was motivated to learn an instrument and is not forced to do so, as this would have negative influence on the project.
The chosen subject is male, 36 years old and lives in Germany. He suffers from dyskinetic cerebral palsy with choreoathetoid which is characterized by irregular, twisting and curving movements.
With regards to the Gross Motor Function Classification System he falls between the categories 4 and 5, which means he is not able to walk and therefore he uses a wheelchair. CP has a strong impact on his daily life as he is unable to eat or drink without assistance. Furthermore, he has problems speaking as his tongue muscles are also affected by CP and he has to live in a home for people with motor impairments.
He does not have any mental impairment and finished secondary school, which means he is able to read and write (with the computer). He is working in a sheltered workshop where he is using the computer to write articles. To control the computer he uses a trackball and a customized keyboard.
When asked about his music abilities in an preliminary interview he stated *"I have been trying to play keyboard for a while but I never had proper music lessons"*. He later explained that he was playing with one finger only and that he stopped because the keys were to close to each other so he often pressed the wrong key. Furthermore he stated that he would like to learn to play the guitar.

2.3 Assistive Technology

In this section we will first describe general interfaces for people with motor disabilities and later focus more on musical interfaces.

2.3.1 Interfaces for people with motor disabilities

As mentioned in chapter 1, people with Cerebral Palsy or other motor disabilities are often not able to control a computer keyboard or a mouse with the accuracy of a non-impaired person. Trewin & Pain have done a detailed analysis of errors that occur throughout mouse and keyboard interactions performed by people with motor impairments [47]. Furthermore Hwang, Keates, Langdon & Clarkson analysed the submovement structure of motion-impaired users [23]. Some of the findings were that the user-group *"with motor disabilities took approximately two or three times as long to perform the typing and mouse tasks than the comparison group, excluding error correction time and participants with motor disabilities spent, on average, 7.3% of their time correcting keyboard performance errors, compared to an average of 1.7% in the non-disabled group"* [47].
The aim of Assistive Technology (AT) is to reduce these errors by providing the user with an access solution which is less prone to errors. Tai, Blain & Chau propose a model which states that an access solution includes access technology, user interface and functional activity [45] (Fig 2.2). The access technology can be further split into access pathway, which consists of the actual sensors and the signal processing which processes the sensor input.

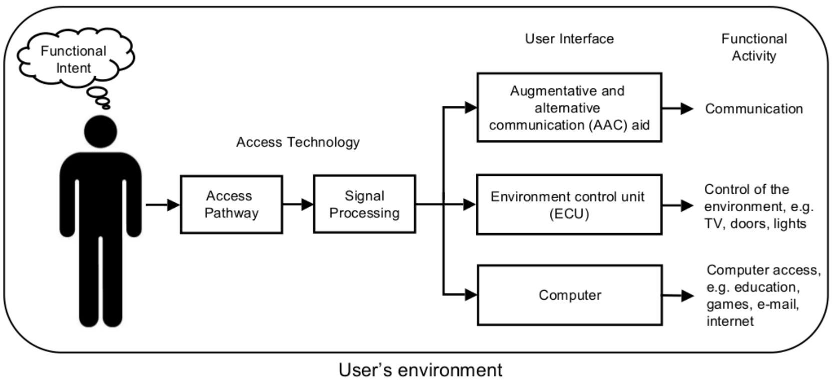


Figure 2.2: Access solution model proposed by Tai, Blain & Chau

A comprehensive review on access technology from 1996 till 2006 was done by Tai, Blain & Chau [45]. In their review access technology is been categorized into the following groups: Mechanical Switches, Electromyography (EMG), Infrared Sensing, Oculography (EOG and VOG), Computer Vision (camera-based), Electroencephalography (EEG), Electrocorticography, Intracortical Recordings and Electrodermal Activity. These categories are based on the user's level of physical movement and are not entirely exclusive as seen in figure 2.3. This classification can be useful when deciding on which technology to use for each user depending on his/her ability.

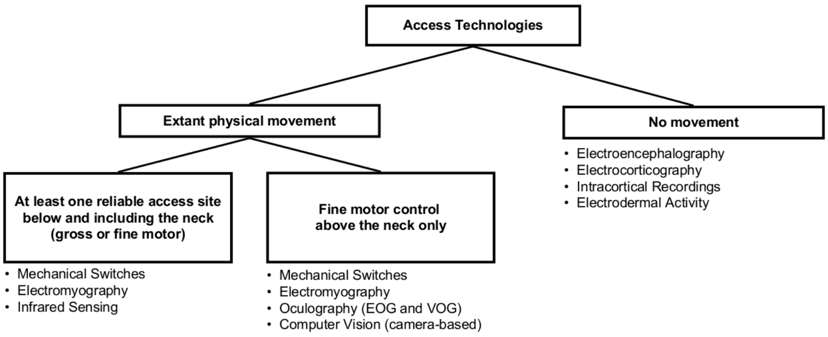


Figure 2.3: Classification of Access Technology as proposed by Tai, Blain & Chau

We will now discuss some of the access solutions proposed in recent years. Probably the most successful solution based on computer vision is the *CameraMouse*, a system which tracks the user's movement of nose, finger or other limbs and hence controls the mouse cursor based on the movement [18]. The *CameraMouse* software is freely available and can be used with a standard webcam. This system has been extensively used for various applications. A full review of those applications was done by Betke in 2010[17].
For people with motor disabilities so advanced that they are not able to move any limbs or the head, an interesting approach is to take advantage of the voluntary tongue movement. One study analysed changes in the airflow pressure that occur in the ear canal during tongue movement and therefore they could distinguish between different tongue gestures [48]. Based on her/his tongue movement the user was than able to communicate with a computer or control devices. A similar but vision-based approach was done by Leung & Chau, who developed a system, where the user can control switch activities by tongue movement [27].
Besides developing novel input devices, there is another approach to access solutions which involves using standard input devices such as a trackball and only change the signal processing or the user interface. This allows for the adaptation of the standard devices to an assistive solution.

Wobbrock & Myers for instance developed an application which lets the user use a standard trackball for text entry through gesture recognition [52]. Shih & Shih distributed multiple mice among their limbs with remaining ability and hence let them control mouse pointing due to the combined interaction [41].
Other research has been conducted by diverting devices such as game controller from their intended use. The Nintendo Wii controller has been successfully used as assistive technology in several studies [42],[40].
As we can see, most of the research conducted in the field of assistive technology focuses on cursor control and text entry as these are the essentials of Human-Computer-Interaction. These input methods are designed for general purpose tasks such as internet browsing or desktop control where timing does not influence the outcome. For musical interaction however, it often needs more specific interfaces as temporal control is one of the key aspects in music making. In the next section we will have a deeper look at different interfaces which were especially designed to produce music.

2.3.2 Assistive Music Technology

As we saw in chapter 1, the therapeutic benefits of music are well known. However, the research of assistive music technology seems to be rather small. Below we will give an overview of the state of the art in assistive music technology. The research will be categorized based on the used technology. We will start with tangible interfaces which require at least one reliable limb and then move on to interfaces which can be controlled by only head movement such as head tracking and finally we will end with biometric interfaces for people with severe motor impairment.

Tangible Interfaces

The most obvious advantage of tangible interfaces is the provided tangible feedback, like a real acoustic instrument.
One notable interface is the *Skoog* which is a pressure and deformation sensitive cube one can squeeze [11]. The *Skoog* can by played by pressing, squeezing, rubbing, stroking, tilting or shaking it. Each zone of the *Skoog* has a different sound or instrument assigned to it and can be adjusted by the accompanied software. Unfortunately there is no subjective evaluation of the *Skoog* except several case studies provided on the company website. Even though the *Skoog* seems to be a practical interface for basic music interaction, it seems like it is lacking in expressiveness.
Another tangible interface specially designed for people with cerebral palsy

is the *TouchTone* developed by Bhat [19]. The *TouchTone* is similar to a piano with only ten keys which are arranged in two rows. The keys are also bigger than on a traditional piano and therefore require less fine motor skills to play it. Furthermore the *TouchTone* can be set to learning mode, so a song can be loaded onto the instrument and than an LED indicates which key to press. The *TouchTone* was evaluated by user observation and interviews and was found that it allows children to make music easily and enables them to develop specific physical abilities.

Motion Sensing

By motion sensing we mean technology based on computer vision or distance sensing.
Probably the first commercially available assistive music technology was the *MIDICreator* developed by Kirk, Abbotson, Hunt & Cleaton [25][8]. The *MIDICreator* is a physical interface which can be connected to a set of different sensors and converts the voltage of those sensors to MIDI data. The user is then able to control notes, scales, chords and other musical events through the sensors. There is a wide range of sensors, like the *MIDIgesture*, an ultrasonic beam to detect the position of an object within a range, or the *MIDIcushion*, a cushion filled with electrically conductive foam which changes its voltage when pressed. The *MIDICreator* goes hand in hand with the *MIDIGrid* [22]. The *MIDIGrid* is a graphical user interface which slices the screen into a grid where the user can assign a musical event to each cell. This musical event can then be triggered by different means of input. Musical events can be individual notes, simultaneous notes (chords) or sequences of notes and chords (tunes). The cell-size depends on the total amount of cells and can be adjusted by the user between 1 and 200 cells. Live performances can be recorded and then assigned again to a cell for later use.
Another and currently most often used assistive music technology is the *SoundBeam* developed by Swingler [44]. The *SoundBeam* is a musical instrument which was inspired by the Thereminvox. It works by emitting inaudible high frequency audio pulses in the form of a beam and by interrupting this beam the pulses are reflected back to the device. This allows the *SoundBeam* to measure distances from 25cm to 6m. The distance, the speed and the direction of the movement can then be converted into MIDI data. The range in which the *SoundBeam* is reactive can be set to a small range to detect small movements and to a larger range to detect big movements. The *SoundBeam* has a variety of preset music material which the user can choose from. It is also possible to add switches to the *SoundBeam* to provide

more functionality. The *SoundBeam* is a commercial product and can be purchased on the company website[12].
Another well studied system is the *Movement-to-Music System (MTM)* developed by Lamont et al. [26]. The system is based on computer vision and can be used with any inexpensive standard USB camera. The user can trigger sounds of different instruments or notes by applying movement to a certain area in his/her surrounding. The area where movement has to be applied can be predefined by the user and is shown on a screen. The *MTM* system has been proven to have the potential to improve children's body functions and allow children to have independent and self-directed play activities, while learning basic music knowledge [46].
A similar and more recent approach is the *Adaptive Use Musical Instrumenti (AUMI)* by Oliveros, Miller, Heyen, Siddall & Hazard [33]. The main objective of this research was to create an interface which lets children with severe motor disabilities participate in a drum class together with other children. Similar to the *Movement-to-Music System*, the *AUMI* tracks the user's position and movement with a standard webcam and triggers sounds depending on the location of the user. The number of sounds as well as the area where each sound should be triggered can be predefined by the user. Furthermore there are different modes the user can choose, so he/she can play drums or keyboard. The system has been tested in two schools over more than one year and music therapists have observed positive effects in participants using the interface.
Another big area in motion sensing is eye-tracking which became more and more popular in recent years due to the availability of low-cost and DIY eye-trackers.
Several studies have been conducted to control an instrument with gaze only, such as the *EyeHarp*[49], the *EyePiano*[20] and the *EyeGuitar*[50]. Each of these systems provide the user with a graphical user interface and depending where the user is looking, he/she can trigger musical events. The *EyeGuitar* is rather a game and the user is not able to play his own songs, but rather trigger note events for a given song. The other two systems let the user play his/her own songs freely and the *EyeHarp* furthermore provides a step sequencer which can be programmed to accompany the real-time playing.
One problem with all these interfaces described above is the lack of tangible feedback like that which an acoustic instrument would provide.

Wind Controllers

The aforementioned solution are not suited for all people with motor disabilities as they mainly required at least some kind of limb-movement. In some

cases however the motor-impairment is so severe that no limb-movement is possible. For such disabilities wind controllers can be suitable means of user input. However, the described wind controllers below need some additional input besides the blow sensor, such as head movement.
There are some commercially available wind controllers which convert the breath pressure into MIDI data, such as the *Yamaha WX* models [14] or the *AKAI EWI* modells[1]. These however are not developed for people with impairments, as they are further controlled by small keys, which can be inaccessible for people with severe motor impairments.
The *Magic Flute* on the other hand is a wind controller designed especially for people with severe motor impairments[6]. The user can change the volume of the notes by varying his/her breath intensity. The flute is usually mounted on a camera mount so the user tilts the flute by small vertical head movements and therefore changes the note's pitch. The *Magic Flute* has an onboard soundcard and the user can choose between different scales from easy ones with only five notes to more difficult ones with up to 15 notes.
Aziz, Warren, Bursk & Follmer provide a low cost version of the *Magic Flute* named *The Flote* [15]. As the *Magic Flute* requires expensive hardware, the focus of *The Flote* is to make the software freely available and provide low cost hardware by adding an IR-LED to a microphone of a standard computer headset so the head movement can be tracked by a webcam. The interaction remains the same as with the *Magic Flute*.
Even though the main input of the wind controllers were through breath, a second input was needed to provide more expressiveness.

Biometrics

Sometimes people with motor disabilities cannot use the above described systems due to limited movement or limited breath strength. One approach is then to use biometric data such as Electromyography (EMG) or Electroencephalograph (EEG).
Miranda, Magee, Wilson, Eaton & Palaniappan differentiate between three approaches when making music with the help of EEG: *direct sonification, musification*, and *control* [30]. With *direct sonification* the measured brainwaves are directly translated into sound, whereas with *musification* the measured brainwaves are triggering musical sequences based on the behaviour of the EEG. These two approaches can be useful for scientific applications, but they are less useful for Brain-Computer-Music-Interfaces (BCMI) because in those cases the user does not actively control the music, but rather passively influences the musical outcome. With the last approach (*control*) the user intentionally creates specific EEG patterns to control musical software.

This approach was used in their latest study where they developed a BCMI based on Steady State Visual Evoked Potential (SSVEP) [30]. In this system the user can stare at four different visual stimuli, which are blinking at different frequencies on a computer screen. Those frequencies can be recognized in the EEG and therefore it is known at which stimuli the user is looking at. It is also possible to distinguish the rate of attention with which the user is looking at a certain stimuli by analysing the amplitude of the frequency. Each of the four stimuli contains an array of five notes. The user can choose which note to play by changing the his/her attention to the given stimuli by looking away or starring at the stimuli. The system was tested with a subject which suffered a stroke and could only move her eyes. The subject could play given notes after a short introduction and outperformed a person without impairment who used the same system.
Miranda & Soucaret conducted research on the musification approach by converting the power of certain frequency bands (alpha and beta waves) to a channel of a music mixer and therefore allow the user to mix music with his mind [31]. Another musification approach by Miranda, Brouse, Boskamp & Mullaney is the *BCMI-piano* [29]. The *BCMI-piano* consist of an analysis module which performs power spectrum and Hjorth analyses of the EEG and a music engine module. Depending on what the the most prominent frequency is and how complex the EEG is, the music engine generates music for the upcoming musical bar based on a given set of rules. If the lower frequencies are dominant the system would generate music with more Schumann-like elements, where higher frequencies would generate more jazzy music. The complexity of the EEG influences the tempo where high complexity increases the tempo and vice versa.

2.4 Conclusion

As seen in this chapter there is a variety of different types of CP which affects the body movement in different ways and degrees. Besides this variety the assistive technology also varies from tangible interfaces for people who are still able to move, to brain computer interfaces for people without any movement. With this in mind it is essential to analyse the subject first and then design the interface based on the needs of the subject. To make the system adaptable for other means of input we will therefore separate our interface into a software part and a hardware part. The hardware part will be designed especially for our subject and serves as a controller for the software. The software part should be easily adaptable to other means of input such as blow sensors or eye tracking.

Chapter 3

DESIGN

The following chapter will guide us through the design process. As mentioned in the previous chapter, the system will be divided into a hardware part which will in our case be a tangible user interface and a software part, including the graphical user interface. Figure 3.1 shows the design overview, where we can see that the software is the same for different cases of CP, while the hardware should be adapted to each case of CP.

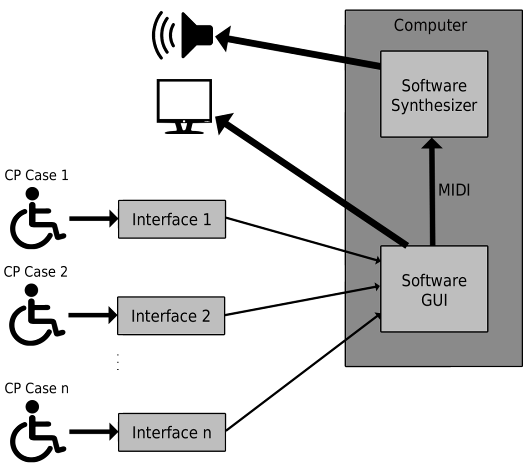


Figure 3.1: Design Overview

The main idea of the system is that the user is able to select and trigger a chord/note via the hardware. The user selects the chord/note with the help of the hardware and afterwards also triggers the chord/note with some input to the hardware. The hardware sends the user's input to the software, where the data is processed and used for visual feedback as well as sent via MIDI to the software synthesizer.

3.1 Software

In this section we will discuss the design of the system's software part which has several tasks such as processing the user input, providing the user with visual feedback, sending MIDI data to the software synthesizer, accompanying the user while playing and letting the user set up songs as well letting the user edit previous songs. To keep the graphical user interface clear with this broad range of tasks, it will be organized into different modes. Each mode will only process and provide information for tasks the mode is dedicated to. For instance when playing a song it is not necessary to see which USB port the hardware is connected to but rather to get visual feedback about the current state of the hardware.
Figure 3.2 shows a model of the software with its different modes and the corresponding tasks.

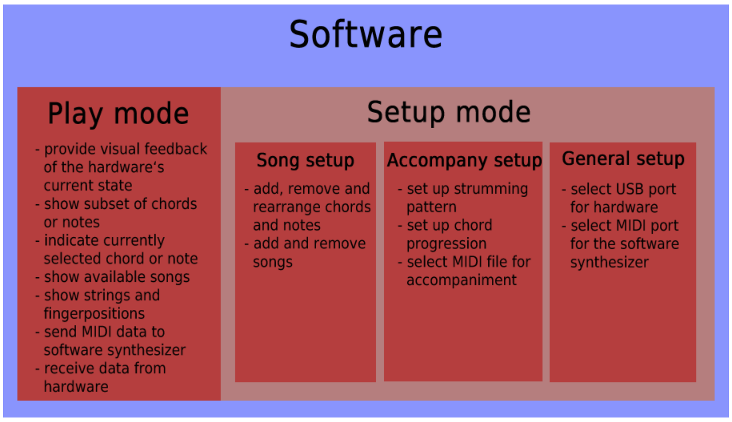


Figure 3.2: Software structure

As we can see the software is separated into two modes: the playing mode and the setup mode. The setup mode is furthermore divided into three sub modes.
The software is controlled by at least two continuous inputs from the hardware. As mentioned above, the hardware should be adapted to each case of CP, but at least two means of continuous input must be provided to the software: one input for selecting a chord/note and another one for triggering the chord/note. The selection process is done by sliding through an 'array'

of chords depending on the user's input. In figure 3.3 we can see three examples for input values of 10%, 50% and 78%. In the shown example the user can choose between five chords, which means the 'array' is divided into five equally sized 'sections'. If the input value is between 0% and 20% the first chord is selected, if the input value is between 20% and 40% the second chord is selected and so forth.

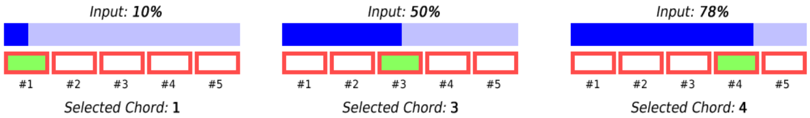


Figure 3.3: Three examples of the chord selection process

If the user wants to play notes instead of chords, he/she has to switch to note mode. In note mode the user can select notes by using the same procedure as for the chord selection.
Once a chord or note is selected it has to be triggered. This is done by the second continuous input from the hardware and is very similar to the chord/note selection process. Instead of having 'sections' on the array like in the chord/note selection process, we have six 'spots' on the array, one for each string. When the input value passes a spot a certain string is plucked. Figure 3.4 shows two examples for the string trigger procedure. If the input value moves for instance from 9% to 11% it passes 10%, the spot for the first string and therefore plucks the first string. If the input value goes from 0% to 100% all six strings are plucked after each other.

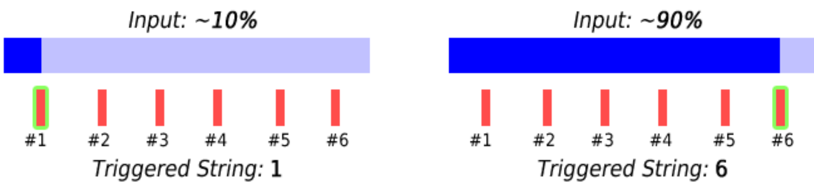


Figure 3.4: Two examples of the string trigger process

Changing the input value from 0% to 100% can be a difficult task to accomplish depending on the input method. Therefore the software should provide a trigger support function. If this function is activated the user has to trigger only the first two strings and the software will trigger the remaining four strings on its own. The remaining strings are triggered with the same time interval as that with which first two strings were triggered. For example, if the user triggered the second string 60ms after the first one,

the third string will be triggered 60ms after the second, the fourth 60ms after the third and so forth. This allows the user to trigger a whole chord with only small changes of the input value.
As mentioned earlier the user is able to select and trigger chords with the hardware. Selecting a chord from all available chords is a rather tedious task and therefore the software provides the user with the possibility to choose just the chords which are needed for a specific song and therefore a subset of chords is created. The user can then pick a chord out of the subset which makes the selection process faster and less accuracy is needed. In figure 3.5 we can see the total amount of chords in the middle and the subsets for each song. The user has to select one song and can then choose between the chords of this song. As one can imagine it is easier to find and select the desired chord in a subset rather than in the whole set of chords. The same holds true for the note selection process.

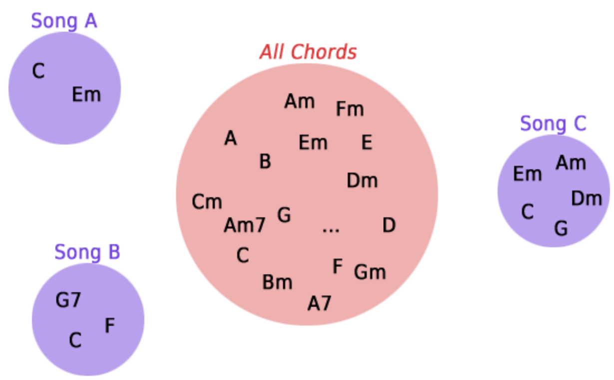


Figure 3.5: Chord subsets compared to all chords

Furthermore the software should provide an accompaniment function, where the user can load a MIDI file which will accompany the user while practising. This will allow the user to improve his/her timing and also gives the feeling of playing in a band.
The software should also facilitate a function which allows the user to focus on one input while the other input is operated automatically. For instance the user can strum on his/her own while the chords are changed automatically. This mode will be named auto-fretting or auto-chord mode. Vice versa the user could only do the chord changes, while the software is strumming automatically (auto-strumming mode). For this function the software should provide a menu where the user can set up the strumming pattern as well as the chord sequence for each song.
The software should give the user control over the port selection, such as

MIDI output and hardware input.
Having covered the main design choices for the software we will continue in the next section with the design of the hardware part of the system.

3.2 Hardware

The design of the hardware is heavily based on the user's movement abilities. Where a person without the ability to move his/her body needs a eye tracking device, a person who is able to move his/her arms could use a tangible interface. Therefore those abilities should be identified and the design should be based on the available abilities.
Before testing those abilities we have to consider which inputs for the software are needed. As mentioned in the software design section 3.1 we need at least two kinds of continuous input: one for strumming and one for fretting. To allow the user to control the software without any secondary input devices, additional inputs to switch between chord and note mode and to change songs are needed. Furthermore velocity control would enhance the expressiveness of the interface.
To identify the user's movement abilities a preliminary prototype was developed which allowed the user to interact with an initial version of the software. The prototype consisted of different means of input which addressed a broad variety of movements. For instance the finger movement was tested with the aid of buttons, while arm movement was tested by the use of a proximity sensor.
In figure 3.6 we can see the preliminary prototype which facilitates sensors such as buttons, a thumb joystick, touch-sensitive strings, a slide potentiometer and a proximity sensor.

Figure 3.6: The preliminary prototype with all its sensors

Besides the aforementioned sensors the EyeTribe [5] was used for testing eye-tracking as well as the Camera Mouse [18] software for testing head-tracking. With all those sensors the following movements were analysed:

- Finger movement (buttons)
- Finger movement (thumb joystick)
- Finger movement (touch-sensitive strings)
- Hand movement (slide potentiometer)
- Arm movement (proximity sensor)
- Guided arm movement (proximity sensor)
- Head movement (camera)
- Eye movement (camera)

Each of the above listed movements were tested for about two minutes first for fretting and afterwards for strumming. While the user was strumming, the software was set to auto-fretting so the user could focus on one movement while the software changed chords itself. Vice versa when the user was asked to change chords, the software was set to auto strumming. Figure 3.7 shows the user interacting with the preliminary prototype.

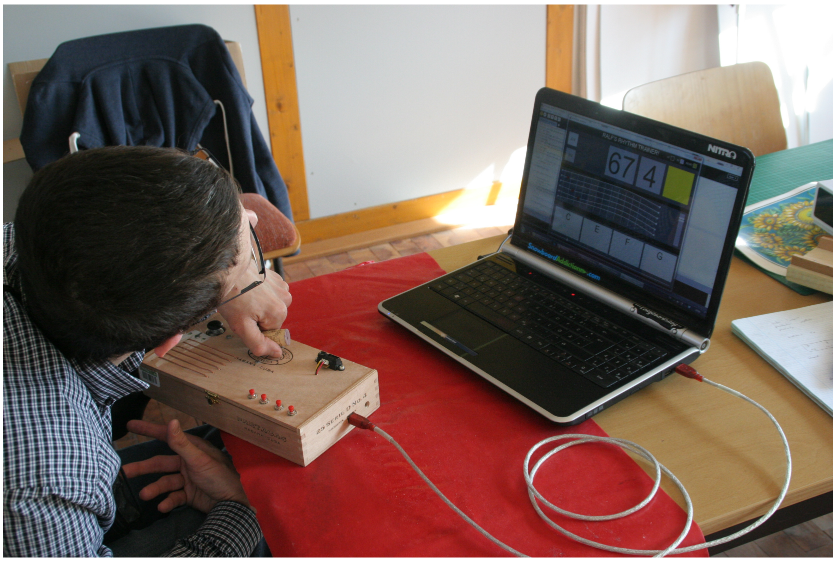


Figure 3.7: Preliminary test to identify the user's movement abilities

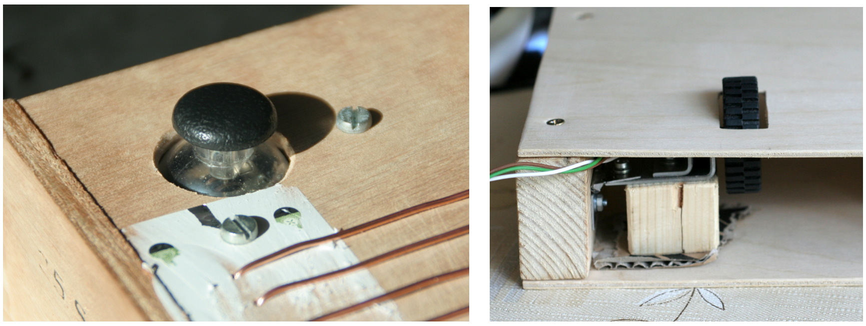
While the subject was interacting with the prototype he was observed and afterwards asked to rate each input method. The observer rated each input method as well. Table 3.1 shows the user's ratings as well as the observer's ratings for the each input method. As the subject was wearing glasses it was not possible to calibrate the eye-tracker properly and therefore eye-tracking was neglected. Also using the head movement for strumming was neglected as the fast movement of the user's head could be harmful to the patient.

Movement (Sensor)	Strumming		Fretting	
	User Rating	Observer Rating	User Rating	Observer Rating
Finger movement (buttons)	3	2	3	3
Finger movement (thumb joystick)	**4**	**5**	2	1
Finger movement (touch-sensitive strings)	3	2	N/A	
Hand movement (slide potentiometer)	2	2	2	3
Arm movement (proximity sensor)	1	1	1	1
Guided arm movement (proximity sensor)	2	3	**5**	**5**
Head movement (camera)	N/A		2	3
Eye movement (camera)	N/A		N/A	

Table 3.1: User and Observer Rating for different input methods

The observer's ratings agreed with the subject's ratings and indicated that he had most control over the fretting when moving his arm from left to right. For the strumming and therefore the rhythm the subject rated the finger movement with the thumb joystick the highest.
Even though the user preferred the thumb joystick over the other input methods he was stating that the thumb joystick has two axis, where one should be sufficient and easier to use. With this in mind, a one axes scroll wheel was designed and tested against the thumb joystick. Picture 3.8 shows the

prototype of the wheel compared to the thumb joystick.



(a) Thumb Joystick (b) Wheel

Figure 3.8: Prototype of the wheel compared to the thumb joystick

The user preferred the wheel over the thumb joystick as it *"gave more control and felt more natural as there were small bumps, like real strings"*. The use of the wheel also enables the addition of a force sensing resistor and therefore measuring the pressure on the wheel, which can be used for velocity control.
During the testing the frail construction of the preliminary prototype was damaged due to involuntary movements of the user and was pushed around the table as it was too lightweight and without proper grip. This led to additional requirements for the final prototype, namely the need to be robust and steady.
Based on the findings from the initial prototype the final design will consist of a slider where the user can move a "sledge" from left to right and a wheel where the user can "scroll" up and down. The left and right movement of the arm will change the chords/notes and the finger movement will trigger the chords/notes. Furthermore the wheel should be pressure sensitive to give control over the velocity. Another aspect to consider is to add some inputs to the physical interface, so the user has control over essential functions of software to avoid the use of secondary devices while playing. Therefore three additional buttons should give control over basic functions such as next song, previous song and change between chord and note mode. During the preliminary test it was identified that normal buttons can be pressed involuntarily and hence the buttons on the final prototype should be guarded to avoid unintended pressing.
With the previously discussed design choices in mind a sketch of the final prototype was made, which can be seen in figure 3.9.

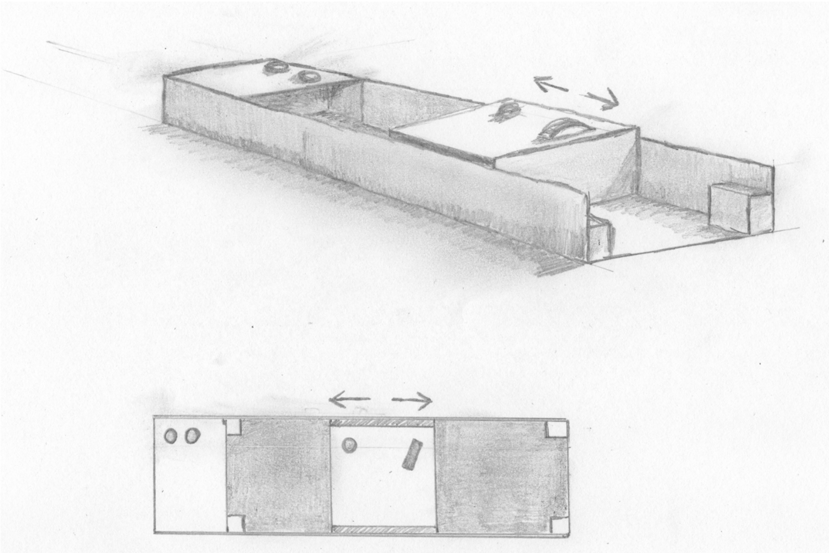


Figure 3.9: Design sketch of the final prototype

Chapter 4

IMPLEMENTATION

The following chapter will explain how the final prototype was implemented. We will first give an overview of the system and later focus on the software and the tangible user interface.

4.1 System Overview

The user provides input to the tangible user interface, with the means of three buttons, one pressure sensitive scroll wheel and one sliding sledge. The tangible user interface sends the input to the computer which runs the software. The software processes this data and provides the user with visual feedback. Furthermore the software analyses the input, converts it to MIDI data and sends it to the connected software synthesizer. In our case the synthesizer is the VirtualMIDISynth [13] for Windows and QSynth [10] for Linux. The synthesizer then provides audio feedback to the user. An overview of the system can be seen in figure 4.1.

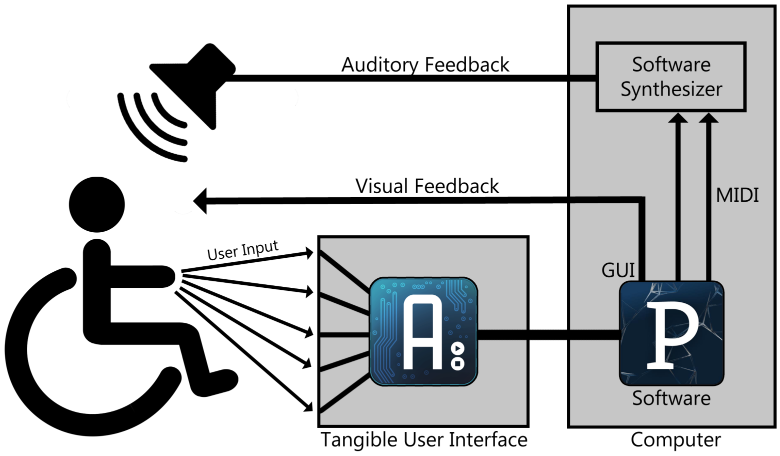


Figure 4.1: Overview of the implemented system

4.2 Software

As the software should be cross-platform compatible it was decided to implement it with the processing programming language [9] which runs on Windows, Linux and Mac. Additional libraries such as the MIDIBus library [7] for midi input, the Beads library [2] for timing and the controlP5 library [4] for user interfaces make processing a great tool for this project. Furthermore it is easy with the processing programming language to receive data from the Arduino micro-controller which is used in the tangible user interface.
As discussed in the software design section 3.1 the graphical user interface should be separated into different modes. This is put into practice by having a tab for each mode. Figure 4.2 shows the GUI in play mode.

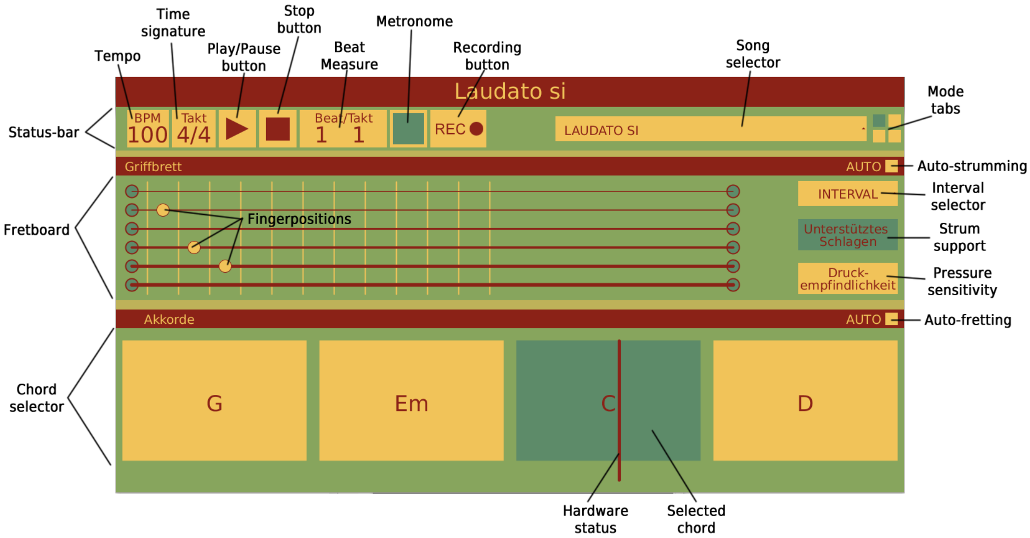


Figure 4.2: The graphical user interface in play mode (chord mode)

At the top we can see the name of the current song, in this case "Laudato Si". Below we have the status bar which shows us the tempo, the time signature, the play button which starts the metronome as well as the accompaniment, the stop button, the current beat, the recording button which starts the recording of the user's movements, the song selector and finally the four squares where each square represents one mode.
On the right side of the screen we can see the auto buttons for the fretboard as well as for the chord selector. If those buttons are activated the software strums automatically or changes chords automatically.
Below the status bar we can find the fretboard which shows us the strings and the finger-positions for the currently selected chord. When a string is triggered through the tangible user interface the virtual string starts to vibrate and therefore provides the user with visual feedback. On the right side of the strings we can switch off the wheel's pressure sensitivity and activate supported strumming which was explained in the software design section 3.1. Supported strumming assures a full strum and therefore eases the strumming if the user does not have total control over his/her strumming movement. Furthermore we can set the time after which the software considers a strum as finished. If the interval is set to 500 ms, the user has 500ms to plug the next string or the software considers the next pluck as a new strum and starts plucking from the top or bottom again, depending on the strumming direction.
At the lower third of the screen the subset of chords for the current song is shown. In the case of the shown example the song consists of a G, E minor, C

and D chord. The vertical red line represents the current location of the tangible interface's 'sledge' and depending on this position a chord is selected. In the case of figure 4.2 the C chord is selected. If the sledge would be moved left or right, the line would move left or right respectively and another chord would be selected. If the user wants to play notes instead of chords he/she has to switch to note mode. In note mode we can select and trigger single notes instead of chords as seen in figure 4.3.

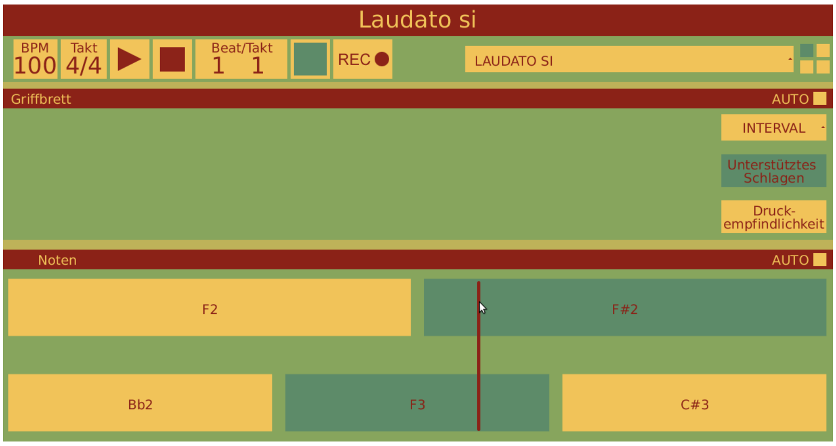


Figure 4.3: The graphical user interface in play mode (note mode)

In note mode the fingerboard disappears and instead of one array of chords we can now see two arrays of notes. In those arrays, two notes are always selected: one in the top and one in the bottom array. If the wheel on the tangible interface is now scrolled up, the top note is played and if scrolled down, the bottom note is played.
To add, remove or change order of the previously discussed chords or notes we have to switch to song edit mode which can be seen in figure 4.4.

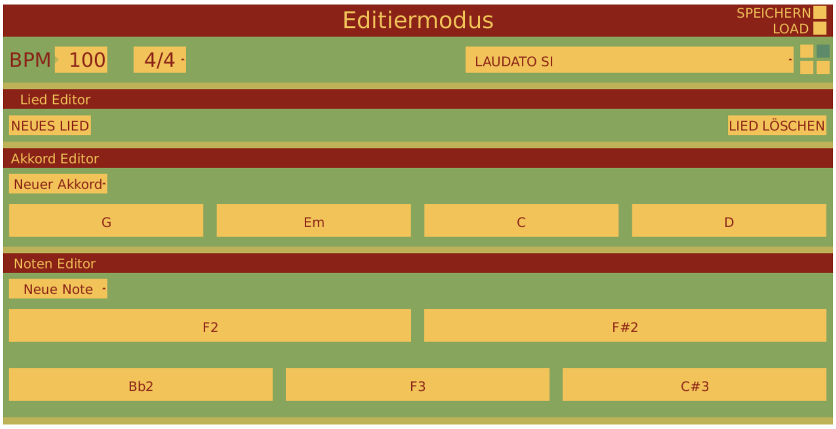


Figure 4.4: The graphical user interface in song edit mode

In the song edit mode we can change the tempo and the time signature of the currently selected song in the status bar. Furthermore we can create new songs or delete existing songs. For each existing song we can add, remove or rearrange the chords and notes.
For the auto-strumming and auto fretting-mode the software needs to know which chords to play and at what position to strum up or down. Therefore the user can set a strumming pattern as well as a chord sequence for each song. This is done in the accompaniment edit mode which can be seen in figure 4.5.

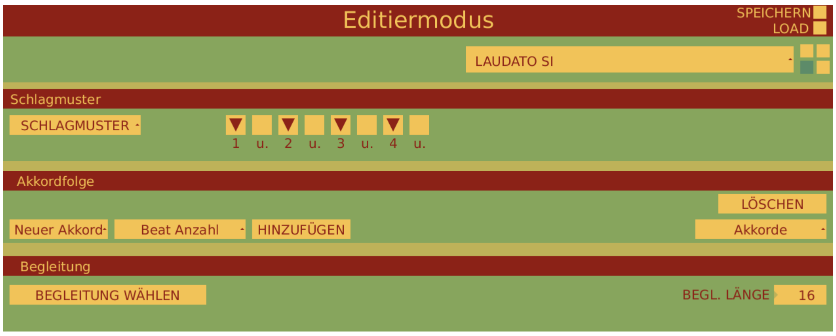


Figure 4.5: The graphical user interface in accompaniment edit mode

In this mode the user can also select a MIDI file which accompanies him/her while playing. The last and final mode lets the user choose which MIDI port the software should connect to and which USB port the tangible user interface should be connected to. Figure 4.6 shows the graphical user interface for the settings mode.

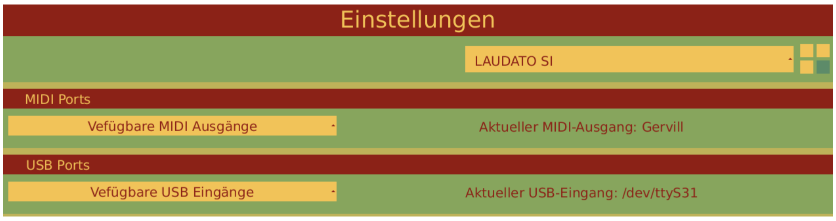


Figure 4.6: The graphical user interface in settings mode

4.3 Hardware

In this section it will be described how the design choices discussed in section 3.2 were implemented. One important aspect of the tangible user interface was to be robust and steady so it was decided to construct the interface out of metal. This makes it resistant against involuntary hits and steady enough not to slide on the table while being played. Figure 4.7 shows the latest version of the prototype.

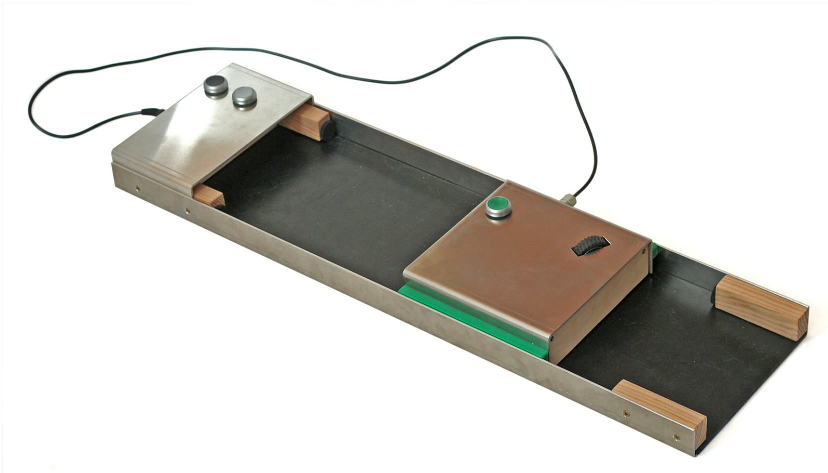


Figure 4.7: Latest version of the prototype

The TUI has a length of 80cm, a depth of 23cm and a height of approximately 4cm. The sledge has a size of 20cm by 20cm and has a moving range of approximately 50cm. The resistance of the sledge (how easy it can be pushed) can be adjusted. The sledge's position is estimated with the aid of a HR-SC04 ultrasonic sensor which has an accuracy of up to 3mm. The buttons are rather big so they are easy to press, but have additional a 'guard' around them which avoids pressing them by involuntary movement. Figure

4.8 shows the ultrasonic sensor as well as the buttons.

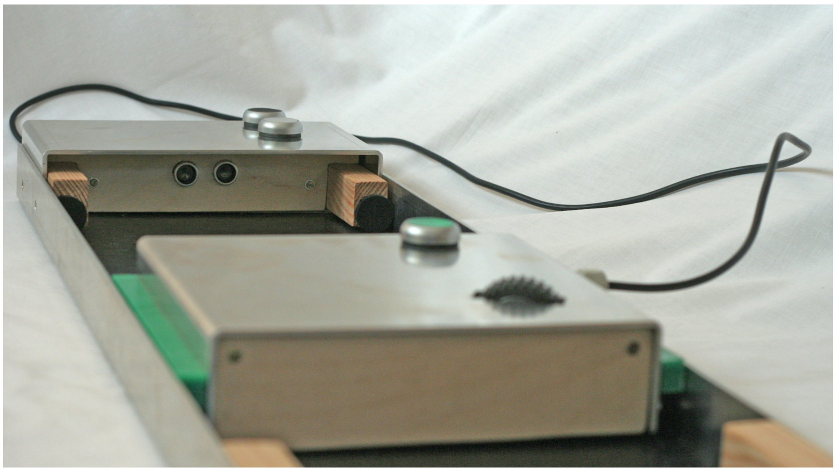


Figure 4.8: The ultrasonic sensor and the guarded buttons

The scroll wheel has a diameter of approximately 5 cm, and is implemented through a rotary encoder with 30 detents. A detent is equivalent to a string and therefore provides tactile feedback to the user. The rotary encoder is fixed to a hinge which is placed on top of a force sensing resistor. This allows the user to press the wheel a little bit into the interface and hence gives control over velocity. This mechanism can be seen in figure 4.9.

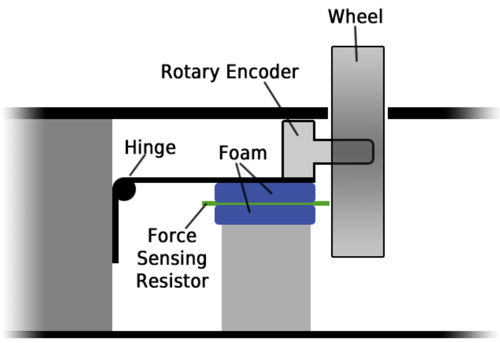


Figure 4.9: The mechanism of the pressure sensitive wheel

All the inputs are connected to an Arduino Uno which analyses the inputs and sends them via a serial connection to the computer, where the data is further processed by the software. The data from the HR-SC04 ultrasonic sensor is filtered by the Arduino to smooth the signal and therefore avoids 'jumps' between chords.

Chapter 5

EVALUATION

After the prototype was implemented it was given to the subject so he could use it on a daily basis and practice playing it. Figure 5.1 shows the subject playing the final prototype.

Figure 5.1: The subject using the guitar controller

The evaluation of the prototype was made based on four different evaluation methods. First the prototype was evaluated according to the user's playing ability over time. Besides this quantitative method, three additional quantitative evaluation methods were used. A usability and user experience test, an interview with the subject's supervisor and a music therapist were asked to review the interface. In the upcoming four sections the results for the different evaluation methods will be presented and the last section of this chapter will discuss the gained results.

5.1 Accuracy measure

The accuracy measure aims to track the user's playing ability over time and how it is effected by the song's complexity. For this test the user was asked to play and practice three different songs with increasing complexity. The songs were chosen based on the user's musical preferences. Knowing the strumming pattern and chord progression of the chosen songs, one can compare the played songs of the user to the original songs.
The first and easiest song consists of only two chords. The second song consists of four chords but in a very simple and straight forward sequence. The last and most complex song consists of four chords as well, but the chord progression is more complex and the user has to change between chords more often and in a more challenging pattern. Table 5.1 gives an overview of the three songs used during the evaluation procedure.

Song	1	2	3
Name	Die Welt	Laudato Si	Hallelujah
Tempo in BPMs	80	80	80
Chords	A,D	G,Em,C,D	G,D7,Am,C
Complexity	low	intermediate	high
Strum pattern	D-D-D-D-		
Time signature	4/4		

Table 5.1: Songs with different complexity

Each song was recorded for approximately one minute in each mode: first with auto-strumming support, then with auto-fretting support and last without any support.
The purpose of the quantitative evaluation is not only to know how the user is playing during a single session but to track his playing accuracy over time. Therefore the subject was asked to record each song on each mode once a week over a period of nine weeks.
The recorded data for each song, mode and week was analysed and features

such as chord amount, missing chords, additional chords, wrong chords and correct chords were extracted. The data was extracted from an excerpt of the recordings, namely from the beats between beat 7 to 97 and therefore consists of 90 beats. The chord amount (CA) is the amount of chords the user played within those 90 beats. The additional chord (AC) feature shows how many additional chords were played besides the chords which were supposed to be in the song. On the other hand the missing chords (MC) feature indicates how many of the supposed chords were missing. Wrong chords (WC) show how many of the chords which were played in the correct position had a wrong chord name. The correct chords (CC) show how many chords were played within the correct beat with the correct chord name. Furthermore the mean difference between the position of the correctly played chords and the the supposed positions of the chords were calculated.
To analyse the data a software was implemented which reads the recorded data, compares it to the original song, provides visual feedback and lists the aforementioned features such as chord amount, missed chords, wrong chords and additional chords. Figure 5.2 shows an example of the output window of the analysis software.

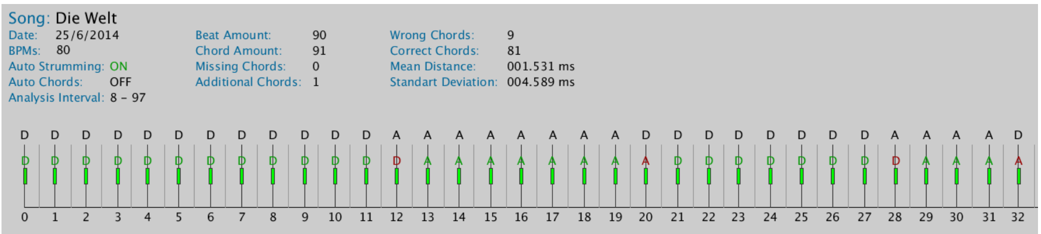


Figure 5.2: Output of the analysis software for the song "die Welt" in auto-strumming mode

In the example shown above, auto strumming was activated and therefore the strumming is very accurate and perfectly on time. In the upper left corner of the output window we can see information about the tempo of the recording, the time signature as well as the date of the recording. Wrong chords are indicated with a red letter whereas correct chords are green. Below we can see another example for the same song but in auto-fretting mode.

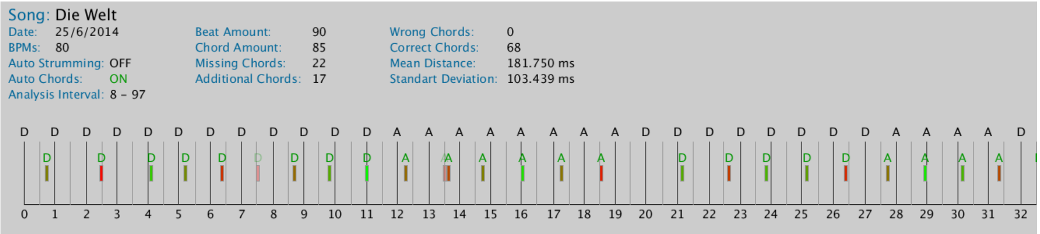


Figure 5.3: Ouput of the analysis software for the song "die Welt" in auto-fretting mode

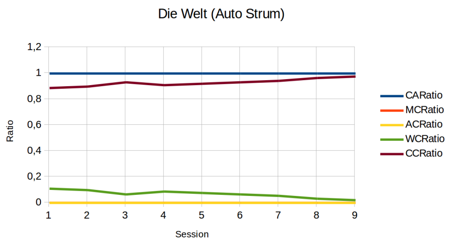
We can see that there are no wrong chord names as the chord changing is controlled by the software. On the other hand most of the strumming is very off which can be seen in the chords' colors. The color of the chord indicates how far the chord is from its supposed position, where green means close to the supposed position and the more red it gets the further the chord is from its supposed position.
From the features mentioned above the chord amount ratio (CAratio), the missing chord ratio (MCratio), the additional chord ratio (ACratio), the wrong chord ratio (WCratio) and the correct chord ratio (CCratio) were calculated. Table 5.2 shows how those ratios were computed.

Ratio	Calculation
CCratio	chord amount / beat amount
MCratio	missing chords / chord amount
ACratio	additional chords / chord amount
WCratio	wrong chords / chord amount
CCratio	correct chords / chord amount

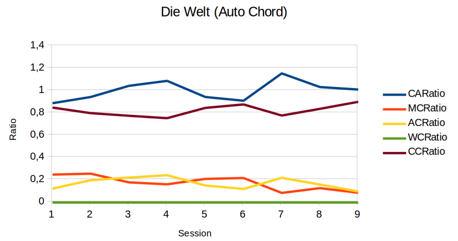
Table 5.2: The calculation for each ratio

Results

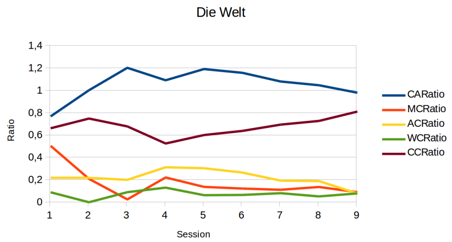
The graphs in the three following figures 5.4, 5.5 and 5.6 show the results for each song over all nine sessions. The first subfigure (a) shows the ratios with auto-strumming activated, the second subfigure (b) shows the ratios with auto-fretting activated and the third subfigure (c) shows the ratios without any support function activated. The last subfigure (d) of each figure shows the mean distance for each mode (auto strumming, auto chord, no support). All features for each song, mode and session can be found in appendix B.



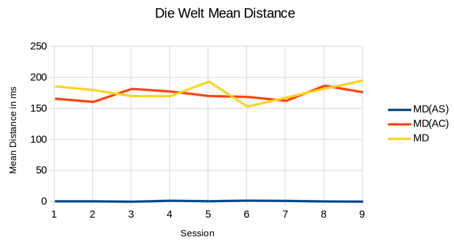
(a) Auto Strumming



(b) Auto Chord

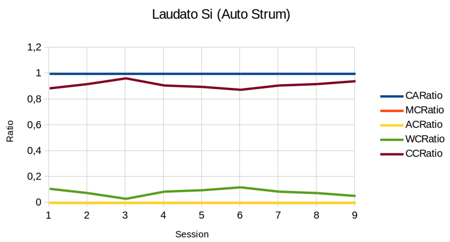


(c) No support

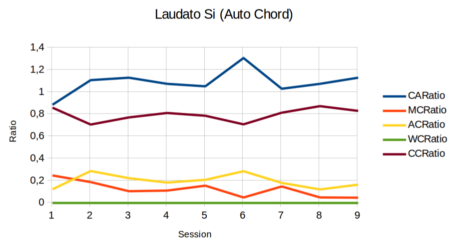


(d) Mean distance

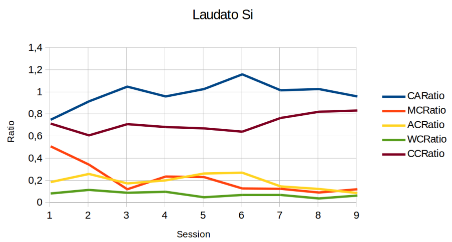
Figure 5.4: Results for the song "die Welt"



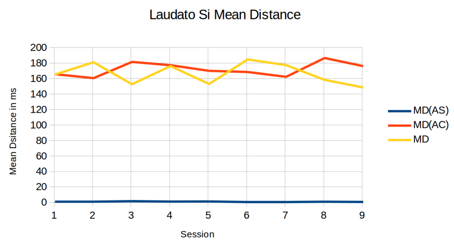
(a) Auto Strumming



(b) Auto Chord

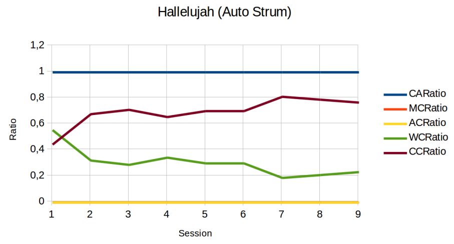


(c) No support

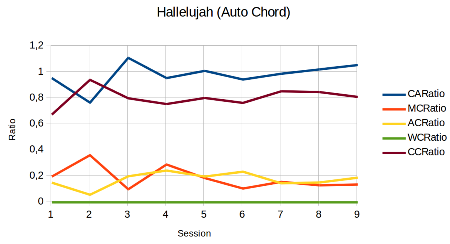


(d) Mean distance

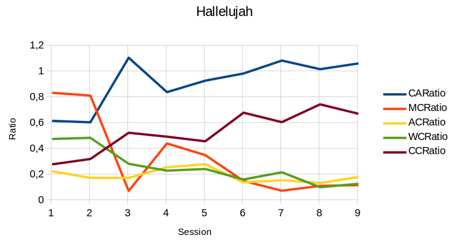
Figure 5.5: Results for the song "LaudatoSi"



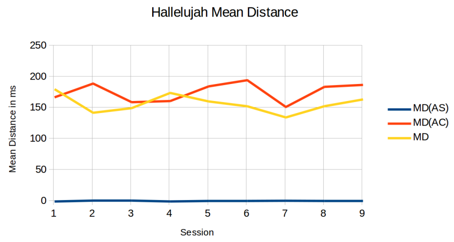
(a) Auto Strumming



(b) Auto Chord



(c) No support



(d) Mean distance

Figure 5.6: Results for the song "Hallelujah"

5.2 Usability and user experience test

The usability and user experience test aims to provide information about the subject's ability to achieve given goals and how he experiences the interface. For the usability test the subject had to accomplish a list of given tasks. While doing those tasks he was observed and asked to think aloud. After all tasks were accomplished the subject was asked to freely explore the interface and was interviewed afterwards. In the interview he was asked to tell the interviewee about his experience while using the interface as well as how the interface affected his life in general.

The usability test does not aim to test how well the user can play a song with the interface but rather if he can achieve goals such as setting up a song or changing the MIDI port. The usability test started with simple tasks such as *"Start the software!"* and progressed to more difficult tasks such as *"Add a song called "Laudato Si" which has a tempo of 100BPMs and a 4/4 time signature!"* and *"Press play and play along with the first part of the song!"*. The tasks were designed to cover the most important features of the soft- and hardware. A full list of all given tasks can be found in the Appendix A.

User experience tests usually focuses on the experience while using a product or interface over a short time and are mainly meant to indicate the short term experience. In our case we focussed more on the overall experience after using

the interface for several weeks and how the usage has influenced the life of the user. For a user experience test to be successful the user should use the product over a longer period of time in a natural environment. As our subject used the interface for more than eight weeks in his workshop, those previously mentioned requirements are fulfilled.
For the user experience test an unstructured interview was chosen to let the subject freely express his feelings without giving him the impression of being interviewed.

Results

For the usability test the subject was able to fulfil all the given tasks. However as an observer the following problems were noticed:

- buttons to change modes were not clear to the user
- change of hand positions when using auto strumming mode and the other modes
- hand moved on sledge while sliding
- user changed fingers while strumming

When the user was asked to express his feelings about the project he stated: *"I'm happy that I can finally learn to play the guitar. It is still difficult to play the songs, especially the strumming. But as with a traditional instrument, it needs a lot of practice to become an expert. With the auto strumming activated I can play already a few songs and I even gave a small performance to my colleagues. When Roberto (his supervisor) was accompanying me with the piano I felt like playing in a band and it made me really proud when my colleagues were listening to me playing guitar. My goal is to practice a lot so I can play at our workshop's anniversary next year. It is still a long way but I'm eager to practice."*

5.3 Supervisor interview

In the previous section the subject itself was interviewed and asked about his experience. However, self report can be biased and therefore we will in this section interview the subject's supervisor. This gives a second opinion and a more neutral view on the subject's conditions. First the supervisor was asked about his personal opinion of the interface. Afterwards the supervisor described the subject's condition and lastly he explained how he experienced changes in the subject's life throughout the introduction and use of the interface. Below one can find the questions(Q) and answers(A).

Interview

Q: What is your personal opinion about the interface?

A: *Within the therapeutic pedagogy educational objectives are categorized into several personal areas. Those areas are the area of senses and perception, the cognitive area, the motor area, the social area and the language and communication area. It is rare that one can access all those areas with a single activity. However with the proposed guitar interface this is possible.*

Q: Can you tell us little bit more about Ralf and what his tasks are at the sheltered workshop.

A: *Ralf has a strong physical impairment, but he has no mental handicap. That is why he has limited access to many activities as well as every day situations. Even though he is bound to the wheelchair due to his strong impairment, he is able to use the computer with the aid of a mouse and keyboard specially designed for his needs. He is writing for the sheltered workshop's internal newspaper. Even though his voice is very "fuzzy" and "washed-out" he always sings along if he hears a song. That is probably one reason why he is interested in music and so eager to learn a musical instrument.*

Q: Have you noticed any changes in Ralf's behaviour and if yes, how did he change?

A: *Throughout the project I noticed improvements in basically all areas of his personality. Ralf has been very motivated and determined during the whole project. He started to deal with his impairment in a different way and therefore extended his own boundaries. He became more open and I also think he became more extroverted. The project gave him a new awareness of life. It is hard to describe how happy he is when we do some recordings together, but statements like "This interface is awesome" give a glimpse into his enthusiasm. When colleagues are visiting him and are interested in the interface he excitedly explains it to them and demonstrates what he can perform already. His interpersonal skills definitely improved and he can strongly identify himself with the interface. All this added to an increase of his self-esteem. Based on the concentration over a long period of time and the progression of* *difficulty of the songs he has to train his cognitive skills. This extended concentration could also be noticed in other everyday activities such as writing on the computer or reading. Another important part of this project is the improvements in his motor skills. Due to the sliding of the sledge from one side to the other and the simultaneous scrolling of the wheel his hand-eye coordination gets trained and in my opinion has improved since the beginning of the project. In the beginning it was hard for him to move the sledge to a certain spot, now the movement is much more precise. Now he also uses both hands to control the sledge. He uses one hand for scrolling the wheel and moving the sledge and his second hand supports the other hand by acting like a 'brake' for the sledge. This is interesting because usually Ralf does not use his weaker hand for any task. I'm sure this will improve his coordination between both hands and in future he might use his weaker hand also in everyday tasks. Based on the increased verbal communication between him and his colleagues and friends, I could notice improvements in his articulation during the last six months. He pronounces the words and sentences more clearly and less hectically, so misunderstandings decreased and the communication with him is just easier. This might seem like small improvements, but in therapeutic pedagogy improvements usually take months or years to be significant. We can already see good first signs and I believe that the previously mentioned improvements will still develop further.*

5.4 Review by an music therapist

During the project it became more and more obvious that the interface might be useful for music therapy. Even though this was not the main focus of the research it is interesting to know a music therapist's opinion about the interface. Therefore a music therapist was contacted and asked to write a review on the interface. The review can be found below.

Review

In the beginning mainly instruments from music education were used for music therapy, but later instrument makers and music therapists started to develop instruments for therapeutic use. These instruments are usually easy to handle and can be played without any musical background knowledge. Often instruments such as the "Klangliege" are used for receptive music therapy where the user is listening to music rather than actively creating music.
Even though a broad range of therapeutic instruments exists, the range of instruments for people with severe motor disabilities is still rather small. Many

motion sequences, which seem natural, are nearly impossible to execute for patients with motor disabilities and therefore most instruments are just too complex and hence unplayable.
The guitar requires very complex fine motor skills and therefore people with motor disabilities are usually very limited in playing the guitar or not able at all. The proposed interface allows those people to play the guitar and hence it is from a music therapeutic point of view very useful. The patient is able to play complete songs by moving his hands and therefore he experiences a strong feeling of self-efficacy. The experience to actively execute an operation is very rewarding, especially for people with motor disabilities and the feeling even increases if the operation is something joyful like playing an instrument. It is not necessarily essential that the musical outcome is very accurate but rather that the patient has the feeling that he/she is able to achieve some outcome with his movements. The sense of self-worth can increase enormously if the patient can play a musical instrument which he/she has chosen, instead of taking one of the available instruments which he/she would be able to play with his/her disability. Movements which the patient has to execute while playing will be improved and through the music the patient can experience new ways of expression, different interaction patterns, appreciation, joy and a better quality of life in general.
As the guitar controller could be extended to other instruments and can be adjusted to the patients abilities, it has a lot of potential in music therapy for people with motor disabilities. Until now the usage of digital media in music therapy is at least in Germany still in the beginning stages, especially if its for people with severe disabilities. I think there is a lot of potential in the new media. An important requirement for the proposed interface as well as other novel interfaces is a positive attitude in regards to new interfaces on the music therapist's side. In the Netherlands for instance the usage of digital media is already included in the education of music therapists and is well accepted. It would be desirable if in future the same would happen in Germany and other countries.

5.5 Discussion

In this section we will discuss results which we gained in the previous four sections. We will keep the order as presented above and therefore start with the results of the accuracy measurements.
When looking at the first graph for each song (with auto strumming activated) we can see that the chord amount ratio (blue) stays one. This is because auto-strumming is activated and therefore the amount of played chords

equals the amount of supposed chords. We can also see a slight improvement of correct chords over the nine weeks for all three songs. However these improvements are not even and sometimes the user has a slightly worse result in a following week compared to a previous week. This could be because the recordings are just control samples and maybe in the recorded minute the user had a "bad or good moment" or was somehow distracted.
Slight improvements also hold true for the strumming only, with auto chords activated. The user improved his performance over the nine weeks. We can also see some outstanding performances such as session seven for the song "die Welt", session six for the song "Laudato Si" and session three for the song "Hallelujah". These peaks could be noise, based on the fact that the recordings are just control samples.
The performance with no support is as expected still much lower compared to the performances with auto modes activated. However, even here we can see an improvement from the first session to the last session. It is interesting to see that the performance of the most complex song increased the most in the case of no support.
The mean distance from the correct chords to the original chords stayed around 180ms for all three songs which indicates that the strumming is still random. The maximum distance from a played chord to the original chord at a speed of 80 BPMs and a down strum for every beat is 375 ms, and therefore a random strumming would average between 0ms and 375ms which is 187ms.

The usability test suggests a few improvements for upcoming prototypes. For instance the functions of the software buttons seem to be unclear and should have a more clear design. A small label could for instance enhance the understandability of the graphical user interface. Another very important observation is that the user applies different hand positions when playing the interface in different modes. When auto strumming is activated he rests his left hand on the edge of the sledge, so just his fingers are on the sledge, but his palm is in front of the sledge and his thumb is being used as a "brake". However, with this hand position he is not able to reach the wheel with his fingers and if he has to strum he has to move his hand to another position. Changing the location of the wheel could change this behaviour. It was also observed that his hand moves around the sledge when sliding movements are executed. This leads to the fact that he has to use different fingers for the strumming depending on his hand position. A broader wheel as well as some kind of hand guidance could be implemented to avoid those problems. To see if those changes would aid the user and improve his/her performance additional testing would be needed.
Besides the previously described problems the user is really satisfied and

happy when playing the interface. This could be clearly observed in his facial expressions as well as deduced from his interview given in regards to the user experience. Even though he did not mention in particular that his self-confidence increased, a rise could be noticed by his supervisors as well as by the observer and his colleagues. Overall he became more open and sees his disability from a different angle. These indications corresponds to the music therapist's statement from section 5.4 who says that is not necessarily essential that the performance's outcome has to be very musical, but rather that the user has the feeling of being able to make something happen. This could explain why the user shows signs of satisfaction even though the accuracy measure indicates that the strumming is still random.

Even though the qualitative tests show that the user enjoys playing the instrument and also the accuracy measure partly indicates that the user improved his performance, it is important to keep in mind that this research is based on a single subject. Therefore it is impossible to make any general conclusions and further research should be conducted with a higher amount of participants.

Chapter 6

CONCLUSION

This research was conducted to determine if the limited movement of a person with Cerebral Palsy can be mapped to a guitar controller interface which allows the user to access the benefits of music and hence improve their quality of life.
For this purpose a universal software prototype as well as an individual hardware prototype was designed, implemented and tested. The results show a slight improvement in the users performance for the chord changing movement, however the strumming movement is still rather random. Besides this quantitative results, the qualitative results indicate an improvement of self-confidence and interpersonal interaction. One can conclude that those improvements will result in a better quality of life. However all the results are strongly individual and further research with more participants should back up those findings.
All in all, the work presented in this thesis shows a way in which an interface for people with motor disabilities can be developed, implemented and tested. Even though the quantitative results do not show any significant evidence, the interview with the subject himself as well as the interview with the supervisor are very promising and motivating for further investigation.

Chapter 7

FUTURE WORK

The research conducted in this thesis belongs to a relatively new field of research and therefore there are many possibilities for further research.
The most obvious direction would be to improve the current prototype with suggestions made based on the discussion 5.5. This could be for instance a broader wheel and a different wheel location. Furthermore a single-board computer such as the Raspberry Pi could be incorporated into the system to make the prototype independent from an external computer and therefore more ergonomic.
To make any final conclusions the prototype should be tested with more participants to back up the results we gained during this research. Even participants with disabilities other than Cerebral Palsy but similar symptoms could be used to see how the prototype would perform for them. One could also test how people without disabilities and without musical background knowledge would perform over time using the proposed interface. Another group with which to test the prototype could be children.
An option would also be to step back from the current design and reconsider the hardware design choices. When the different sensors were tested, we decided to test each sensor for about two minutes based on time limitations. But what if for instance the joystick and the wheel had learning curves as shown in figure 7.1?

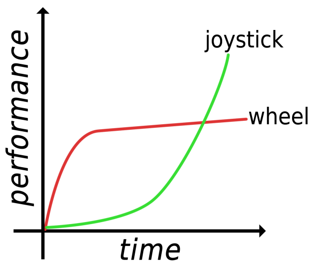


Figure 7.1: Hypothetical learning curves for a joystick and a wheel

After a short amount of time it seems like the wheel would outperform the joystick but in the long run the joystick would have been a better choice. This example indicates that further research in the field of sensor technology in regards to interaction with people with motor disabilities is needed.
Another interesting possibility would be to test the interface which was designed for musical purposes in other fields of human computer interaction. For instance one could try to use the interface as a mouse pointing device where the sledge position determines the x-position of the cursor and with the wheel the user can control the y-position of the cursor.
It could also be possible to try to map the interaction from the interface to a normal mouse where the user can change chords with the mouse movement and trigger them by either pressing a button or using the mouse's scroll wheel.
As mentioned earlier the software part of the system should be compatible to other means of input besides the tangible user interface developed during this project. One could try to develop other means of input to control the software such as an eye-tracking device, an blow sensor or a different tangible interface.

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Appendix A

USABILITY TASKS

1) Start the software!
2) Create a new song!
3) Name the song "Test"!
4) Set the tempo of the Song "Test" to 80 BPM!
5) Set the time signature of the Song "Test" to 4/4!
6) Add a C chord, a G chord, a A chord and a F chord to the "Test" song!
7) Remove the A chord!
8) Switch positions of the C and F chord!
9) Add a C3, a G7, a F7 note to the "Test" song!
10) Create a combined note by adding a F3 to the C3 note!
11) Switch positions of the C7 and F7 note!
12) Add a Down, Down, Down, Down strumming pattern to the "Test" song!
13) Add a C,G,F,G chord progression to the "Test" song where each chord should last 4 beats!
14) Add a MIDI file for accompaniement to the "Test" song!
15) Add a song called "Laudato Si" which has a tempo of 100BPMs and a 4/4 time signature!
16) Save your song setup!
17) Go back to play mode and switch back to "Test" song!
18) Activate auto strumming and check if it is sucesfully activated!
19) Press play and play along (change chords) with the first part of the song!
20) Stop the song!
21) Deactivate auto strumming and activate auto fretting!
22) Check if auto fretting is successfully activated!
23) Press play and play along (strum) with the first part of the song!
24) Stop the song!
25) Deactivate auto fretting!
26) Press play and play along with the first part of the song!

27) Stop the song!
28) Record some of your playing!
29) Deactivate strum support!
30) Play only the first three strings of the first chord!
31) Play the last two strings of the last chord!
32) Activate pressure sensitivity!
33) Play a chord with full velocity!
34) Play a chord with low velocity!
35) Switch to note mode and plug a C7!
36) Delete the "Laudato Si" song!
37) Change the USB port to some other port!
38) Change the MIDI port to some other port!
39) Close the software!

Appendix B

ACCURACY MEASURE RESULTS

Table B.1 shows all the results for each song, mode and session. The abbreviation for the features are: CA=Chord Amount, MC=Missing Chords,AC= Additional Chords, WC=Wrong Chords, CC=Correct Chords, MD=Mean Distance and SD= Standard Deviation

	AutoChord	AutoStrum		17.06.14	24.06.14	02.07.14	15.07.14	22.07.14	29.07.14	05.08.14	12.08.14	19.08.14
Die Welt	OFF	ON	CA	90	90	90	90	90	90	90	90	90
			MC	0	0	0	0	0	0	0	0	0
			AC	0	0	0	0	0	0	0	0	0
			WC	10	9	6	8	7	6	5	3	2
			CC	80	81	84	82	83	84	85	87	88
			MD	1,55	1,531	0,738	2,268	1,506	2,393	2,012	1,143	0,8
			SD	4,604	4,589	3,218	5,466	4,587	9,079	5,209	4,08	3,399
	ON	OFF	CA	80	85	94	98	85	82	104	93	91
			MC	20	22	17	16	18	18	9	12	8
			AC	10	17	21	24	13	10	23	15	9
			WC	0	0	0	0	0	0	0	0	0
			CC	68	68	73	74	72	72	81	78	82
			MD	164,333	181,75	169,123	182486	188,111	205,708	152,222	180,648	174,84
			SD	104,168	103,439	101,835	105969	110,542	103,191	99,798	151,29	103,305
	OFF	OFF	CA	70	91	109	99	108	105	98	95	89
			MC	36	20	4	23	16	14	12	14	9
			AC	16	21	23	32	34	29	20	19	8
			WC	7	1	11	14	8	8	9	6	8
			CC	47	69	75	53	66	68	69	70	73
			MD	186,894	180,696	171,156	170,981	194,409	154,015	168,56	183,133	196,116
			SD	92,637	113,046	112,838	103,267	110,254	95,606	104,015	116,951	116,029
Laudato Si	OFF	ON	CA	90	90	90	90	90	90	90	90	90
			MC	0	0	0	0	0	0	0	0	0
			AC	0	0	0	0	0	0	0	0	0
			WC	10	7	3	8	9	11	8	7	5
			CC	80	83	87	82	81	79	82	83	85
			MD	2,175	2,048	2,678	2,146	2,309	1,405	1,756	1,963	1,655
			SD	5,389	7,944	5,85	5,393	5,51	4,407	4,984	5,158	4,706
	ON	OFF	CA	80	100	102	97	95	118	93	97	102
			MC	20	19	11	11	15	6	14	5	5
			AC	10	29	23	18	20	34	17	12	17
			WC	0	0	0	0	0	0	0	0	0
			CC	69	71	79	79	75	84	76	85	85
			MD	166,862	161,746	182,718	178,459	171,2	169,726	163,486	187,785	177,259
			SD	95,69	110,24	107,789	105,24	106,555	100,994	101,835	103,177	111,159
	OFF	OFF	CA	68	83	95	87	93	105	92	93	87
			MC	35	29	12	21	22	14	12	9	11
			AC	13	22	17	18	25	29	14	12	8
			WC	6	10	9	9	5	8	7	4	6
			CC	49	51	68	60	63	68	71	77	73
			MD	166,449	182,275	153,868	177,3	154,222	185,897	178,635	159,519	149,684
			SD	94,104	102,236	87,182	114,321	104,917	101,688	103,686	102,582	106,547
Halleluja	OFF	ON	CA	90	90	90	90	90	90	90	90	90
			MC	0	0	0	0	0	0	0	0	0
			AC	0	0	0	0	0	0	0	0	0
			WC	50	29	26	31	27	27	17	19	21
			CC	40	61	64	59	63	63	73	71	69
			MD	0,775	2,344	2,019	0,814	1,444	1,476	1,918	1,514	1,667
			SD	3,29	5,593	5,165	3,42	4,437	4,525	5,056	4,506	4,783
	ON	OFF	CA	86	69	100	86	91	85	89	92	95
			MC	17	25	10	25	17	9	14	12	13
			AC	13	4	20	21	18	20	13	14	18
			WC	0	0	0	0	0	0	0	0	0
			CC	58	65	80	65	73	65	76	78	77
			MD	168,052	190,138	160,23	162,031	185,644	195,523	152,526	184,833	187,959
			SD	104,962	107,56	102,597	101,707	109,415	103,568	101,22	104,768	112,899
	OFF	OFF	CA	56	55	100	76	84	89	98	92	96
			MC	47	45	8	34	30	14	8	11	12
			AC	13	10	18	20	24	13	16	13	18
			WC	27	27	29	18	21	15	22	10	13
			CC	16	18	53	38	39	61	60	69	65
			MD	181,052	143,222	150,679	175,105	161,41	153,623	135,717	153,787	164,635
			SD	98,011	75,165	92,614	100,456	110,91	91,029	98,477	93,386	112,978

Table B.1: Results for each song, mode and session