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THE ACTUATED GUITAR

I INVESTIGATING HOW LIMITED EXPRESSIVENESS AND LATENCY OF A FOOT PEDAL/ACTUATOR AFFECTS ONE-HANDED PLAYING OF AN ELECTRICAL GUITAR FOR HEMIPLEGICS

BY
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The Actuated Guitar

Investigating how limited expressiveness and latency of a foot pedal/actuator affects one-handed playing of an electrical guitar for hemiplegics

Ph.D. Dissertation

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Jeppe Veirum Larsen received his M.Sc. in Medialogy Design from Aalborg University, Denmark in 2011. He worked as a research assistant at Aalborg University before starting his PhD in March 2013 in the Media Technology department at Aalborg University. While working on his PhD, Jeppe spent several prolonged periods at the Helena Elsass Center in Charlottenlund, Copenhagen run by the Elsass Foundation, which works to improve opportunities through research and communication for people with cerebral palsy. There he collaborated with Professor M. D. PhD Jens Bo Nielsen from the University of Copenhagen. Jeppe has been involved in the supervision of undergraduate and graduate students on the topics of image processing and computer vision, game design, and alternate input devices, and he has taught the courses A/V Production and Human Senses and Perception in the Medialogy bachelors program.

Abstract

With a growing number of stroke patients anticipated as the elderly population increases worldwide, the costs of stroke rehabilitation will also rise in the coming years. Successful self-rehabilitation at home is important for keeping those costs down, and sustaining a patient's motivation is crucial to the success of self-rehabilitation. The use of musical instruments in self-rehabilitation is beneficial for stroke patients, and the use of existing musical instruments removes the risk of stigmatization and likely increase uptake. This thesis focuses on how limited musical expression and high latency might affect long-term motivation related to self-rehabilitation at home through the use of modified existing musical instruments. The investigation includes the use of a modified electrical guitar in both supervised and unsupervised settings by hemiplegic users with either inherent (spastic) or acquired brain damage (stroke) as well as by those with no brain damage in a supervised setting. The thesis starts by introducing HCI in the context of rehabilitation after brain damage and how music can contribute to rehabilitation. This is followed by a presentation of the areas within assistive technology and musical expression, the existing literature in the area, and the three iterations of the modified electrical guitar (The Actuated Guitar). As a contribution to the research area, the thesis also presents seven papers within the area of interfaces for musical expression.

Resumé

Det forventes, at antallet af mennesker, som rammes af blodpropper eller blødninger i hjernen, vil stige, eftersom den ældre andel af befolkningen vokser verden over. Derfor er succesfuld selv-rehabilitering i hjemmet vigtig for at holde omkostningerne hertil nede. For at selv-rehabilitering skal blive en success, er det vigtigt at facilitere og fastholde en vedvarende motivation hos patienten til at selv-rehabilitere. Brugen af musikinstrumenter er gavnlig for patienter med hjerneskade, og inddragelse og brug af eksisterende musikinstrumenter er med til at mindske evt. stigmatisering og sandsynligvis øge brugen. Denne afhandling fokuserer på, hvordan begrænset musisk udtryk og stor forsinkelse muligvis påvirker motivation over tid i forhold til selv-rehabilitering i hjemmet, når der anvendes et modificeret eksisterende musikinstrument. Undersøgelserne omfatter en modificeret elektrisk guitar anvendt af delsidigt lammede brugere, som enten har medfødt eller erhvervet hjerneskade, i både superviserede og ikke-superviserede sammenhænge. Ud over disse er der også testet på ikke-hjerneskadede personer i en superviseret sammenhæng. Denne afhandling starter med at introducere HCI i en hjerneskaderehabiliteringskontekst, og hvordan musik kan bidrage til rehabilitering. Dette er efterfulgt af en præsentation af eksisterende litteratur inden for området og de tre iterationer af den modificerede elektriske guitar (The actuated guitar). Som et bidrag til forskningsområdet præsenterer denne afhandling også syv artikler inden for området brugergrænseflader for musisk udfoldelse.

Contents

Preface

This thesis is submitted as a collection of papers in partial fulfilment of a PhD study in Media Technology, Department of Architecture, Design and Media Technology, Aalborg University, Denmark. The thesis is organised in two parts. The first part contains the motivation, background and a summary and conclusion of the included papers. The second part contains the included papers. The work was conducted from March 2013 to June 2017. I would like to thank everyone at the Department of Architecture, Design and Media Technology for their support and every person who participated in my studies. Thanks to my supervisors Thomas B. Moeslund for this opportunity, Dan Overholt for his insights and knowledge within the field and Hendrik Knoche, who provided extraordinary assistance. I also would like to thank the Ludvig and Sarah Elsass Foundation for making this PhD possible and Peder Esben Bilde, Jens Bo Nielsen and Jakob Lorentzen for organizing access to the Helena Elsass Center.

Jeppe Veirum Larsen
Aalborg University, August 15, 2021

Part I

Introduction

Chapter 1

Introduction

The western world's population is ageing. More and more people from the huge 'post-war' or 'baby boomer' generation are retiring. Better living standards and improvements in medicine and health care have prolonged their life expectancy. The combination of a growing population of elderly people and a simultaneous decline in the birth rate presents a conundrum as the minority must increasingly support the majority. This change in demographics will strain national health care budgets as health care costs increase in tandem with a growing elderly population.

The number of stroke victims worldwide is also growing; 70% of stroke victims are over 65 years of age [7]. In Denmark the number of stroke victims will increase by around 40% by the year 2035 [3], caused by the gradual increase in life expectancy. If the stroke rate increases by just 1% the number of stroke victims will more than double by 2035. In 2001 treatment of stroke victims in Denmark cost 2.7 billion DKK, which was, at that time, 4% of the total health care budget [3].

Following a stroke, acute treatment starts with a focus on life-saving treatments, limiting damage to the brain, and preventing new strokes. In the following weeks spontaneous recovery happens during which the victim recovers some of their lost abilities along with rehabilitation of the most basic functions. The victim is moved from the hospital to a rehabilitation center where intensive rehabilitation continues until they are sent home. This can take from a few weeks to half a year, depending on the severity of the person's disabilities [2].

When the patient is sent home they can find it difficult to keep up the motivation to carry out self-rehabilitation [15]. Rehabilitation is hard work that requires many repetitions to yield results, which can be extremely frustrating for the person, especially when they do not have a therapist to help plan, motivate, and execute the rehabilitation. This can result in complete abandonment of any self-rehabilitation that otherwise could give them better physical and cognitive skills and make them less dependent on others for support and care.

Many of the devices designed for rehabilitation are large complicated machines or weights that are similar to those found in a gym made for static repetitive exercises. This type of rehabilitation is good for people who are motivated by repetitive exercises, but many end up abandoning this type of exercise as it is not motivating in the long term. Stroke also has a social cost, and many lose a large part of - or their entire - social network as they can no longer do what they used to do, need special care, and thereby lose a part of their identity.

A way to keep people motivated and active in their social circles is through assistive devices that help them self-rehabilitate through activities they did before they had the stroke. Help a person who loved to paint to keep painting. Help a woodworker who loved to turn vases on his lathe to keep turning wood. Help a person who loved playing music to continue playing his instrument, etc. As with all assistive devices, however, these means are limited compared to what the user could do before the stroke. The big question is whether the limitations of the devices are too large and eventually cause the person to lose motivation and abandon self-rehabilitation.

1.1 Hypothesis and Research Questions

Little research has been done within the field of interfaces for musical expression that explicitly targets people with physical disabilities. Of the research that has been done the main focus has primarily been on alternate controllers with highly reduced complexity and little to no resemblance of existing musical instruments. This research consists primarily of proof of concept studies that look for new or alternate interactions. There is no focus on the long-term implications of the controllers, either for general use or in a rehabilitation context. Furthermore, there are no examples of studies that focus on how to make interfaces that enable people to play existing musical instruments. Increased self-rehabilitation eventually leads to less dependence on support and aid in everyday tasks. Using already existing and established technologies (in this case, musical instruments), the user can tap into already existing activities and materials supporting musical instruments.

For this thesis I have constructed the following hypothesis:

Enabling or re-enabling people with disabilities to play an existing musical instrument can serve as a long-term motivator for self-rehabilitation through musical activity and improve their quality of life.

For the purpose of testing this hypothesis I address the following research questions:

- *How can an electrical guitar be modified to make it usable for people with hemiplegia?*
- *How does the potential reduction in musical expression through latencies or delayed auditory feedback affect the ability to produce rhythmical music and influence the level of motivation and long term use of the guitar?*

1.1.1 Motivation

As a musician I know firsthand the fun, joy, and satisfaction that playing a musical instrument provides. Being able to play the instrument of one's hero, express oneself through music, learn and play along to one's favorite tunes, and write one's own music are extremely satisfying and motivating. Playing music is also a social endeavor through which one comes together and interacts with other musicians to perform or improvise a tune as well as interact with an audience that can enjoy and applaud the performance.

Some people are not so fortunate, however. Some never get to experience the fun and joy music can give because of disabilities that prohibit them from interacting with and playing musical instruments, while others are suddenly unable to play an instrument because of a disability caused by, for example, a stroke. Enabling people with no prior access to existing musical instruments and re-enabling former musicians access to existing musical instruments are the motivation for this thesis. The core idea is that playing a musical instrument is so rewarding that all people should be allowed to try it.

1.1.2 Paper Overview

During my work on this thesis I published a total of seven papers. In this section I briefly describe the papers and how the they connect to each other and the thesis. An overview of the papers can also be seen in Table 1.1 on page 9.

The Actuated Guitar: A Platform Enabling Alternative Interaction Methods (P1) suggests an exploratory platform called the actuated guitar that facilitates simple strumming and flexible mapping of user input for one handed use. The platform utilizes a normal functioning electrical guitar fitted with an actuator for strumming and a micro-controller processing sensor data. The idea the paper builds on is to modify existing musical instruments for a greater feeling of empowerment and inclusion in society.

The Actuated Guitar: Implementation and User Test on Children with Hemiplegia (P2) extends the work of (P1) as a proof of concept study, investigating whether children in the age range of 11 - 13 were able to interact with the actuated guitar as intended. The paper also investigates through interviews how the children used music or musical instruments of any sort in their everyday life. The results show that children with hemiplegia were able to interact as intended with the guitar, producing rhythmical movement across the strings. The actuated guitar empowered the children by allowing them to use a musical instrument that would otherwise have been impossible to play. The interview revealed that the children used music like any other children, but the use of musical instruments in school and at home were extremely limited. The children were highly aware of their own physical limitations and did not set goals, like playing a musical instrument, which seemed impossible.

During a stay at the Helena Elsass Center I observed a rehabilitation class to get a better understanding of how the center carried out their rehabilitation. The publication *Exercising the Tibialis Anterior Muscle of Children with Cerebral Palsy for Improved Neuroplasticity using an Electrical Guitar* (P3) is a short paper suggesting how the actuated guitar, using a foot controller for player input, can improve or extend a common exercise to improve dorsiflexion for combating foot drop. The paper discusses how the use of the actuated guitar with a foot pedal could serve as functional therapy, going from a passive to active exercise, neuroplasticity and thereby improving neurorehabilitation to improve gait.

The Prospects of Musical Instruments For People with Physical Disabilities (P4) is a review paper based on the knowledge gathered through my literature review. The focus of the paper is within the field of musical instruments for people with physical disabilities and looks at the current state of development. It includes a survey of 16 custom designed instruments, augmentations/modifications of existing instruments, and recent trends in the area and provides insights for potential future work.

States and Sound: Modelling User Interactions with Musical Interfaces (P5) is the second paper originating from the literature review. During the literature review it became evident that there was not a common vocabulary for modeling and describing the musical expressiveness of an Interface for Musical Expression. The paper suggests a model based on the idea of states to inspire the community to discuss and work on a common vocabulary to further enhancer their work and research.

Latency is often described as the most important factor when evaluating sound devices, be it instruments or recording interfaces. But despite the large amount of focus on this topic many musical instruments exhibit an inherent latency or delayed auditory feedback between actuator activation and the occurrence of sound. To better understand how the latency of the actuated guitar affected musically trained and non musically trained people I published *Hear You Later Alligator: How delayed auditory feedback affects non-musically trained people's strumming (P6)*. This paper investigates how Delayed Auditory Feedback from the actuated guitar affects people's ability to synchronise the audible strum of the actuated guitar to a metronome beat at two different tempi, 60bpm and 120bpm. Two different kinds of input devices were used with feedback before or on activation to compare their individual performance. While 250ms Delayed Auditory Feedback hardly affected musically trained test participants, when it was close to a subdivision of the main tempo, non-musically trained test participants' performance declined substantially both in mean synchronisation error and its spread. Neither tempo nor input devices affected performance.

A Longitudinal Field Trial with a Hemiplegic Guitarist Using The Actuated Guitar (P7) investigates how the actuated guitar can be used to avoid a common but significant problem for all rehabilitation, which is abandonment. A lack of motivation often causes people to abandon their rehabilitation, especially when it is carried out at home. During a three week period a post-stroke former guitarist relearned to play the actuated guitar to see if it would help increase motivation for self rehabilitation and quality of life. During the intervention the participant had the actuated guitar at his full disposal. The study showed that the test participant played 20 sessions, despite system latency and reduced musical expression, and displayed signs of high motivation. During the intervention he incorporated his own literature and equipment into his playing routine and improved immensely as the study progressed. The test participant was able to play on his own and keep a steady rhythm that were in time with backing tracks that went as fast as 120bpm. During the study the test participant was able to reduce his error rate to 33% and his average flutter also decreased.

P1, P2, P6 and P7 try to answer the two research questions, while P3, P4 and P5 try to broaden the field of research with interfaces for musical expression.

1.2 Contributions

The thesis contributes a literature review, an artifact, empirical studies, and a descriptive model to support the benefits of musical self-rehabilitation, which I classify below according to Wobbrock's classification of HCI contributions [129].

- An in-depth analysis, classification scheme, and synthesis of the existing literature on assistive musical interfaces (P4 and more detailed in Section 2.6), showing a non-existent approach of modified instruments and poor descriptions of interactions.

- An artifact on conceptualising (P1) and implementing (P2) that enables or re-enables people with physical disabilities to play an electrical guitar.
- Through empirical observations and analysis of training sessions of physically disabled people, I identified exercises that could be replaced by the input mechanism of and with the Actuated Guitar (AG) (P2)(P3).
- A theoretical modelling approach to describe and summarise interactions with musical interfaces by extending the work of Buxton [30] and Hinckley [61] (P4, P5 and Section 2.6).
- Empirical evidence that people with no musical training cannot overcome long delayed auditory feedback even if it is close to a subdivision of the overall tempo (P6).
- A longitudinal empirical case study showing that the reduction of musical expression from simple strumming with the AG did not negatively affect long term-motivation of a musically skilled person (P7).

Table 1.1: My contributed papers.

#	Title	Authors	Outlet	Pages
P1	The Actuated Guitar: A platform enabling alternative interaction methods	*Jeppe Veirum Larsen*, Dan Overholt, Thomas B. Moeslund	SMC 2013 Stockholm	4
P2	The Actuated Guitar: Implementation and User Test on Children with Hemiplegia	*Jeppe Veirum Larsen*, Dan Overholt, Thomas B. Moeslund	NIME 2014 London	6
P3	Exercising the Tibialis Anterior Muscle of Children with Cerebral Palsy for Improved Neuroplasticity using an Electrical Guitar	*Jeppe Veirum Larsen*, Dan Overholt, Thomas B. Moeslund	ICNR 2014 Aalborg	2
P4	The Prospects of Musical Instruments for People with Physical Disabilities	*Jeppe Veirum Larsen*, Dan Overholt, Thomas B. Moeslund	NIME 2016 Brisbane	5
P5	States and Sound: Modelling User Interactions with Musical Interfaces	*Jeppe Veirum Larsen*, Hendrik Knoche	NIME 2017 Copenhagen	6
P6	Hear You Later Alligator: How delayed auditory feedback affects non-musically trained people's strumming	*Jeppe Veirum Larsen*, Hendrik Knoche	NIME 2017 Copenhagen	4
P7	A Longitudinal Field Trial with a Hemiplegic Guitarist Using The Actuated Guitar	*Jeppe Veirum Larsen*, Hendrik Knoche, Dan Overholt	NIME 2018 Blacksburg, VA	6

Chapter 2

Background

This thesis is within the field of human computer interaction, assistive devices, and musical expression. This section will describe core areas of the topics included in the thesis.

2.1 Human-Computer Interaction

The field of *Human-Computer Interaction* (HCI) focuses on the interfaces and interaction between humans (users) and computers. HCI is no longer limited to tall grey desktop computers with a monochrome monitor and a mechanical keyboard. With advances in computer and input technology HCI has found its way into all nooks and crannies of our everyday life and with *Internet of Things* (IoT) around the corner the number of devices with which humans have to interact will only increase.

2.1.1 Human Factors Model of HCI

A classic model in human-computer interaction is the *human factors model*. This model demonstrates in a simple way how a human and a computer interact through a common interface, see Figure 2.1 [66]. In the model the human, on one side, obtains information from the interface using *sensors*. These human sensors are the eyes, ears, nose, tongue, fingers, etc. that cover distinctly different physical properties of the surrounding environment. Vision, hearing, and touch (haptics) are the most commonly used senses in HCI. All the information received by the sensors is converted into electrical signals and sent to the brain where the information is processed. Based on the information received the human reacts using *responders* to, e.g. activate controls on an interface. The human responders can be everything that moves e.g. fingers, hands, and arms, but also vocal chords for microphones or eyes for eye tracking. The computer receives information from the controllers. Just like the human sensors, the controllers consist of different components (knobs, sensors, dials) that can be manipulated by the appropriate human responders. The computer registers the changes to its controllers and updates the interface accordingly. The model can also be used to describe interaction in a musical context. Bongers, for example, used this model to describe the performer's or audience's interaction with musical instruments or musical installations [28].

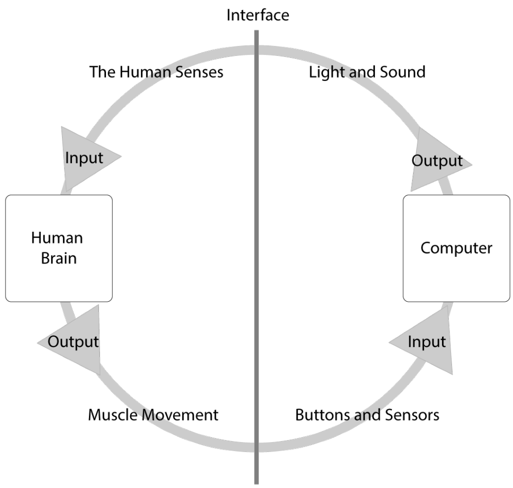

Fig. 2.1: The human factors model describing the fundamental human computer interaction

2.2 Target Users

Brain damage is the leading cause of disability in developed countries. In 2009 alone 22.400 Danes over the age of 18 acquired some kind of brain damage: 56% from a stroke or brain haemorrhage, 12% from traumatic brain injury, and 32% from other causes such as aneurysms, Ischemia, tumors, etc. [1, 14]. According to demographic change projections, that number is likely to increase. On top of these causes, a small number of children are born each year with congenital brain damage. Whether acquired or congenital, brain damage can affect a person's physical abilities, e.g. by spasticity or paralysis, and render them unable to participate in many activities without assistance.

2.2.1 Stroke

In Denmark 12.500 people per year suffer from strokes. 75.000 people live with a diagnosis of either Ischemic stroke (blood clot in the brain) or hemorrhagic stroke (bleeding in the brain), and 50% of the victims suffer permanent injuries as a result. A fourth of stroke victims are affected so severely that they become dependent on care for the rest of their lives. Seventy percent of the victims are over 65 years old [7]. Some of the general effects following a stroke are hemiparesis or hemiplegia, fatigue, cognitive changes, behavioural changes, and decreased field of vision. Common emotional effects following a stroke are depression, apathy, and a lack of motivation [41, 48].

2.2.2 Cerebral Palsy

Each year 180 children are born in Denmark with cerebral palsy (CP) [8] and about 10.000 people in the country live with different degrees of CP. This condition is caused by damage to the brain during pregnancy or birth or immediately after birth because of lack of oxygen, small strokes, haemorrhaging, or infection. The damage is permanent but does not progress. Depending on which areas of the brain are damaged and the extent of the damage, it can cause paralysis, unwanted movements of the limbs, and/or difficulty eating or talking. The most common type of CP is spasticity (75%), which affects either one limb (monoperesis/monoplegia), one side of the body (hemiperesis/hemiplegia), the upper or lower body (diperesis/diplegia), or the entire body (tetraperesis/tetraplegia). People with CP also suffer from increased pain, fatigue, motivation and depressive symptoms [123] .

2.2.3 Rehabilitation and Brain Plasticity

The human brain is plastic and capable of continual change, which is an important and fundamental re-organisational function of the human brain. Throughout life, the brain changes both its functional and structural organisation [93] through experiences and events encountered through life like play, school, sports, games and free time interests. The brain is also capable to recovery from injury, like a stroke or a severe concussion, to coping with the loss of sensory input like visual and auditory input [126]. This truly astonishing functionality of brain plasticity is extremely important throughout life and especially when learning but also 're-learning' following e.g. a brain injury. This knowledge about brain plasticity is used in rehabilitation, following accidents, strokes or in cases of CP. Several studies shows that focused practice, like constraint-induced therapy (CIT) [55, 117, 128], can result in further recovery, even after reaching a point with less progress in rehabilitation [117]. CIT as a method of rehabilitation is a standardised intensive rehabilitation intervention. The healthy extremity, normally arms or legs, is constraint several hours a day, thereby forcing the person to use the impaired arm or leg. The goal is to cause plastic reorganisation of neural networks in the brain through an increase in repetitive use [128]. Rehabilitation and limb-specific exercises are not only relevant for regaining functionality, but are just as important for keeping existing functionality. People with weakness in, for example, an arm can have a tendency to use that arm less frequently and favour the better functioning arm, which can lead to an even weaker arm and so on, causing a unending downward spiral.

Research in the mid-1990s caused a change in the paradigms used within Music Therapy. The new shift focused on the relationship between music and brain functioning by demonstrating experience-dependent plasticity [70, 120]. This suggested that music stimulates complex, cognitive, affective, and sensorimotor processes in the brain [56, 68].

As seen in Fig 2.2, the general distribution of disabilities includes more people with minor physical and cognitive disabilities (close to the vertical axis) and few with major physical and cognitive disabilities (furthest away from the vertical axis). Examples of minor weaknesses are weakness in or lowered stamina of one or more limbs. The further one travels along the x-axis the more severe the disabilities become, ending up in, e.g. locked-in syndrome.

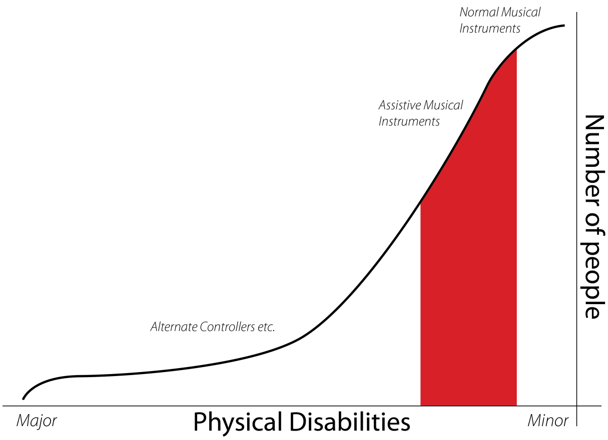

Fig. 2.2: There are more people with minor physical disabilities following, e.g. a stroke or born with CP, than people with severe disabilities. *Source Professor M.D. Jens Bo Nielsen*

2.2.4 Rehabilitation through Music

One of the most demanding cognitive challenges that you can give the human brain is music performance. This requires advanced and precise cognitive and motor skills involving auditory-motor interactions, that activates a number of areas in the brain such as the Superior Temporal Gyrus, the Frontal Cortex, the Dorsal and Ventral Premotor Cortex, the Motor Cortex and of course the Audio Cortex [130]. This is a broad brain exercise and why musicians often are used as examples of brain plasticity. G. Schlaug et al. [113] compared the brain and cognitive effects of young children who were musically trained or non musically trained. The results showed that at an early age certain transfer effects started to emerge, and got continually more pronounced with musical training showing a clear differences between the brains of musically trained and non musically trained.

Not surprisingly the structural changes appear in areas linked to musical training but interesting structural differences also occur in other areas as well. This indicates transfer effects, which could indicate that people playing a musical instrument could benefit of transfer effects in other areas of the brain as well. Research in this area shows that general cognitive rehabilitation and physical rehabilitation could benefit from playing music. Acute stroke patients receiving gait training using simple Rhythmic Auditory Stimuli (RAS) (prerecorded music with metronome overlay) also show significant improvements in regards to gait velocity, stride length and stride symmetry in comparison to those who have received normal gait training for stroke [118].

Research and increased interest in the field of neuroscience and brain plasticity has changed the landscape of music therapy. Music therapy is often associated with areas such as relationship building, emotional response and well-being with. Over the last 20 years a new model called Neurologic Music Therapy [119] that are focusing on rehabilitation following strokes has grown rapidly. S. Schneider et al. has in a series of papers [16, 114, 115] compared the commonly used CIT rehabilitation method, used to improve motor skill recovery, to a music-oriented approach. Schneider et al. suggests a method called Music-Supported Therapy (MST), that builds on repetition and drawing on the additional benefits of active music making as mentioned above. Compared to conventional (CG), functional (FG) the results showed MG as a big improvement in many of the test parameters both pre- and post-test when compared to CG and FG. Their results were not conclusive and further tests should show which variables are significant. Even though, there are interesting and promising aspects of music creation that produce better results than traditional rehabilitation methods [115].

2.2.5 Empowerment and Quality of Life in a Musical Context

Besides the many beneficial effects of music on the brain, musical abilities and skills enable one to participate musically in society and its culture. Musical Empowerment is not about individual skill level, although it is highly regarded in some cultures; rather, it is about the process of regaining the right to perform music. Musical Empowerment gives people a sense of autonomy and agency, providing access to existing resources in the surrounding musical context to make choices and follow plans set by oneself. In everyday life the ability to perform music is a construct to emotional experiences, social experiences, and identity [106]. The ability to play an instrument can be an important contributor to self-esteem. Quality of life in general is a highly subjective matter that involves many parameters heavily affected by social and cultural contexts. However, being involved in music generally strengthens one's sense of identity, and a strong and differentiated identity is one of the factors that increases quality of life [109] [108].

2.3 Accessibility and Assistive Technology

According to Henry et al., *"the purpose of accessibility is to provide equal access for people with disabilities."* This access is not only physical access to a certain environment or location; it also includes products, devices, services and environments [60, 90] and, for the purposes of this thesis, musical instruments. Accessibility can be direct, where small modifications or changes in the general design allow improved access - like wider doors, on-ramps or specially designed web sites. Accessibility can also be indirect, where access requires the use of *Assistive Technology*, which refers to a broad range of devices, services, strategies and practises that give support, aid, or help to people with various disabilities. Assistive technology helps the user gain greater independence and perform tasks they otherwise would be unable to do. Cowan and Turner-Smith defined this as *"an umbrella term for any device or system that allows an individual to perform a task they would otherwise be unable to do or increases the ease and safety with which the task can be performed."* [37]

2.3.1 Abandonment

A major problem when talking about assistive technology is abandonment. According to Trefler and Hobson [122], use of assistive technologies should be as simple as possible in order to avoid abandonment by the user. A device or technology that is too complex can cause the user to reject it even before they have taken the time to learn how to use it. Complexity can also result in long-term abandonment, a situation in which the user starts using the device but stops using it over time due to frustration. Philips and Zhao identified four significant factors related to device abandonment: lack of consideration of user opinion, easy device procurement, poor device performance, and change in user needs or priorities [99]. These factors seem obvious, but then again few people use the advanced functions of TV and DVD player remote controls. In *Hierarchy of Assistive Technology* [122] Trefler and Hobson sorted assistive technology from the least complex and also often least expensive, such as adapting an activity or task, to the most complex and often most expensive, designing and creating custom devices for a single user. According to this schema, one can start at the top and try to solve the problem with the least complex and intrusive method. This can help, e.g. therapists, practitioners and designers, choose the correct assistive technology to avoid potential rejection or abandonment.

1. Adapt the activity or task.
2. Select a device that is commercially available for people without disabilities.
3. Select commercially available rehabilitation products.
4. Combine commercially available rehabilitation products in innovative ways.
5. Modify existing commercially available rehabilitation products.
6. Design and create a new device for a specific individual.

2.3.2 Modalities

In HCI the communication between sensors and responders is categorized as input and output modalities. A modality is a single communication channel for either sensory input or responder output between, e.g. a human and a computer [28]. Systems using only one modality are called unimodal and systems using more than one are called multimodal [111]. Commonly used modalities are vision, audition, and haptics.

Obrenovic et al. suggested describing HCI as modalities where different communication channels are established between user and computer, who pass through four possible interaction constraints: User, Social, Environmental and Device. Each channel can either be unaffected, limited by reduction or filtering of information, or broken, when no information can pass through. User constraints are most often seen in disabilities that present a reduction in sensor and responder input and output. Device constraints are an expression of the device characteristics, e.g. a mouse can only capture movement in two dimensions. Examples of environmental constraints include when the user is unable to drive the car, should not watch a screen, or the environment is too noisy. The social constraint describes a social situation in which the interaction occurs, e.g. silencing one's phone when in the company of other people. The user constraint could present a problem when, for example, a user has impaired vision and visual modality is reduced or filtered. If the user, on the other hand, is completely blind or his vision is heavily impaired the visual modality channel is broken and communication cannot take place [94], see figure 2.4 for a graphical representation.

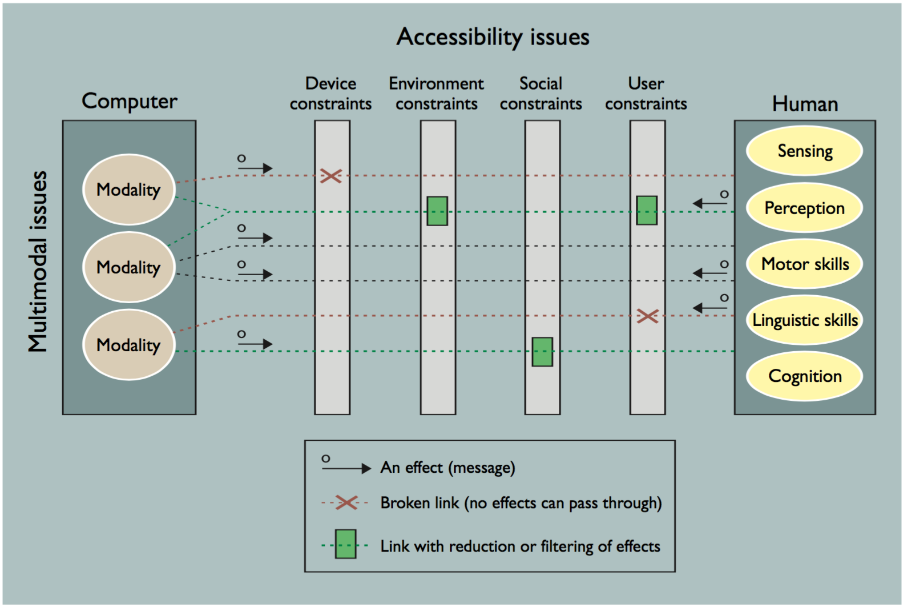

Fig. 2.3: Obrenovic's model of Modalities, constraints and effects. (*With permission from author*)

2.4 Designing Assistive Technology

When designing assistive technology for users with disabilities, one often works with a set of requirements. These requirements can be established through a requirement analysis when one looks at the environment of use, who the users and stakeholders are, and what the tasks and goals are [82]. Obrenovic's model of modalities, constraints and effect (see Section 2.3.2 and Figure 2.4) highlights four accessibility issues that should be taken into account when designing assistive technology: the nature of the disability (user constraints), whether the user has any reduction in or broken modalities, the context of use (environmental and social constraints), where and how it is going to be used, and which technology is available (device constraint), e.g. do the sensors have high latency or low resolution?

2.4.1 Embodied and Tangible Interaction

Baskinger and Gross define the term tangible interaction as *form + computing* [22]. Interaction has always been tangible, but a new paradigm is arising with embodied technology in tactile objects that provide a seamless integration of form and interaction. This integration can enhance our experience and is adaptive, responsive, thinking but still a physical object. Tangible interaction, like the guitar, can draw on skills and integrate knowledge from many areas such as traditional design, engineering, computing, robotics, electronics, and programming. According to Basking and Gross the area is still new and: *"The vocabulary of form, function, and behaviour of computationally enhanced products is still very much under construction; this yields some work that is an engineering triumph yet awkwardly made, or work that is elegant and clever but without apparent function."* Although the article was published in 2010 this point still holds true, despite the fact that we see more and more objects becoming form + computing.

Embodied interaction has many similarities to tangible interaction as its focus is bringing interaction into the human's physical world in order to involve the human's physical being. Dourish says *"how we understand the world, ourselves, and interaction comes from out location in a physical and social world of embodied factors."* [43]. Rex Hartson and Pardha Pyla define embodied interaction as: "interaction is one in which a participant relies on the senses to reach a new fidelity of realism, often using motion or gesture as triggers." [5]

2.4.2 Physical Computing

The term Physical Computing covers systems that can interact with the world around them [62]. It is a broad definition and can cover everything from interactive art installations to automatic watering systems. Most often the term Physical Computing is used when talking about a combination of microcontrollers and sensors. These are used in, e.g. education, research, art, IoT, DIY Hobby driven by Arduino, Raspberry Pi, and the BBC micro:bit [62], see Figure2.1.

Physical Computing is not limited to a certain area, but projects in Physical Computing often try to improve quality of life in some way. This can range from something small, such as a device that reminds you to water your plants, to something large that can have a profound impact on a person's life, e.g. someone living with disabilities [10].

With advances in computing, especially small SoCs (system on a chip) with lower and lower power consumption and higher and higher processing power, Physical Computing is no longer tethered to a wall but is becoming more and more integrated into nearly every aspect of human life.

These prospects are especially interesting for people with disabilities as advances in computing, sensors and actuators Physical Computing can - and probably will - have an enormous influence on their general quality of life in several ways. With shifting demographics in most of the western world Physical Computing is one of the cornerstones of solving problems that will

Fig. 2.4: An Arduino capturing human gestures with an accelorometer enabling people to strum the guitar who otherwise would not be able to.

appear in the years to come.

2.4.3 Designing with the PEO model in Mind

In their journal article Designing for Lived Informatics in Out-of-Clinic Physical Rehabilitation, Bagalkot and Sokoler described how they used embodied interaction in their exploration of the design of digital technology in support of out-of-clinic physical rehabilitation [20]. In addition to the use of embodied interaction, they actively used the PEO (Person-Environment-Occupation) model, which was originally put forward by Law et al. [76], as a strong foundation for their research and collaboration with external partners such as therapists. They applied the model in the three case studies on rehabilitation at home: the MagicMirror, the ReSwing and ReWall, and the ReExercise. According to Sokoler and Bagalkot, the use of the PEO model ensured a holistic approach that helped align the understanding between the them and others in the field.

The model shows that there is a relationship between each of the circles (person, environment, occupation), which can help us understand the actual quality of occupational performance by maximizing the “fit” between each component. This, in turn, can help optimize the functionality for the user.

The PEO model is not a blueprint of how to solve complex designs for

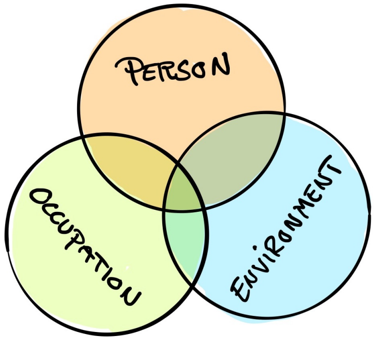

Fig. 2.5: The PEO model describing the balance between the person, environment and occupation (activities).

people with disabilities but one that can help slow down the design process and have a holistic approach considering all the possibilities involved in a person's life.

2.4.4 Do, Feel, Know

Bill Verplank describes interaction in his book 'Interaction Design Sketchbook' as a way to answer three questions: How do you do?, How do you feel?, How do you know? [124]. Verplank describes it as: *"Even the simplest appliance requires doing, feeling and knowing. What I DO is flip a light switch and see (FEEL?) the light come on; what I need to KNOW is the mapping from switch to light. The greater the distance from input (switch) to output (light), the more difficult and varied are the possible conceptual models; the longer the delay between doing and feeling, the more dependent I am on having good knowledge."* [124] He describes DO as either a button or a handle. The button is fitted to be precise or for a sequence of presses. A handle is continuous, more 'analogic' and a gesture rather than a sequence of presses. The FEEL is the chosen senses: hearing, seeing, touching, etc.

The KNOW is the mapping between DO and FEEL and is the complexity of behaviour possible with ubiquitous computers. How do you know what to DO? As designers we need to be conscious and consider what we are expecting of the people for whom we are designing. Verplank gives two examples of interaction. The simplest and easiest is path knowledge. He describes it as the instructions you get on a flight to exit the plane during an accident; information tied together on a string or a given path. The other example is map knowledge. Map knowledge is mental maps and consists of design landmarks, districts, paths and nodes. The paths are sequences of actions/commands. Districts are modes or choices and edges are between modes to construct a more complete map while following various paths.

Verplank sums it up by saying: *"Good interactions are the appropriate styles of doing, feeling and knowing plus the freedom to move from one to the other."* [124]

2.4.5 Affordance

The two main proponents of the term affordance were James Gibson and Donald Norman. James Gibson wrote the seminal work on affordances [47] that was later presented to the HCI community by Donald Norman in his book The Psychology of Every Day Things [92] and later in the popular book Design of Everyday Things [91]. There are some discussions about the use of the term affordance proposed by Gibson and how it might not be exactly what Norman uses. In the description below I primarily use Norman's definition of affordance.

According to Norman's definition an affordance is the design aspect of an object that suggests how the object should be used, e.g. visual clues to its function and use.

In his words: *"... the term affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used. [...] Affordances provide strong clues to the operations of things. Plates are for pushing. Knobs are for turning. Slots are for inserting things into. Balls are for throwing or bouncing. When affordances are taken advantage of, the user knows what to do just by looking: no picture, label, or instruction needed."* [92]

If the affordance of an object or environment corresponds with its intended function the design is said to perform effectively and therefore be easy to use. In contrast, if the affordance conflicts with its intended use it does not perform efficiently and is difficult to use.

An often used example is a door with handles on both sides, as seen in most public buildings. Door handles afford pulling but the door only swings one way. In this case one of the handle's intended uses conflicts with the door's function. If one handle were replaced with a metal plate and nothing to grab you could only push to open the door and you would know on which side to pull and which side to push. This is usually solved not by changing the handle but with describing text such as 'push' or 'pull'.

Affordances are also used when designing non-physical objects like the trashcan or a folder in an operating system. Here the term affordance refers to the properties of real physical objects and their intended use, but the images themselves do not afford anything. The knowledge of, e.g. a button, exists in the mind of the perceiver based on prior knowledge and experience.

2.4.6 Design Hierarchy of Needs

The Design Hierarchy of Need [78, 110] is, as the name implies, inspired by Maslow's Hierarchy of Needs [84] in which humans have to obtain basic and physiological needs before they are able to achieve self-actualisation. The Design Hierarchy of Needs uses the same hierarchical approach as Maslow, where base needs must be fulfilled before you can move up the model, see Figure 2.6. The model consists of 5 levels: Functionality, Reliability, Usability, Proficiency and Creativity. Functionality deals with meeting the basic design requirements, e.g. a music app must provide the ability to play, skip forward and skip backward. Design at this level alone is seen as little or no value. To reach the next step, Reliability, the product has to be stable and consistent in its performance. If the design has periodic errors, components break over time or not responding, the esign is not at the reliability level of the pyramid. Designs at this level are seen to be better but still has a low value for the user. Usability describes ease of use and how forgiving the design is. Setting how many seconds you want your microwave to run in order to defrost meat should be easy. If the difficulty is too great, as it often is with cheap microwave ovens, usability needs are not satisfied. Design at this level is experienced to be of moderate value for the user. Proficiency make the user able to interact with the device efficiently and do it with ease. Does an application allow you to build useful workflows and easily search through your to-dos? Does it Designs reaching the level proficient are seen as and experienced as to function easily and efficiently at a high level allowing the user to do things not previously possible and is considered to be of great value. The peak of the pyramid, Creativity, is reached when all of the underlying needs have been met. The design has a solid base consisting of solid functionality, reliability, usability giving the user the possibility to be proficient and creative using the product in innovative ways. The design allows users to explore and create and expand on the product itself. Designs on this level are seen as the pinnacle of designs and are able to generate a loyal fan bases. To get a good design it is a good idea to keep this model in mind and try to follow it and ensure that lower level needs are finished before continuing to move up the model. I think we all have seen or made projects where some of the levels have not been done properly and the result has been questionable.

2.4.7 Sensory substitution and Amplification

To handle user constraints one can either amplify or substitute. When modalities are reduced, as with poor eyesight or hearing, amplification is often used. Some classic examples of amplification are glasses, magnifying lenses, and hearing aids. These are examples of assistive technologies that improve or assist reduced modalities. For broken modalities such as complete loss of

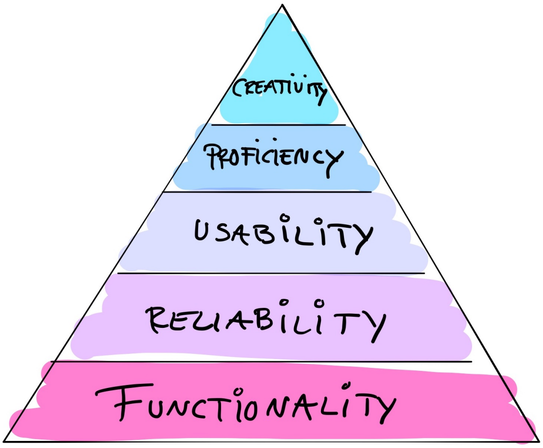

Fig. 2.6: The Design hierarchy of needs model inspired by Maslow's model where lower needs must be satisfied before higher needs can be satisfied.

sight or hearing, sensory or responder substitution is needed to circumvent the broken modality since amplification is not possible; for example, glasses cannot help a blind man, no matter how good they are. Substitution can be done in several ways, e.g. by equivalence or redundancy where more than one modality carries or processes the same information; for example, when adding subtitles to a movie or a cinematic sequence to a video game [51]. When designing for physical disabilities it is the substitution of motor skills.

2.4.8 Function Allocation, Control Site and Control Space

When substituting or amplifying sensors or responders in assistive technology it is important to look at *function allocation* and consider how functions are divided between the human user and the device/helper [79]. The most widely used allocation method is *Leftover allocation*. This type of function allocation focuses on keeping as many functions with the user as possible and only allocates the leftover functions to the device [21]. This is especially interesting in a rehabilitation context as one is often interested in keeping the user as active as possible. *Control sites* [127] are different body sites that can be used for controlling a device. Webster et al. identify commonly used sites for controlling assistive devices [127] as *hand/finger*, *arm*, *head*, *forehead*, *eye*, *leg*, *knee*, *foot* and *mouth*. Each control site is capable of a broad range of movement and actions. Hand and fingers together are preferred for fine control as they are used for manipulative tasks even when the user has limited hand control. Substitution can be as simple as using the other arm or hand or a prosthetic limb or wheelchair. Sometimes it is necessary to improve the function of an existing control site that, e.g. has limited range, power or stamina. This is often done by amplification, when a well-known method is control display gain [80]. A good example is controlling an excavator or a wheelchair by which small physical movements are amplified into bigger or different motions.

2.4.9 Methods of Activation

The human factors model is, of course, a broad and simple model that explains the overall concept of HCI. The only way for people to change the state of the world (system) is through movement. Bongers defined movement that changes states as muscle actions that can either be *dynamic*, like the movement of a computer mouse (continuous), or *static*, like the pressing of the button on the mouse (discrete on/off) [28]. Cook and Polgar described different types of interfaces and how they can be manipulated from an assistive technology point of view and categorized control interfaces based on their methods of activation: movement, respiration, phonation and brain activity [35, 81]. Movement covers *mechanical control interfaces*, which detect the application of force, such as buttons, switches, leavers, etc. *Electrical control interfaces* detect electrical current generated by the human body, e.g. EMG, EOG, capacitive touch interfaces, and touch screens. *Proximity control interfaces* detect movement without any contact, which could be through infrared or ultrasonic range sensors or computer vision systems and eye tracking. Respiration uses *pneumatic control interfaces*, which detect airflow or air pressure through a sip and puff switch (air in/air out). Via a microphone, *phonation* can be used as a switch, e.g. a 'clap' to turn on/off the light, but also in much more advanced systems such as speech-to-text and speech recognition interfaces. Phonation is also seeing increasing use outside assistive technologies in, forexample, mobile phones. *Brain controlled interfaces* (BCI) are a combination of sensors attached to the skull of the user that read brain wave signals and interpret those signals via sophisticated software. The software can be used for communication by allowing the user to spell out words and sentences. This approach requires some training of the system with the actual user.

As seen in the Human Factors model and stated by Bongers, all of these methods, except brain control interfaces, originate from muscle movement. Cook and Polgar, however, looked at the methods originating from muscle movement that can be used for activation, which is critical when designing interfaces for people with disabilities.

2.5 Assistive Interfaces for Musical Expression

Music has been used by music therapists in health settings and therapeutic contexts for many years to help people with their physical and mental health [4, 27]. Assistive technology, in combination with music, enables people with both cognitive and physical disabilities to play, explore, and enjoy music. In this section I review scientific publications and popular commercial products for assistive musical instruments designed for people with physical disabilities.

Interfaces for musical expression can be acoustic instruments (AI), which rely on a mechanical system and the acoustic properties of, e.g. strings, tubes and membranes, or digital musical interfaces (DMI), which consist of a gestural controller or a control surface that drives the musical parameters of sound synthesis, sample playback in real time [87], or a combination of the two. I have defined a category of interface that exists in the overlapping area of the categories of DMI and AI and named it assistive Interfaces for Musical Expression (aIME). An aIME is different from a DMI or AI in that it is specifically designed for people with physical disabilities, see Figure 2.7. An aIME can be a DMI, e.g. Soundbeam, which is completely digital, a combination of DMI and AI, e.g. Robo-tar, which is a combination of an acoustic instrument and digital control, or a purely acoustic instrument with mechanical controls.

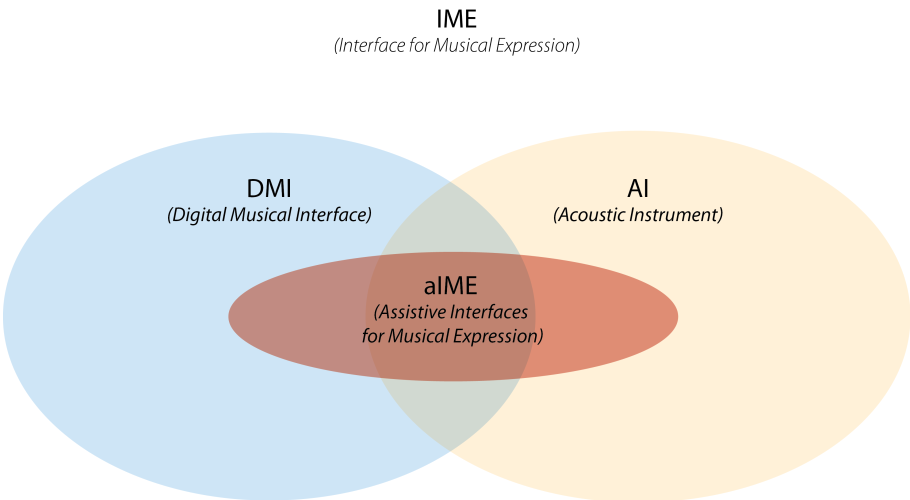

Fig. 2.7: Interfaces for Musical Expression consist (IME) of Digital Interfaces and Acoustic Instruments. Assistive Interfaces for Musical Expression can be either or a combination of both.

2.5.1 Gesture Acquisition, Mapping and Feedback

Every instrument needs input/activation by the performer playing it. In a musical context this input/activation provided by some responder is called a gesture or input gesture. Miranda et al. defined a gesture as *"...any human action used to generate sounds."* [87].

Acoustic instruments have predefined gestures based on their physical properties. A piano key is pressed, a drum is hit, and a string is bowed or plucked. These are interfaces with a built-in sound generator and gestures defined by the instrument's physical properties and attributes of the interface. Today it is possible to separate the interface from the sound generator in Digital Musical Interfaces (DMI). In 1988 Moog identified *"three diverse determinants of musical instrument design and musical instrument structure. The first is the sound generator; the second is the interface between the musician and the sound generator; the third is the... visual reality of the instrument"* [88]. This presents a highly modular system that allows it to be modified, adapted, or replaced, depending on individual needs. This is useful for musicians with barriers to participation as a modular system can offer certain benefits over traditional acoustic instruments.

In newer models of DMIs two of Moog's determinants - the interface and the sound generator - are still used. The third is expanded to not only include the visuals but feedback in general. Miranda et al. presented a model of DMIs, which can be seen in Figure 2.8 [87]. The model consists of two major elements: the gestural interface and the sound generator. The gestural controller takes gestures as input and the interface sends the interpreted input data along to the sound generator. Before it reaches the sound generator the data are mapped to predefined sound parameters. There are several mapping strategies, such as one-to-one, one-to-many, and many-to-one. If the gestures are mapped to, e.g. a synthesizer, with direct access to certain parameters like pitch, envelope, filters, etc. the mapping can be highly complex. On the other hand the mapping can also be simple and involve samples that allow for parameters to control pitch, pitch, and velocity or simply just playback of the sample. The sound generator generates the sounds determined by the input gesture and the mapping. There are two types of mapping. Mappings can be absolute, e.g. such as when the pen on a tablet has a one-to-one correspondence between the pen and cursor position, or relative, when the pen and cursor positions can be offset with a variable mapping [46].

As seen in Figure 2.1, the user gets feedback through sensors when interacting with an interface. The type of feedback emitted by an interface plays an important role. As stated by Obrenovic, limitations or broken sensors (modalities) can alter the possibilities of the correct use of an interface. Vertegaal, Ungvary, and Kieslinger [125] split feedback into primary feedback and secondary feedback. Primary feedback includes the visual, auditory, and haptic feedback from the interface itself, e.g. the clicking sound of a clarinet or the rough texture of a wound guitar string, where the secondary feedback is the sound produced by the DMI. Bongers [28] distinguished between active and passive system feedback. Take, for example, a synthesizer, which can provide feedback even when turned off. When pressing a key on the synthesizer, the user can feel and hear a click regardless of whether the machine is switched on. This feedback is not produced by the system. Active feedback is provided by the system, e.g the sound generated by the synthesizer, the visual feedback provided by a blinking LED light, or changes to a screen.

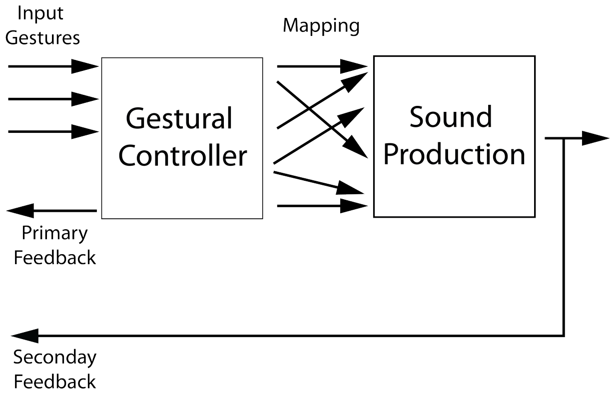

Fig. 2.8: A common model of a digital musical instrument (DMI) with separated interface and sound generator.

Popular technologies for gesture acquisition

Medeiros and Wanderley reviewed the NIME proceedings from 2009 to 2013 in order to identify the different technologies used for DMI gesture acquisition and the occurrence of each technology. They identified four overall classes: analog sensors that provide a continuous electrical signal, digital sensors that provide discreet electrical values, consumer electronics, e.g. cell phones, and Wiimotes, which capture motion such as Kinect, etc. The occurrence was 172 analog sensors, 134 digital sensors, 71 consumer electronics, and 30 motion capture. Medeiros and Wanderley also identified the different kind of sensors used and their occurrence [85], see Table 2.1

2.5.2 Musical Expression

Levitin et al. describe gestures and musical expression through what they call the *musical control space*. In the musical control space the performer can control the temporal stages *beginning*, *middle* and *end* of a musical event, see

Table 2.1: The type of sensor sorted by occurrence based on Medeiros and Wanderley's review of the NIME proceedings from 2009 to 2013 [85]

Sensors	Occurrence
accelerometer	75
force sensing resistors	38
gyroscope	30
buttons and potentiometers	29
video/image	23
IR (infrared)	22
magnetometer	16
capacitive	15
biosensing	13
piezoelectric disc	12
non-definable	12
microphone	11
textiles	11
photo/light	10
bend	9
Hall effect	7
ultrasound	4
pressure/flow	4
fiber optic	2

Figure2.9. During these three stages the performer varies their expressiveness through pitch (selected note, vibrato, slide, etc.), loudness (attack, tremolo, bowing, etc.) and timbre (bow or pick angle, bow or pick position, palm muting, etc.) [77], depending on the musical instrument or DMI.

The model of Levitin's musical control space, see Figure 2.9, shows the overall possibilities of musical expression for all instruments.

This model, however, does not offer a vocabulary to describe, e.g. what feedback is being produced at certain stages. This is important when trying to describe assistive musical instruments as common knowledge, e.g. about feedback from existing musical instruments, which might not be true for assistive musical instruments.

Dobrian and Koppelman [42] describe musical expression with a focus on the performer, similar to Levitin, but have a more specific focus on new interfaces for musical expression that might not resemble known instruments.

Musical expression describes a performer's ability to control the beginning, middle and end of a musical event, according to Levitin. But the level of possible expressiveness differs depending on the amount of control the player has over a given instrument, e.g. tempo, sound level, timing, articulation, timbre, vibrato, attack, decay, pause, etc., how the the mapping is between interface and sound engine, e.g. a simple one-to-one or more com-

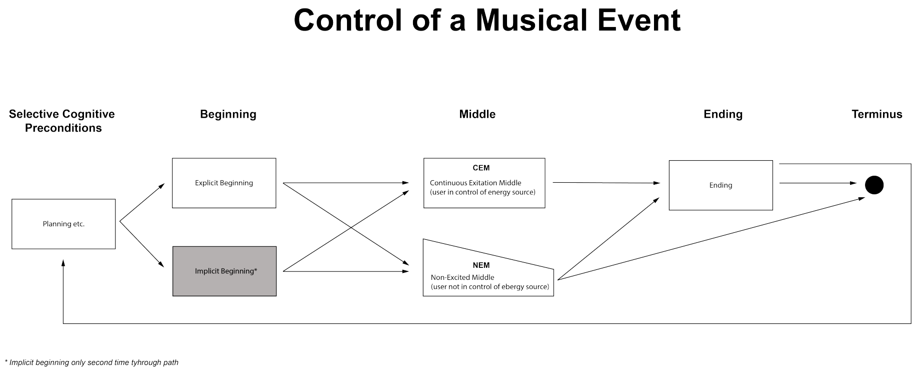

Fig. 2.9: Based on Levetins model showing the musical control space.

plex one-to-many, and the feedback, whether visual, haptic or sonic, that is available to the performer, as discussed by Dobrain and Koppelman.

In the thesis when I use the term *musical expression* I base it on Levetin's Control of a Musical Event. The more control you have over for example tempo, sound level, timing, articulation, timbre, vibrato, attack, slide, bend, decay, pause etc. the more expressive you can be on a given instrument and vice versa.

In the next section I present other ways of establishing a vocabulary to describe complex interactions in general as well as in the context of musical expression.

2.5.3 Modeling Input

The following section and figure 2.10 and 2.11 is from my paper *States and Sound: Modelling User Interactions with Musical Interfaces* (P5) [73].

Buxton's Three-State Model of Graphical Input [30] introduced a vocabulary and modeling template to better describe different interaction techniques that implement a graphical user interface. The model is based on the notation of finite state machines consisting of labeled states (circles) and transitions (arrows) between them that describe how user input (labels on the transitions) from one input device changes the state of a system (see Figure 2.10). State 0 denotes an out-of-range state in which the user has not acquired the input device or control, state 1 allows for movement of a cursor (tracking), and state 2 allows the manipulation of objects (dragging). The transitions between states model discrete events, whereas the self-loop transitions model continuous input or non-input (in state 0).

Many instruments involve more than one input device or extremity. Hinckley et al. extended Buxton's model to address a wider range of design problems, multiple effectors through input devices, and interaction technologies [61] by drawing on Petri net representations [97] and including continuous properties. Hinckley's model uses *tokens (represented as circles inside states in Figure 2.11) to express which state the system is in. The tokens can move along through the transitions to states that have the same outline (solid or dashed). Instead of Buxton's self-loops, (see arrows under each state in Figure 2.10), the model relies on the notion of sensing continuous input, like position, angle, force, or torque, within a state expressed through a named italicized property in the lower half of the state in Figure 2.11. Hinckley also added a prefix to state 0 to distinguish between the two out-of-reach states - touch (T0) and proximity (P0). Different formatting (dashed or solid lines Figure 2.11) of the states, tokens, and transitions indicate the devices. A state name postfix distinguishes between the respective effectors, i.e. input hands (p for the preferred and n for the non-preferred hand in Figure 2.11).*

In addition to providing a language and notation for user interface interaction concepts, state modeling allows one to visually inspect the model and spot asymmetries in the design in case certain states exhibit different behaviours [121]. Figure 2.10 is a case in point of symmetry, and Figure 2.11 illustrates that state 2np is special in terms of the larger number of transitions to and from it and its overlap.

Birnbaum et al. suggested a dimension space for musical devices using a spider web representation [25]. The axes in the spider web have different representations, e.g. required expertise, musical control, and feedback modalities. The axis values vary, e.g. high/low, none/extensive, few/many, etc., depending on what they are describing. Hattwick and Wanderlay further expanded the dimension space to evaluate collaborative music [59]. Vertegaal and Ungvary investigated the relationship between body parts, transducers, and feedback modalities [125] in music controllers. Overholt presented the Musical Interface Technology Design Space (MITDS), which provides a theoretical conceptual framework and guidelines for describing, analysing, designing, and extending the interfaces, mappings, synthesis algorithms, and performance techniques for interactive musical instruments [96]. Morreale et al. also presented a conceptual model called MINUET, which offers a way to understand the elements involved in musical interface design [89]. Most of these frameworks, however, do not provide a sufficient graphical representation of the musical interfaces and do not model different states and feedback to user interactions. MIDI, for example,

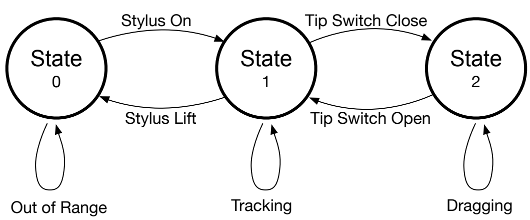

Fig. 2.10: Buxton's Three-State Model with stylus and a tablet. [73]

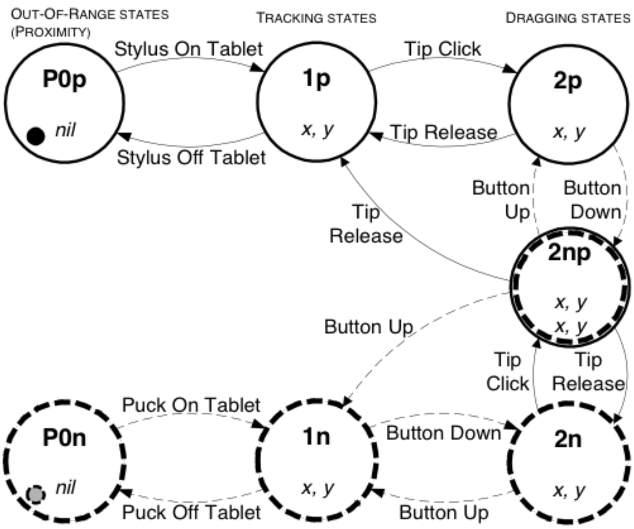

Fig. 2.11: Hinckley et al.'s two-handed input example of stylus and a puck on a tablet. [73]

does not concern itself with how users actuate sounds and which feedback the system provides apart from the generated sound.

2.5.4 Classification

Miranda and Wanderley [87] suggested a classification system comparing new digital musical interfaces on their relationship to existing acoustic instruments in the classes, augmented musical instruments, instrument-like controllers, instrument-inspired controllers, and alternate controllers. I extended the original classes with the class Assistive Musical Instrument placed between augmented musical instrument and instrument-like controllers, see Figure 2.12. I placed an indicator for existing musical instruments in the model as a reference point for easier comparison of the different classes. The extended classification system is not exhaustive and classes may overlap, but as a discrete system it allows for easy comparison and discussion and is therefore used for that purpose in this thesis.

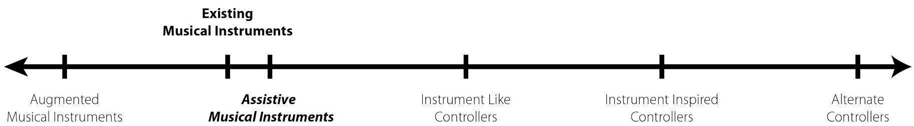

Fig. 2.12: Classification based on similarity to existing musical instruments with the added Assistive Musical Instrument Class and indicator for Existing Musical instrument (in bold).

Augmented Musical Instruments Augmented musical instruments are acoustic (sometimes electric) musical instruments extended by several sensors. These provide the performer with the ability to control extra parameters, which extend the capabilities of the original instrument. The instrument, with its original features, continues to make the same sounds, but the added features tremendously increase its functionality.

Assistive Musical Instruments

Assistive Musical Instruments are existing acoustic (sometimes electric) musical instruments fitted with sensors and actuators that allow people with physical disabilities to play the existing musical instrument despite their physical limitations. Compared to augmented musical instruments, however, these do not extend the original capabilities or sounds of the original instrument. Assistive Musical Instruments allow people to learn or use the existing gestural vocabulary for the existing musical instrument by letting technology assist them.

Instrument-like controllers

These controllers try to model existing instruments and their control surface as closely as possible in order to allow for already known skills from existing acoustic musical instruments to be more or less directly transferred to the new interface.

Instrument-inspired controllers

The instrument-inspired controllers do not seek to reproduce precisely the control surface from an existing instrument but are inspired by some of the same design ideas as existing musical instruments and inherit some of the same gestural vocabulary. This type of controller can be very different than its original acoustic model, which can make it difficult to distinguish between instrument-inspired controllers and alternate controllers.

Alternate Controllers

Alternate controllers do not bear any strong resemblance to any existing musical instruments and can take any shape, use any gesture, and/or extend any object.

2.5.5 Music Control Interfaces

As defined in Section 2.5.1 a gesture is any human action used to generate sounds. All interfaces - not just interfaces for musical expression - require certain gestures in order to be operated. These gestures are based on what input technology the interface incorporates and its physical shape and size. Ferrimond et al. [44] identified and grouped what they call music control interfaces, which are used in special education and disabled music settings, as the five types of interfaces: distance sensing and motion tracking interfaces, touch screen interfaces, tangible interfaces, wind interfaces, and biometric interfaces.

Distance Sensing and Motion Tracking Interfaces

Distance sensing and motion tracking technologies cover touchless technologies such as infrared and ultrasonic distance sensors, cameras, Kinects, etc. The technologies can operate in one dimension (distance to the sensor), in two dimensions (as a camera's x and y axis), and in three dimensions (in a depth sensing camera's x, y and z axis, such as the Kinect.) Distance sensing and motion tracking technologies can be scaled easily to span from a few centimeters to several meters, which makes them adaptable to different users with varying degrees of movement. The common trait for these technologies is that they are touchless, which means that they require no force. This makes them well suited to people with limited strength and limited range. The downside of these technologies, however, is that they do not, by virtue of the fact that they are touchless, provide any haptic feedback during operation.

Touch Screen Interfaces

As the name implies, touch screen technology covers instruments made or operated by two dimensional touch screens. These include big screen TVs, mobile devices such as smartphones and tablets, and dedicated interfaces only for making music. What is common across all of these is that they lack the intrinsic tangible interfaces because they are fitted with hard flat surfaces that provide no additional haptic feedback.

Tangible Interfaces

Tangible interfaces, not be confused with tactile interfaces, which also include the aforementioned touch screens, are interfaces that have a more tangible experience that most musicians know from a physical musical instrument.

Wind Interfaces

Some users are unable to use any of the above mentioned interfaces due to, e.g. complete paralysis, which prevents them from manipulating an interface or moving their body. Wind controllers allow these users to use their breath to operate a 'sip' and 'puff' pneumatic controller. Besides reacting to a sip and a puff some wind controllers also react to the amount of pressure applied by the user's breath and the angle of the interface.

Biometric Interfaces

The term *biometric* normally refers to the metrics related to human characteristics that are often used for identification, such as fingerprint, iris, retina, DNA, etc. Ferrimond et al. defined biometric interfaces as interfaces that measure the electrical activity emitted by the human body. One example of this is Electromyography (EMG), which measures the activity in the muscles and is usually attached to the arm using a special type of arm band. Another example is Electroencephalography (EEG), which measures the brain's electrical activity. This requires special equipment, which includes a mesh of electrodes that need to be placed correctly on the user, and this can be difficult without help or expert knowledge. As with the distance and motion tracking interfaces, the biometric interfaces do not provide any haptic feedback.

2.5.6 Latency and Delay

Many instruments exhibit an inherent latency between actuator activation and the occurrence of sound. Pianists can increase the latency as much as 100ms, by moderating their velocity when pressing a piano key to the audible onset of a soft note [19].

While some musicians can detect latencies as low as 7-10ms [45], people with no musical training who tap along to a beat have a larger bias to tap before the actual beat. Aschersleben found that this *anticipation bias* was around 50ms in musically untrained people and about 14ms for people with musical training [17]. Drummers tend to have the smallest anticipation bias, and Fujii et al. reported that professional drummers had mean asynchronies ranging from 0 to –13ms, depending on the type of drum and tempo. Dahl found that the relative size of the flutter increased with slower tempos, which suggested that the inter-onset-intervals of the consecutive onsets can vary substantially. The anticipation tends to be smaller for trained musicians than non-musicians [71]. The average flutter between IOIs ranged between 2 and 8% of the associated tempo, which suggests that tempo affects the anticipation bias. The synchronisation bias doesn't affect the ability to keep a continuous and steady beat where variation in inter-tap intervals can be as low as 4ms [107]. Increased delayed auditory feedback from activation causes disruption and leads to note errors (sequencing of notes), elapsed time, key stroke velocity, and inter-hand coordination. It peaks at 200ms, whereupon it diminishes again [45, 98]. People are more sensitive to *auditory* *advance* than *auditory delay* as they can detect auditory advance asynchronies between video and sound at around 20 - 75ms and auditory delays from 100 - 188ms [18]. Asynchronies of 50ms or more between different orchestra members are common in musical performances due to, e.g. flutter, but even the spatial arrangements increase asynchronies, e.g. a distance of 10 meters adds 30ms delay to the sound because of travel time [100].

According to Jack et al. [65], even small amounts of latency can affect significantly the subjective quality assessment of a musical instrument based on what he called action-to-sound latency. Zero latency was consistently rated more positively than latencies as low as 20ms or 10ms with jitter conditions. Dahl and Bresin [40] showed a possible breaking-point between 40 - 55ms, at which point subjects started to show difficulty in keeping a steady rhythm on a drum pad as conflict occurred between the tactile feedback and the auditory feedback. Quality assessment of an assistive device and noticeable latency from activation to feedback is extremely important to avoid any potential device abandonment, especially within rehabilitation, see Section 2.3.1. Latency as small as 20ms or 10ms with 3ms jitter can lead to significantly lower quality ratings and a higher level of difficulty in playing when compared to the 0ms or 10ms latency [103].

2.5.7 Measures of Timing of Musical Performance

Dahl measured the inter-onset interval (IOIs), defined as n between stroke number n and $n+1$, in order to evaluate the short term variations in music performance, *flutter*, and long term variation (drift). Flutter was measured as the difference between adjacent IOIs $n+1-n$, and Dahl used this to find the maximum flutter and the average flutter. The recorded sequences were recorded without metronome or backing track support, so Dahl plotted the IOIs and fitted a trend line, $ax+b$, to reveal any drift in tempo when the tempo increased if the trend line had an $a>0$ or decreased if $a<0$. To find variability the IOI data were plotted as a percentage of all strokes using 4ms bins [39]. Pfordresher [98] also measured the IOIs but computed for each trail the coefficient of variation (CV), which is defined as the standard deviation to the mean as the measure of timing variability. Takano recorded each tap, e.g. stroke, and stimuli, e.g. metronome, and measured the time difference between the two, which he defined as synchronization error (SE). He then used a correlation coefficient to compare the SE averages to the inter-onset averages [116]. Repp and Doggett [102] also compared tapping to stimuli, in their case an isochronous note sequence, but called it tone tap asynchronies rather than synchronization error. They compared the mean asynchrony to inter-onset interval and the mean standard deviation of asynchronies to inter-onset intervals.

2.6 State of the Art of Existing aIMEs

2.6.1 Definition of an aIME

Assistive interfaces for musical expression (aIME, pronounced aim) is a term I created to refer to interfaces - digital or acoustic - that are designed for people with physical disabilities. aIMEs include all classes of instruments, from alternate controllers to augmented musical instruments, and can be digital, acoustic or both, see Figure 2.7.

2.6.2 Survey

Search Terms

I conducted multiple searches for relevant literature during the course of my PhD and selected a number of keywords that I considered necessary to finding aIME publications of interest. The keywords containing an asterisk were written in their short form in order to get capture possible variations of the word (e.g. disab* for disability, disabled, disabilities etc.) The keywords identified were: disab*, access*, special needs, hemip*, cerebral palsy, music*, instrument, interface*, control*. These keywords were used in different combinations to maximize the likelihood of finding all relevant articles and papers.

Selection Criteria

The focus of the survey was on aIMEs for people with physical disabilities; therefore, I searched only for papers and products that explicitly targeted people with physical disabilities. Papers that only included the word 'disabilities' (but did not focus on people with disabilities) were not considered, e.g. EyeMusic [64], which could be used by people with disabilities but was not designed with physically disabled people in mind. Sound exploration, scenes, and soundscape instruments, such as the instruments in the RHYME project [63], were not included.

2.6.3 Results of the Literature Search

I used Google Scholar to conduct a series of broad searches based on the selected keywords. These searches returned a surprisingly low number of results that matched the selection criteria. Most of the results had nothing to do with musical instruments or disabilities. The results that matched the keywords and that had something to do with musical instruments and disabilities were primarily about cognitive disabilities, anxiety, depression, etc. and therefore did not match all the selection criteria.

To increase the likelihood of finding relevant literature, I narrowed the scope of the search and focused on publications from the International Conference of New Interfaces for Musical Expression (NIME). I used the same keywords as I had used for the broad searches in Google Scholar on the abstracts and keywords of the 1458 papers published at the NIME conference from 2001 to 2016. Only 15 of the papers (1%) returned were targeted at disabilities and impairments. Of those five papers (0.3%) fit the selection criteria that specifically targeted physical disabilities but excluded sound exploration/scenes/soundscape instruments. In the end I added commercial products as one of the selection criteria. The search resulted in a total of 12 aIMEs.

2.6.4 Comparison

Instrument focus

The large majority (10 out of 12) of assistive interfaces for musical expression in the survey were alternate controllers. Five of the 10 alternate controllers used distance and motion tracking sensor interfaces [13, 31, 33, 36, 49], three used tangible interfaces [12, 50, 104], and two used biometric interfaces [34] and wind interfaces [9]. The single instrument-inspired controller and the single assistive musical instruments used tangible interfaces.

The most common control site across all the instruments in the survey by far was hands and fingers. The only two instruments not using hands or fingers were the MusEEG [34], which used the head, and the Magic Flute [9], which used the mouth.

To accommodate users with limited range of motion or fine motor control, four out of five instruments that used distance and motion interfaces were equipped with the ability to scale the control interface [13, 33, 36, 49]. The *alternate* and *instrument like controllers* using tactile interfaces had a fixed interface and a compact design that used large targets placed close together. This made the targets easier to navigate and push/hit/squeeze [12, 50].

Eight of the aIMEs offered no possibility for simultaneous input (polyphony), while three allowed for it [11, 12, 31], and two was unreported [50, 104]. The simultaneous input was required to operate the Robotar [11], whereas it was optional for the Octonic [31] and the Skoog [12]. All the aIMEs besides the Robotar were restricted to certain and often simpler scales such as the pentatonic scale. Four of the aIMES were velocity-sensitive and used different sensor technologies such as tangible (force of push) [11, 12], wind (force of blow) [9] and distance and motion tracking interfaces (distance to the sensor) [31]. All other aIMEs had fixed velocity. One of the aIMEs could manipulate the sustaining note through vibrato [12] and one the velocity (dynamics) [31].

Only two of the publications reported the latency of the instrument [34, 49]. When looking at primary feedback, six aIMEs - all alternate controllers that either used distance and motion sensing or biometric interfaces - had no feedback [13, 31, 49] or only visual [33, 34, 36] feedback. All aIMEs using tangible interfaces provided primary haptic feedback. Three provided both primary visual and haptic feedback [12, 24, 50], and one had primary visual, auditive and haptic feedback [11].

Five of the aIMEs were using the MIDI protocol to communicate with sound generating software, five were unreported, one used synthesis [34] and two were acoustic instruments [11, 75].

Research focus

The main research contribution on aIMEs in the survey was, not surprisingly, artefact contributions [129]. Most papers included a simple definition of the target group 'disabled', but did not include any specific conditions or the type of disability [31, 34, 49, 50, 104]. A few papers [24, 33, 36] did try to limit the target group by targeting certain conditions such as CP (cerebral palsy) or SMA (spinal muscular atrophy), but both CP and SMA are, in and of themselves, very broad diagnoses. All the studies lacked clear descriptions of how interactions with the specific artefact allowed certain disabilities or impairments to be overcome by the aIME.

The publications were often proof of concept, pilot or exploratory studies investigating different aspects of the aIME. These could be the aIME's potential for, e.g. facilitating or showing new interactions [31, 50], whether certain sensors were fitting candidates for certain interactions [34, 49], or how the aIME could fit into rehabilitation [33, 36].

The evaluation approaches were primarily qualitative (6/8) and entailed either expert evaluation (therapist/teacher) combined with user observation in a lab environment [], observation in the field [24, 31, 36, 50, 104], or via an unsupported (i.e. no researcher present) field trial with expert (teacher/therapist) interviews/debriefings following the completion of the test period [104]. Two studies had a more quantitative approach [34, 49] investigating the actual performance of the artefact measuring latency and time to complete certain tasks. Both studies used aIMEs that were touchless as they used a Kinect (distance sensing and motion tracking interface) and a BCI (biometric interface)

Evaluations were typically conducted on one to six participants within the target group, the majority of which were children. However, one study used 11 participants (staff) outside the target group [34] and one had an unreported number of participants [31]. Four studies ran single sessions lasting between 15 and 60 minutes per participant [24, 34, 36, 49]. One study was a 6-week longitudinal study with a single lab session each week and free use of the artifact at home [33]. Three studies did not report on duration and the number of sessions [31, 50, 104]. Common variables measured during evaluation of this type of research had little focus on a musical context. Instead they focused on general variables surrounding the user, such as overall system evaluation, fun, looking for new interactions, or exploration of the artifact, see Table 2.13.

2.7 Summary of Background Research

It was surprisingly difficult to find aIME research in the existing literature, which could indicate that this particular area of research is underexposed. The studies that were found consisted of artefact contributions in which short feasibility studies were conducted with no focus on the longitudinal implications of the artefact such as motivation or abandonment. The target users were vaguely defined, and broad terms such as *'people with disabilities' and 'CP'* were often used without taking into account broken or filtered modalities. The publications did not describe the different artefacts in detail - how they worked or generated sound, whi ch feedback they provided, or how it was actually tested - making it impossible to recreate the artefact and validate the results. The vast majority of the instruments in the survey were alternate controllers [129], all unique in their design and way of capturing and mapping gestures, which makes it nearly impossible to transfer knowledge from artefact to artefact. Most of the artefacts were monophonic and locked into simple scales, reducing the complexity and possibility for expression. Half of the artefacts used some sort of touchless input technology that provided no haptic feedback. When playing an instrument the haptic feedback helps the player navigate and operate the instrument and if it is an acoustic instrument the player can feel the instrument vibrate according to the note being played. None of the research and only one of the commercial instruments focused on assistive musical instrument to enable or re-enable people to play an existing instrument. Using an existing musical instrument opens up the existing musical context such as tuition, sheet music, etc.

	Target Group	Test Methods	Participants	Length Single Session	Total Duration	Variable Measured	Outlet	Year
MTM System [13]	disbaled	Interview with parants	6 children (home and lab)	10 - 30 min. (lab), home undefined	6 - 8 weeks (lab), home undefined	Parental experience using the MTM system with their child	Research	2007
The music Cre8Tor [87]	disabled	Feedback from public school teachers	children and their teachers	Undefined	"several years" location undefined	Undefined	NIME	2007
MusEEGk [29]	severely disabled	Post-Experiment Questionaire (1-7 Likert scale)	11(Staff non-disabled)	1 hour pr. Session (lab)	1 hour (lab)	Accuracy, Selection pr. Min., difficulty, enjoyment, liked compositiom.	Research	2011
Augmented Reality Musical System [31]	CP	Expert Evaluation, Observation (lab)	1 music therapist, 1 child	30 min. (lab)	30 min. (lab)	System evalation	ALE	2009
Octonic [26]	Sensory Impairments	Observation by specialist teacher, non scriptetd.	Groups of 4 - 5 pupils Number of groups unknown.	Undefined	Undefined	Unspicific observation looking for new interactions through free improvisation	Journal of Digital Creativity	2011
NoiseBear [41]	Physical and cognitive disabled children	Formative Evaluation using Obervation and teacher interview	4	Undefined	Undefined	System Evaluation	NIME	2013
Adaptive Music Technology Using the Kinect [40]	Disabled and non disabled	Measurement of time elapsed doing predefined tasks	2 (1 normal, 1 disabled)	30 min. (lab)	30 min. (lab)	latency, time (to complete a chord progression)	PETRA	2015
TouchTone [20]	Hemiplegic CP	Expert evaluation, Individual Exploration(lab), Group Session (lab)	6 children (lab)	15 min.	15 min.	playability, attention, exploration	TEI	2010
Actuated Guitar [62, 63]	Hemiplegic	Longitudinal Case Study,	1(home)	10 - 30 min. (home)	3 weeks (20 sessions at home)	Motivation, sync. error rate, latency	NIME	2014

Fig. 2.13: A comparison of research topics of the aIMEs.

	Class	Controller Interface	Input Technology	Interaction	Tracked Parameters	Control Variables	Polyphony	Possible Simultanous Input	Activator Latency	Scaleable Interface	Control Site	Primary Feedback
Soundbeam [11]	Alternate Controller	Distance and Motion Tracking	Ultrasonic distance sensor	Intersect	Distance	Pitch	Monofonic	1	Unreported	Yes	Hands	None
Augmented Environments for Pediactric Rehabilitation	Alternate Controller	Distance and Motion Tracking	Camera	Intersect	2D hand position	Pitch	Monofonic	1	Unreported	Yes	Hands	Visual
Augmented Reality Musical System [31]	Alternate Controller	Distance and Motion Tracking	Camera	Intersect	Occlusion of AR-marker	Pitch	Monofonic	1	Unreported	Yes	Fingers	Visual
Adaptive Music Technology Using the Kinect [40]	Alternate Controller	Distance and Motion Tracking	Kinect	Move arm	Arm gesture	Pitch	Monofonic	1	120ms	Yes	Arms	None
Octonic [26]	Alternate Controller	Distance and Motion Tracking	Eight IR-Distance sensors	Intersect	Distance	Pitch, velocity, volume	Polyfonic	8 (Nearly impossible because of spacing)	Unreported	No	Hands	None
NoiseBear [41]	Alternate Controller	Tangible	Pressure sensitive stuffing	Push/Squezze	Change in resistance	Unreported	Unreported	Unknown	Unreported	No	Hands	Visual, Haptic
Skoog [10]	Alternate Controller	Tangible	Five pressure sensitive buttons, rest unknown	Push/Squeeze	Pressure	Pitch, velocity, vibrato	Monofonic/ Polyfonic	5 (Nearly impossible bcause of size)	Unreported	No	Fingers/Hands	Visual, Haptic
The music Cre8Tor [87]	Alternate Controller	Tangible	Four 'motion sensors'	Move/Shake/ Wiggle	Acceleration	Rhytmic relationship of notes	Unreported	1	Unreported	No	Hands	Haptic
MusEEGk [29]	Alternate Controller	Biometric	BCI	BCI Selection Matrix	B300 reflex	Pitch	Sequencer	1	20 sec.	No	Head	Visual
Magic flute [8]	Alternate Controller	Wind	Pnumatic Sensor	Blow and Move	Breath, Angle of device	Pitch	Monofonic	1	Unreported	No	Mouth/Neck	Haptic
TouchTone [20]	Instrument Inspired Controller	Tangible	Five Pressure sensitive pads, Momentary switch	Push	Pressure	Pitch	Monofonic	1	Unreported	No	Fingers	Visual, Haptic
Robotar [9]	Assistive Musical Instrument	Tangible	Guitar, Button	Push and Strum/Pluck	Button push	pitch	Polyfonic	6(Fingers) / 1(foot)	Unreported	No	Fingers/Foot	Visual, Auditory, Haptic
Actuated Guitar [62]	Assistive Musical Instrument	Tangible	Guitar, Button	Push and Fret	Button push	Pitch, bend, slide, vibrato	Polyfonic	6(Fingers) / 1(foot)	73ms	No	Fingers/Foot	Visual, Auditory, Haptic

Fig. 2.14: A comparison of the aIMEs.

Chapter 3

Methods

In this chapter I address how the two research questions relate to the publications and the methods that were used in this process.

3.1 Alignment of Research questions and publications

The two research questions are:

- How can an electrical guitar be modified to make it usable for people with hemiplegia?
- How does the potential reduction in musical expression through latencies or delayed auditory feedback affect the ability to produce rhythmical music and influence the level of motivation and long term use of the guitar?

The first research question is addressed in papers P1, P2 and P7. The Actuated Guitar: A platform enabling alternative interaction methods (P1) focuses on the first part of the question *"how can an electric guitar be modified..."*. The paper suggests a platform and approach for how a regular electrical guitar can be modified to allow alternative interaction methods using different control sites to execute a strum of the strings. The second publication The Actuated Guitar: Implementation and User Test on Children with Hemiplegia (P2) seeks to answer the last part of the first question *"...to make it useable for people with hemiplegia."* with slight design changes and a small-scale usability test with the target group. A longitudinal field trial with a hemiplegic former guitarist and music teacher using the actuated guitar (P7) is a real case scenario that tries to answer the entire research question during a three week intervention.

P6 and P7 address the second research question. Hear You Later Alligator: How delayed auditory feedback affects non-musically trained people's strumming (P6) answers the first part of the second research question: *"How does the potential reduction in musical expression through latencies or delayed auditory feedback affect the ability to produce rhythmical music..."*. Low latency and delayed auditory feedback is often mentioned as one of, if not the, most crucial part of a DMI. Despite the measured latency of the Actuated Guitar it was still possible to play and hence we wanted to investigate how the musically trained and non musically trained reacted to high and extremely high latency and delayed auditory feedback. A Longitudinal Field Trial with a Hemiplegic Guitarist Using The Actuated Guitar (P7) answers both the last part of the second research question but also the whole question. To answer the question a longitudinal field trial was needed to investigate whether the limitations in musical expression and latency would hinder a former guitarist in playing rhythmical music and finding it motivating.

P3, P4, P5 were not published to answer any of the research questions directly but are supplements to the overall scope of the thesis. Exercising the Tibialis Anterior Muscle of Children with Cerebral Palsy for Improved Neuroplasticity using an Electrical Guitar (P3) suggests how the guitar can be used to replace or supplement existing training exercises commonly used to negate drop foot. The Prospects of Musical Instruments for People with Physical Disabilities (P4) is a publication that contributes to the findings from the literature research centered on musical instruments for people with physical disabilities. States and Sound: Modelling User Interactions with Musical Interfaces (P5) is also based on the results of the literature review where I found the research field fragmented and suggested a model to describe user interactions with musical interfaces.

3.2 Methodical Approaches

During my thesis I have used several different methods. In this section I cover the methods used based on publications in order to align the process.

3.2.1 Literature Review

To get a better understanding of the research field I conducted a broad literature review. I began by focusing on the NIME (New Interfaces for Musical Expression) Conference because it is the main outlet for exploratory research of musical expression and used this as a stepping stone to the broader research area. First I did a keyword search of the proceedings, *https://www.nime.org/archives/*, using select key words found in the initial stages of the thesis such as special, CP, cerebral palsy, disability, disabilities, rehabilitation, rehabilitate etc. The first search using keywords was on titles and abstracts, and the second was a manual search on all titles to find papers not caught by the key words. Based on the results of the keyword search I used the same approach on the references to identify potential literature from other outlets branching out. Based on the results from the NIME proceedings I used Google Scholar with the same keywords as well as vocabulary learned from the review of the NIME proceedings. I also used Google Scholar to find literature about CP, Rehabilitation, music and brain plasticity, motivation, etc. which are outside my field of educational.

3.2.2 Design Methods

The actuated guitar has been the centre of this thesis and has been the central part of P1, P2, P3, P6 and P7. The choice to use an existing musical instrument as the foundation for the actuated guitar as a research vehicle is based on several design approaches/frameworks, including Physical Computing, Embodied Interaction, Tangible Computing/Interaction and affordance. Physical Computing, Embodied Interaction and Tangible Interaction all share many of the same overall perspectives, e.g. that human computer interaction is more than a screen, mouse and keyboard and how we can fit the computer to the human and not the human to the computer and how we can integrate the computer, sensors and actuators so it almost disappears in the design. These ideas, paired with Norman's take on affordance where an object or environment corresponds to its intended use, e.g. like a guitar string or a drum that affords plucking or hitting, created a splinter in my brain that wouldn't go away: *"how to create something that doesn't make people with special needs feel any more different and special than they already do, but offer something that integrates them into the 'normal' context?"*.

When designing the guitar I used the iterative method in combination with the design hierarchy of needs to integrate the above mentioned design approaches, methods and frameworks. The iterative method is a commonly used method for problem solving and development that goes through the phases analysis, design, implementation and implementation. The design hierarchy of needs was used as a guide to ensure that the development and research was done in the right order: functionality, reliability, usability, proficiency, creativity. P1, P2 and P7 are in line with this approach: P1 focused on the initial design of the guitar, outlining its functionality; P2 tested the reliability and usability of the actuated guitar; and P7 tested proficiency and creativity. I also took into consideration Verplank's idea of Do, Feel, Know. Especially his expression about the longer the delay between doing and feeling, the more dependent you are on having good knowledge which in my case is important regarding latency in musical instruments.

When talking about the 'normal context' it quickly becomes clear that the target group is not living in this 'normal context.' This presents some challenges that need to be addressed in the design process in order to make sure that the developed item actually functions and can be used by the target group. The PEO model and PACT framework are methods/frameworks that ensure a holistic approach to introducing new occupations/activities/technologies to certain people in a certain environment. With a special target group it is even more important to be aware of the intended use and setting. In much of the literature in this field the research has not focused primarily on users with special needs and the context they live in; therefore, it was important to be aware of this topic when designing the actuated guitar.

The actuated guitar was developed with PEO and PACT in mind. Many rehabilitation devices are big and expensive, which makes it impossible to acquire them and set them up and store them at one's own home. Furthermore, they require special knowledge to use and operate and rely on repetition of non functional training. The actuated guitar addresses PEO as it is cheap, does not require special equipment or training other than what anyone needs when learning to play the guitar. It interfaces with normal guitar amplifiers and effects and does not take up more space than a regular guitar.

3.2.3 Evaluation Methods

Several evaluation methods - qualitative (P2), quantitative (P6) and mixed methods (P7) - were used in the writing of this thesis to gather information and evaluate results. These methods were used in both lab and field studies.

Interviews

The semi-structured interview was the primary method for gathering qualitative data about the participants outside the study, e.g. prior experiences, personal data, etc. as well as subjective data about them following a study or how they experienced something. This method worked well because the target group was extremely small and complex and a regular questionnaire would not have been conducive to gathering as much information [29, 38]. The semi-structured aspect of the interviews allowed me to explore interesting responses or leads that came up. With a complex target group the flexibility of the semi-structured interview was perfect as no case of CP is similar and there were always small deviations worth following. A drawback of the semi-structured interview is that it can be time consuming to both conduct and process, but the small number of participants reduced this problem. Semi-structured interviews were used in P2 and P7.

Observation

A key method of extracting data or trends from the use of the guitar was through observations [29, 38]. In P2, observation was used to evaluate whether the children were able to control and interact with the guitar. I acted as observer while conducting the test, noting down my observations on paper. To catch any other or missed observations I also used a camcorder to record the children while they were interacting with the guitar. Using a camcorder gives you the ability to sit down afterward and watch for small visual details that you might have missed, such as facial expressions or body language, as well as listen to the audio for what the subject said or what they were able to play during the session.

In P6 I made observations while conducting the test and noted the observations down on paper. I also recorded the test to ensure that I did not miss important observations as I conducted the test and instructed the participants. Observation was used to compare how the participants used the two different types of pedals, since it would not have been enough to use the numbers as this did not explain how they used the pedals or whether they struggled with anything.

In P7 I also conducted observations when present at the house of the test participant and noted my observations on paper. This was combined with video recordings. When I was not present during the three week intervention the video observation was delegated to the wife of the participant. Her role was to turn on the camera each time the participant had a playing session, and she did this flawlessly. Once a week I collected the data and studied it before the next visit in case I saw something I needed to address while the intervention was ongoing.

Questionnaire

Questionnaires were used on one occasion during the data gathering stage to establish a baseline before an intervention during P7. Questionnaires are a good method for gathering comparable data both in qualitative and quantitative research [29, 38]. Questionnaires used in qualitative research often use open-ended questions, which provide a unique data set and require individual interpretation, which can be extremely time consuming. Questionnaires with a standardised and fixed number of answers, like the Likert scale, are good for gathering big amounts of data that does not require individual interpretation. The questionnaire used in my research was developed by the World Health Organisation (WHO) to extract information about people's quality of life according to 100 items. The questionnaire is called the *WHOQOL 100*. The questionnaire was used at the first meeting with the participant before he used the guitar and again a week after the intervention ended.

Automatic Data Gathering

Gathering big amounts of data through visual observation is feasible but, like interpreting questionnaires manually, is not possible when the data set goes above a certain size [29, 38]. To evaluate whether the users of the guitar strummed the strings at a certain interval, I created a data logging device that logged 12 data points each millisecond. The data point including timestamps, dates, metronomes beep, settings on the guitar, etc. I needed the data for the effects of latency and auditory feedback for P6 and the longitudinal field study P7. With big data sets and many data points it was possible to carry out comparisons between data points and extract otherwise hard to discover connections and results.

Chapter 4

The Design Process of the Actuated Guitar

As seen in the literature review, most musical research and commercial products focus on alternate controllers or instrument-inspired controllers. These controllers play a crucial role in making musical expression available to many people who would otherwise be excluded from the experience. The complexity of these types of instruments is heavily reduced, e.g. by simplifying the layout of the interface or limiting the input and output to single notes and certain simple scales, which makes them easier to play and helps the player 'sound good'. The consequence of this approach is that the controller has to be set up properly in the right key and scale and adjusted to the user's range of motion and position before every use. Alternate controllers do not support the use of already existing knowledge, e.g. known gestures from prior use of existing instruments or the use of existing information available for existing instruments such as chords, tabs, how to play videos, etc.

Instead of making a completely new and unique controller/instrument the idea is to give people the ability to play an instrument that already exists. Many stroke patients and people with CP suffer from hemiplegia and still have full functionality of one side of their body. By using the idea of leftover allocation one would let the user control all possible functions on the non-affected side of their body and let technology take care of the rest. This approach would allow the user to draw on learning by imitation, which is the most common learning rule [86], learn to play a real musical instrument, or use their already existing knowledge to play an instrument again. This would empower the user granting access into 'the original musical context', e.g. giving people the ability to take the actuated guitar to normal guitar tuition, find chords on the Internet, hear the instrument on the radio, and play in regular band.

4.1 Common Interactions with a Guitar

A guitar is a two handed instrument that requires asymmetric bimanual action [54], see Figure 4.2 for a description of the anatomy of an electrical guitar. Guiard defined the instrument as a parallel assembly in which each hand is dependant on the action of the other hand. The right hand is used to introduce energy into the strings (main resonators), which controls the Beginning of the Musical Event. This can be done in many ways, but the main gestures are pick/pluck or strum. Strumming is typically done when a finger or a guitar pick strikes several strings in quick succession and plays a chord. Pick or pluck of individual strings is similarly done using a finger or a pick, e.g. playing single note phrases or arpeggios that also involve string skipping and string dampening/muting. The left hand is used to fret notes along the neck, typically from one to six notes at a time (one per string) and spanning four octaves (on a 24-fret guitar). If the player has access to the note generator during the Middle of a Musical Event (the fretted strings), the left hand can manipulate the fretted notes, e.g. by bending strings or sliding up or down the neck, changing the pitch. The left or right hand can control the End of a Musical Event by dampening the strings (main resonators) or letting the note decay, which is only possible on instruments like the guitar that have a Non-Excited Middle. The mapping between gestures and control dimensions can be seen in Figure 4.1. To summarize using Bonger's taxonomy [28] (see Section 2.1), the right hand picking or strumming uses movement (displacement) whereas the left hand can use both isometric (pressure) when fretting a note and movement when, e.g. bending a note or sliding.

4.2 Design Considerations

Playing a guitar usually requires the use of both hands. The design should enable or re-enable people who are not able (or have lost the ability) to play the guitar, and only focus on replacing the right hand gestures and how that hand interacts with the guitar. The right hand was chosen because its main gestures are confined to a smaller area of the guitar and are not as complex as those of the left. The common interactions of the right hand have been identified in Section 4.1 and they involve strumming, picking, muting and string skipping. Three possible development stages were identified and ordered by level of complexity:

- Stage 1: Strumming
- Stage 2: String picking and string skipping
- Stage 3: String muting

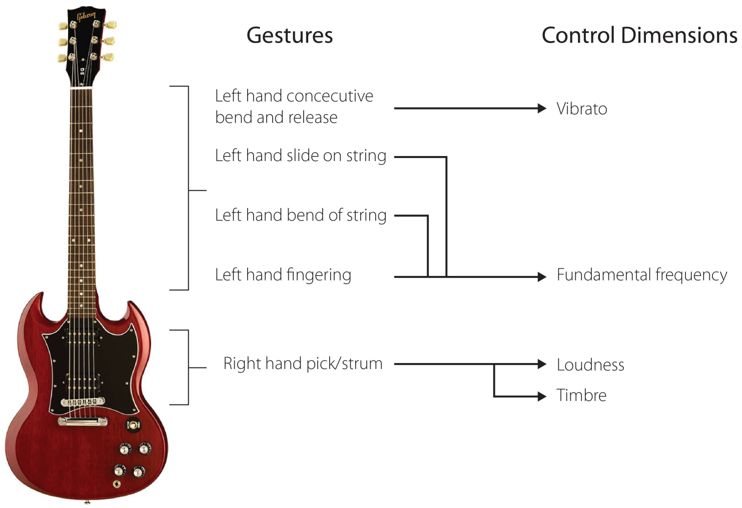

Fig. 4.1: The mapping of common gestures of the left and right hand playing an electrical guitar.

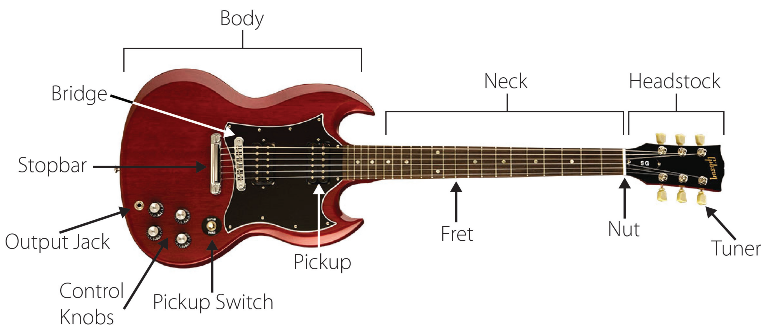

Fig. 4.2: The anatomy of a electrical guitar.

The design approach was divided into the above stages, based on their complexity where stage 1 is the simplest form of interaction to implement and stage 3 the most difficult. I decided to focus solely on strumming as the best candidate for a proof of concept to investigate the possibilities before including any of the other types of right hand interaction.

4.2.1 Context of use

The context of use include the characteristics of the users, tasks and technical and physical environment.

Environment

The system is being implemented in a home and guitar tuition environment. The system can be operated by a single individual, e.g. when practicing alone at home or when being taught. It is light and movable for easy transport to and from tuition, band practice, or gigs, and it is easy store when not in use. It fits into the existing environment, and can be used with existing devices such as standard amplifiers and effects. The guitar is designed to be played either standing or sitting.

Users

The users of the guitar are children in their teens and adults with congenital or acquired brain damage that resulted in hemiperesis or hemiplegia (weakening or paralysis of one side of the body). The users have different sensory, motor or cognitive disabilities, but all have one fully functioning arm and hand. They can have some cognitive disabilities but not so severe that they are unable to operate the guitar or need to communicate through a helper or device, see Section 2.2.

Tasks and goals

The goal is to increase motivation for longitudinal self-rehabilitation by playing guitar. Besides motivation the system can also enhance other areas such as:

- Action/reaction activities
- Training of intentional movement
- Multi-sensory activities
- Learning activities
- Cognitive training, e.g. memory
- Social empowerment
- Identity

Requirements

The following section describes the system requirements and their justification:

- R1: Low cost

- R2: The system has to be lightweight and easy to move
- R3: Supports both left and right handed players
- R4: Simple setup (no need for an expert)
- R5: Should work with existing hardware
- R6: Robust enough for longitudinal use
- R7: Low system latency
- R8: Supports the possibility for different control sites
- R9: Avoids unintentional trigger of strum
- R10: Must not interfere with the existing electronics
- R11: Should be able to strum the strings of a guitar.

The system has to be low cost - not just because of the small PhD budget but also to show that assistive technology can be low cost, which makes the adoption of the system more plausible (R1). The system should be light and easy to move, giving the user the ability to store it or bring it to different locations (R2). The guitar has to be light for comfort and prolonged use (R2). As some people are naturally left-handed and hemiplegia hits random sides of the body, it should be possible to operate the guitar with both left and right hands (R3).

The system as a whole must also be easy to set up. Complicated procedures to get the system up and running or with the need of help from, e.g. a therapist, etc., can result in abandonment (R4). To further simplify the setup the system must be compatible with existing hardware such as amplifiers and guitar effects that do not require proprietary hardware (R4)(R5), which would also increase cost (R1). The prototype of the system has to be robust enough to withstand logitudinal use to be able to evaluate motivation (R6). For the system to be playable latency has to be as low as possible because latencies that are too high have a negative impact on playability (R7). As the effects of hemiplegia are highly individual the system should use a kind of input that would allow for use for different control sites (R8). Unintentional strum triggers must be avoided as they will make the system unreliable and could result in abandonment (R9). Any of the added components of the system cannot interfere with the sound of the guitar (R10).

4.3 The First Prototype

The first prototype was a proof of concept that investigated how a normal right hand strumming gesture could be substituted by an actuator controlled by alternative input gestures. The proposal and description of the initial idea and first prototype were published as *The Actuated Guitar: A Platform Enabling Alternative Interaction Methods* [74].

Fig. 4.3: The first proof of concept of the Actuated Guitar testing out different types of input, in this case an accelerometer.

4.3.1 The Guitar

The guitar model used was an Epiphone SG electric guitar, chosen because of its low cost, the type of body and symmetric body shape it has, the fact that it is light weight, and its large control cavity (R1)(R2). The symmetric body shape allowed the guitar to be flipped and restrung to encompass both left- and right-handed players (R3). The construction of the SG model was a solid body, meaning that it was a solid piece of wood several centimeters thick, compared to the acoustic guitar, which is only a few milimeters thick. This makes the instrument sturdy and also makes it possible to make alterations to the guitar without weakening its construction (R6). The guitar was also light, which increases comfort for prolonged use (R2). In addition, it had a flat top rather than an arched top, making it easier to mount equipment on the surface. The large control cavity with two volumes, two tones, and a pickup select switch were useful for securing, e.g. additional electronics, see Figure 4.4 (R6).

Fig. 4.4: The Epiphone SG model is a flat top solid body electrical guitar with a large control cavity. The model is used as a base for this project. (Source: Epiphone.com [6])

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4.3.2 The Strumming Device

A device capable of perpendicular movement across the strings was needed to substitute the right hand strumming gesture, Figure 4.11 (R11). Inspired by the firefader's use of motorised faders [23], the strum was substituted by a motorised fader normally used in mixing desk. The motorised fader was mounted above the bridge pickup by driving a glued-on pick across the strings. An Arduino Nano V3 and a 2Motor motor-controller managed the speed and direction of the pick, see Figure 4.8b.

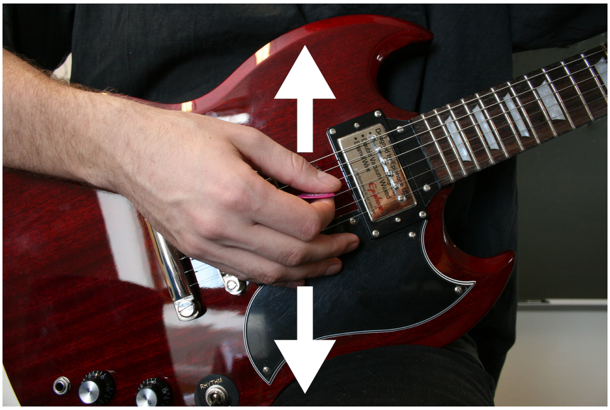


Fig. 4.5: To strum a guitar the right hand travels across the strings in a near perpendicular fashion using a finger or a guitar pick to strum the strings.

The fader mount was fixed without any movable joints. This prevented the pick mount from tilting back to allow string skipping, or dampening of the strings, which could have allowed the device to strum one string after an other in either direction. This also allowed the strumming device to control only the Beginning of a Musical Event and the speed of the strum. The speed of the pick was controlled using Pulse Width Modulation (PWM). The standard PWM frequency used by Arduino Nano V3 resulted in a loud and clearly audible high-pitched noise from the motor every time the motor moved the pick. The noise was captured by the pickup in the guitar, making the strumming device unusable in that current state and incapable of achieving the requirement of (R10). Setting the PWM frequency to 31,250H (well above the range of human hearing) by changing a flag in the Timer/Counter Control Register B of the Arduino Nano V3's ATMega328 chip solved the noise issue. To be on the safe side the bridge pickup was removed to avoid any potential static or magnetic interference from the motor (R10). Shielding could also have solved magnetic interference, but it would have been a more involved and cumbersome process.

Fig. 4.6: The motorised fader used in the Actuated Guitar.

4.3.3 Input candidates and mapping

An infrared distance sensor and a 2-axis accelerometer were used to investigate different gestural inputs and mappings for strumming the guitar. The two types of sensors were chosen based on the scalability of their input and flexibility in positioning different control sites, availability, and popularity of use in DMIs as seen in Table 2.1. The accelerometer had to be mounted on a limb to register movement, while the IR sensor could be mounted either on a limb or a surface. Both were scalable to accommodate differences in range of movement. Each sensor was tested in the lab during implementation to discover any useful gestures and mappings and see if they were viable for strumming the guitar. Initial attempts employed absolute mappings, see Section 2.5, where the distance or angle registered by the sensor was mapped one-to-one to the travel of the pick. The accelerometer was extremely noisy, which resulted in unwanted strumming triggers. Filtering was used to solve the unwanted triggers, but this also introduced a lot of latency because of the limited processing power of the Arduino Nano V3, which made absolute mapping for the accelerometer unusable.

The IR sensor was less noisy and also required filtering to avoid stuttering of the motor and pick resulting in strum of a few string at a time. The filtering of the IR-sensor also resulted in increased latency, making it impossible to play consistently. The next approach was to map a strum to a certain movement threshold for the accelerometer and a distance threshold for the IR distance sensor. When the threshold was reached, e.g. breaking the IR beam or a rapid movement by the accelerometer, the strumming device would do a complete strum of all strings at a fixed speed. Filtering was still needed to avoid unintentional strums for both sensors, and this added a small but still perceivable amount of latency. I decided to try a momentary push button as it gave the same potential as the threshold mapping strategy to strum all strings at once; it was also a popular choice of sensor in DMIs [85]. The benefit of using the button was that it did not require any data filtering, and therefore caused no further increase in latency as it was either on or off, see Figure 4.9a. Another advantage of the button was that the buttons come in all shapes and sizes to accommodate various requirements of control sites and range of motion, e.g. size or force required to engage the button (R8). The button could also be placed either on the body or a surface.

(a) (b)

Fig. 4.7: (a) The front of the guitar showing the motorized fader mounted above the strings. (b) The back of the guitar showing the Arduino Nano v3 and the motor controller used for controlling the strum.

4.4 Second Iteration

4.4.1 The Guitar

The guitar was modified before the first user study. The study participants were children diagnosed with hemiplegic cerebral palsy who had no prior musical training. The guitar was tuned in an open chord to make it easier for the participants to play chords with no prior knowledge and make the experience as sonically pleasant as possible for both the untrained participants and me. Inspired by Guitar Hero, I attached coloured stickers to the fretboard, which labeled certain chords, see Figure 4.9b.

4.4.2 The Strumming Device

The motorised fader got a sturdier 3D printed mount that could withstand rough handling and was screwed directly into the body of the guitar (R6). The mount had grooves that allowed the fader to be quickly adjusted to the correct height of operation with a normal screwdriver if needed, or else it was knocked out of place (R4). To protect the fragile electronics the volume and tone controls were removed from the control cavity, and the Arduino and Motor-Controller were moved into the emptied control cavity. These were attached to an adhesive breadboard for easy modification if needed, see Figure 4.8. The pre-drilled holes were used to connect the fader to the Arduino and motor-controller (R6).

4.4.3 The Pedal

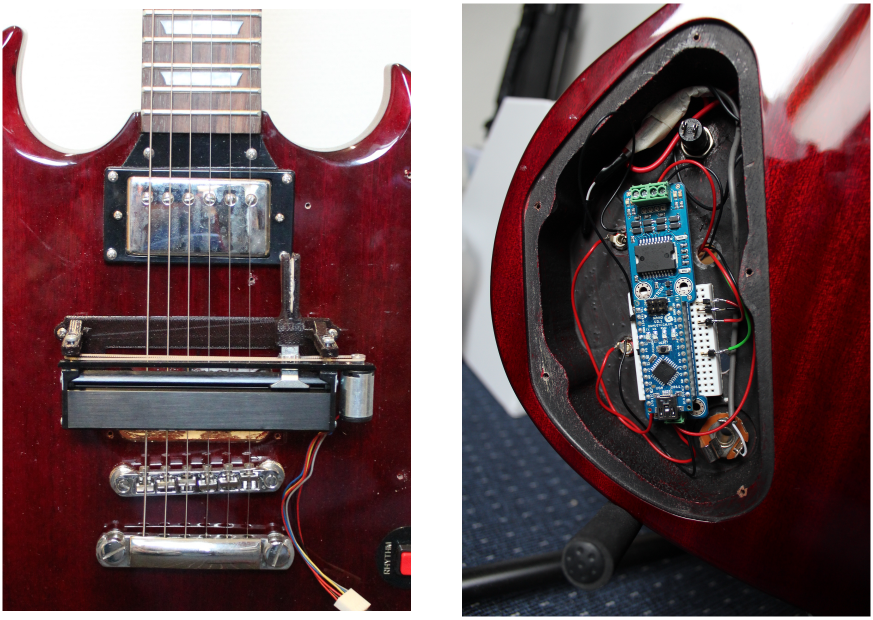
As the children were paralyzed on one side of their body, the momentary button was fitted into a 3D printed foot pedal, see Figure 4.9a. The pedal allowed the children to use their better functioning foot as a control site to strum the guitar. The pedal was connected to the guitar with a wire to ensure the lowest amount of latency. The user study was published as *The Actuated Guitar: Implementation and User Test on Children with Hemiplegia* [75].

4.5 Third Iteration

Several changes were made in the third iteration of the Actuated Guitar. The changes were made for the guitar to withstand continuous use during a longitudinal case study and gather data about its use. The test participant in the longitudinal case study was a former school teacher and musician who was 15 years post-stroke and had complete paralysis of his right hand, arm, and shoulder and hemiparesis in his leg. He used an ankle brace on his right foot in order to walk. The case study is reported as a technical report, see P7.

Requirements for the third iteration of the Actuated Guitar:

- Equipping the guitar
- Increased durability
- Data logging
- Tuning the guitar

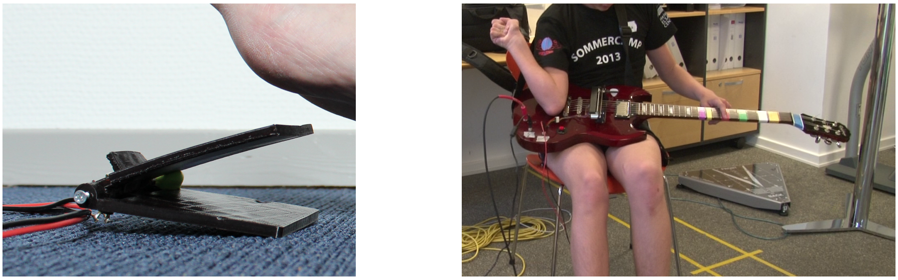


(a) (b)

Fig. 4.8: (a) The front of the guitar showing the motorised fader mounted above the strings. (b) The back of the guitar showing the Arduino Nano v3 and the motor controller used to control the fader for strumming.

4.5.1 The Guitar

Only a few changes were made to the guitar itself. The design using the motorised fader and the electronics hidden in the control cavity had been robust enough to avoid any breakdowns during handling and tests. Two foam stoppers were installed at each end of the fader to shorten the distance the pick had to travel, to lower latency, and to reduce noise when the pick hit each end of the fader R(7). This was based on feedback from showcasing the instrument at the ICNR conference and from several therapists and users. The comments about the noise were only an issue when the guitar was not amplified. If the guitar had been used with an amplifier the noise from the pick hitting the mount would have been inaudible R(5). A hemiplegic user needed assistance from another person to put on/equip the Actuated Guitar, as use of the instrument required a regular guitar strap. However, the regular strap was replaced by a click strap that could easily detach at each end and thereby make it easier for the user to equip the guitar R(4).



(a) (b)

Fig. 4.9: (a) The 3D printed pedal with the embedded momentary button. (b) The guitar in use at the test on children with CP.

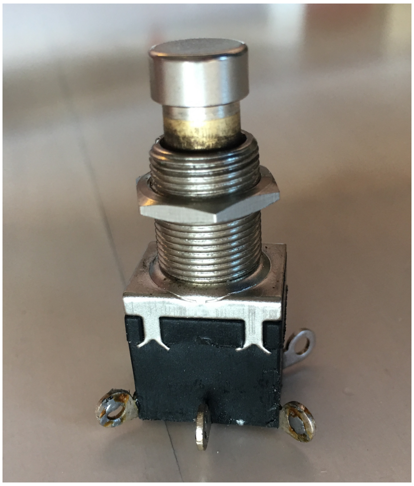
4.5.2 The Pedal and Data Logger

The main changes before the longitudinal test were made to the pedal. The pedal design from the user study [75], as seen in Figure 4.9a, was not suitable for longitudinal use. It turned out to be too difficult for the user to control the pedal as it easily skidded around on the floor and made it difficult for him both to press the pedal and strum the guitar. The small momentary button used in the original design was not able to withstand prolonged use and, following the user study, had started to fail periodically.

The test sought to explore how motivated the test participant was to play the Actuated Guitar and whether he improved his ability to play the guitar during the study. This required capturing as much data as possible about when he used the guitar, for how long, how many times he pressed the button, and how hard and how far he lifted his foot off the pedal. The pedal was completely redesigned, including a heavy duty momentary button for improved durability, an IR distance sensor, a force sensing resistor (FSR), and an Arduino Uno with a data logging shield, including a clock and a SD card reader. All the components were fitted into a sturdy plastic casing, see Figure 4.10a. To avoid movement of the casing on the surface the casing and the board were fitted with velcro. A TC Electronic Polytune was included on the board for the user to tune the guitar.

4.5.3 Measuring System Latency

Sensors, microprocessors, and actuators can introduce latency to a system. The Actuated Guitar system consisted of different components that could affect the overall latency of the system, which, in this case, included the computation time of the Arduino, motor-controller and the movement (acceleration, torque and distance) of the motorised fader. Measuring the latency of a targeted device using the device's internal software using time stamps can be



(a)

(b)

Fig. 4.10: (a) The button used in the revised pedal, (b) where a LED was added directly to the button circuit to show exactly when it made contact.

inaccurate because logging internal time stamps does not capture the action and response of the human user. According to Roberts et al. [105], proper measurement of latency is done externally using cameras that allow for observing and timing the complete interaction cycle from action to response.

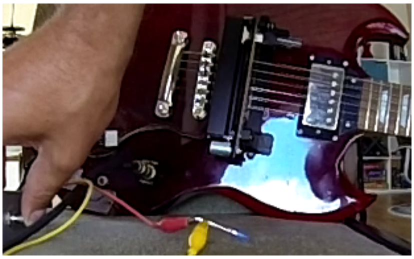
Using a camera with the standard 24 frames per second (fps) would give a resolution with a time between frames of 41.7ms. With a time-sensitive musical instrument, where as little as 7ms can be detected, this would not have been satisfactory. A GoPro Hero 3 could record the interaction latencies at 240fps, and this was the camera with the highest fps I could find. The GoPro gave a resolution, or time between frames, of 4.2ms. A battery-powered blue LED lit up when the momentary button closed to denote exactly when the momentary button had been triggered. The camera framed the pedal, strings and the motorised fader together to compare the LED and the movement of the pick.

The system had a total latency of 84ms from the moment the button was triggered to when the pick stopped moving and another strum could be engaged. The pick started moving after 29ms, reached the first string in 45ms and the last string in 73ms and stopped at 84ms. The complete six-string strum (from hitting the first string to leaving the last string) took 28ms. See Table 4.1 and Figure 4.12d. This could be divided into *software latency* 29ms (from button being engaged to pick starts moving) and *mechanical latency* 44ms (from pick starts moving to picking the last string).

Fig. 4.11: Foam stopper were added to each end of the fader to reduce noise and latency.

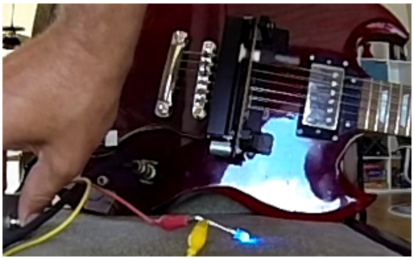
4.6 Fourth Iteration

The fourth iteration of the guitar was made to test how good musically trained and musically untrained people were at compensating for latency when pushing the pedal to the strumming of the guitar, see the publication *Hear You Later Alligator: How delayed auditory feedback affects non-musically trained people's strumming* [72]. The system was extended with a metronome based on an Arduino Uno and a buzzer for the participants to play along to and synchronise to its beat, see Figure 4.14b. The data logger was improved with the capability to log the time stamp of the metronome. A switch was also added to the body of the guitar. When toggled, it added an additional 177ms delay, giving a total delay of 250ms from activation of the pedal to the strum of the guitar. The state of the delay switch was also logged by the data logger. The last addition was a new FSR pedal/button running on its own Arduino board to reduce latency. The FSR button was implemented to investigate whether the type and design of button had any influence on the results, e.g. amount of primary feedback, see Figure 4.14a.

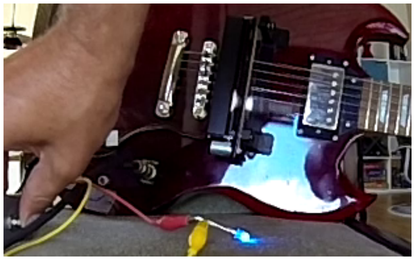


(a)

(b)



(c) Caption 2



(d) Caption 2

Fig. 4.12: (a) LED is off, (b) button engaged and LED turns on, (c) pick reaches first string, (d) pick reaches the last string.

	Milliseconds	**Percent**
Button engaged	0	0
Pick starts moving	29	35
Pick hits first string	45	54
Pick hits last string	73	87
Pick stops	84	100

Table 4.1: The table shows the total system latency from engaging the button to when the pick stops moving.

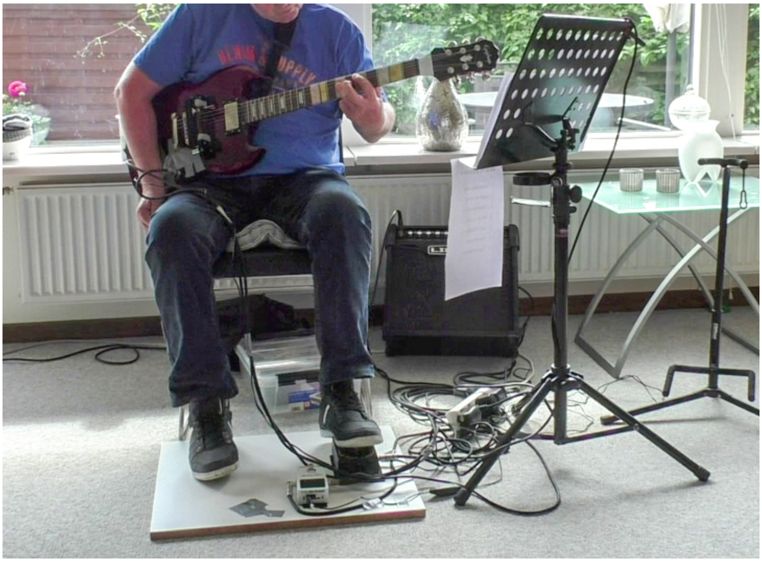
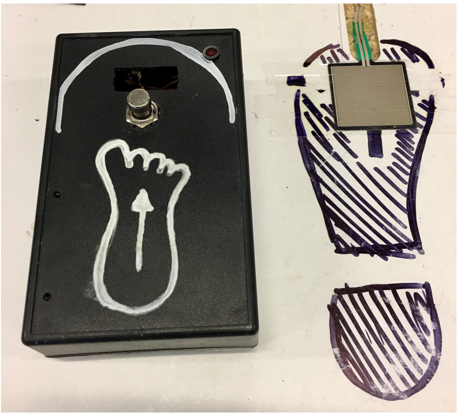
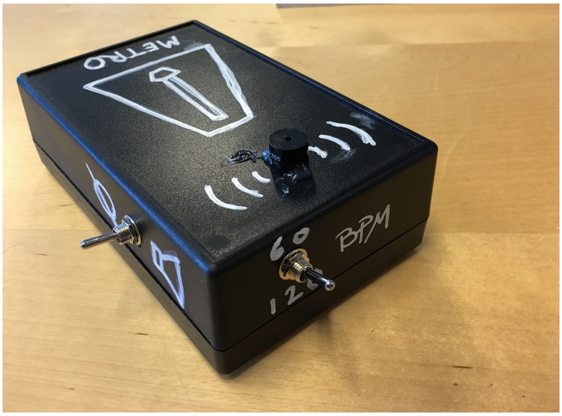


Fig. 4.13: Testing the third iteration of the actuated guitar on a former school teacher and musician, 15 years post stoke.



(a)



(b)

(c)

Fig. 4.14: (a) The pedal and the FSR and button, (b) The Metronome (c) A musically trained test participant.

Chapter 5

Discussion

In this chapter I discuss the contributions (see Section 1.2) and the relevance and further work of the Actuated Guitar.

5.1 aIME Literature

Using different methods I conducted an extensive search for publications, focusing on assistive interfaces for musical expression (aIME) that reestablish what Obrenovic referred to as reduced or broken modalities. In order to increase the likelihood of finding relevant research, I did not focus on specific research outlets. It was surprisingly difficult to find aIME publications *written solely* on people with physical disabilities. Even within the field of music therapy, where one could expect to find literature on this type of research, it was difficult to find relevant aIME literature because the music therapy research primarily focuses on the cognitive aspects of therapy such as developmental disabilities [32], learning disabilities [112], anxiety [53], depression [83], or improving reading skills for children with reading disabilities [101]. Likewise at the conference for New Interfaces for Musical Expression, which focuses solely on research on interfaces for musical expression, a surprisingly low number of publications focused on aIMEs. Only 1% of all publications from 2001 - 2016 focused on aIMEs and only 0.3% on aIMEs on people with physical disabilities.

One reason for the difficulty in finding aIME research could be that the topic itself is fragmented and does not have a common outlet, which results in a similarly fragmented language used to describe aIME research. This fragmentation in both outlet and language could make publications difficult to find using search engines and keywords. Another explanation could be that there simply are not that many aIME publications out there. It is difficult to pinpoint exactly why aIME research is not a popular research topic, but there are some factors that set it apart from other research areas: the limited target group, cognitive and physical disabilities that are highly specific to the individual, the need to involve external experts or therapists, ethics, etc.

The literature review showed that the papers did not describe their target group in any greater detail but used broad terms like *disabled* or *cerebral palsy*, which do not actually convey anything specific about the user's physical or cognitive condition. One person with CP might be hemiplegic, affected throughout one half of the body, while another might be a quadriplegic whose whole body is affected. This lack of a clear definition of the target group also leads to a weak, if any, identification of design requirements, be it to amplify or substitute broken or limited modalities. Most papers conducted single session tests primarily doing proof of concept studies or looking for what they called *new or alternative interactions* or *potential uses*, which means that the instrument was not designed for people with certain disabilities or to solve an actual problem but implemented simply to use in a disability context. None of the instruments went through any longitudinal tests that could answer whether the aIME had any potential in a real use case. A longitudinal study could answer some key questions like whether the instrument could withstand prolonged use, whether users were motivated to play it, or whether it was abandoned.

Most instruments were monophonic improvisational instruments, which played on top of another layer of music locked in certain scales (most often the pentatonic scale). It is clear that some target groups need extremely simple interfaces, e.g. because of severe cognitive implications, but looking at the aIME target group from a broader perspective, this approach can have some significant drawbacks. Many people who have a disability do not have cognitive disabilities, like amputees or people born without a limb, or their cognitive disabilities are minor. They can, of course, use simple instruments but the simplicity can be too great, making the instrument seem like a toy and negatively affecting their motivation, which results in abandonment.

5.2 Modeling aIMEs

Based on the literature review it was clear that there was no common language - either written or illustrative - used to describe designs, interactions, or feedback in aIMEs. In (P5) I propose a modelling approach to summarise interactions with musical interfaces, extending the work of Buxton [30] and Hinckley [61]. The challenge when making a model is to balance simplicity and complexity. The model has to be complex enough to carry the information one wants to convey but simple enough not to confuse the reader.

The model proposed is not meant to be the 'end all be all' model, but is a contribution and a call to the community to start focusing on how they communicate in a clearer and more descriptive language, e.g. using models in the description of the aIMEs on all levels. As Buxton motivated the need for his Three State Model [30]:

"One is the lack of a vocabulary that is capable of capturing salient features of interactive techniques and technologies in such a way as to afford finding better matches between the two. In what follows, a model (first suggested in Buxton, Hill and Rowley, 1985) is developed which provides the start to such a vocabulary."

The current state of the model does not easily allow for visualising how expressive and dynamic an aIME is. The model can, for example, not show if it is restricted to a certain key and scale or how dynamic and expressive the instrument is in terms of velocity, timbre, loudness or pitch. Extending the model further in its current shape would bloat the model and cause confusion. A solution could be to split the model into two separate models where one would describe the gestures and feedback and the other describe the mapping and input technology. This would also follow the more common model of a DMI, see Figure 2.8.

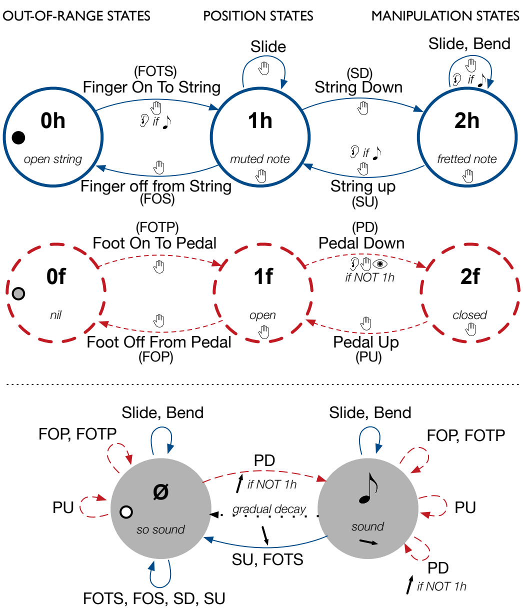


Fig. 5.1: An example of the complexity of describing a highly expressive musical instrument with the danger of bloating a model, e.g. by adding tonal information.

5.3 Delay

The delayed auditor feedback study (P6) showed that musically trained people who used the Actuated Guitar had significantly fewer synchronisation errors - both in terms of the mean and its spread - than non-musically trained people. This was most likely due to a lower anticipation bias. Non-musically trained people had a synchronisation error spread of 73ms - almost twice that of the musically trained (44ms) [72]. The study found that the synchronisation error of musically-trained people (44ms) was within the typical range playing in an orchestra, [100] indicating that musically trained people were able to incorporate the actuated guitar's latency into their playing.

The overall strumming latency of 45ms for the Actuated Guitar, from actuation (button press) to reaching the first string and producing sound, is comparable to Harrison and McPherson's adapted bass guitar for one handed playing, which took 56ms from actuation to fretting of a string [58]. While their system latency was much smaller (6ms) than that of the Actuated Guitar (29ms), their mechanical latency of fretting the string was much higher (50ms) than the time it took from when the pick began to move to hitting the first string in the Actuated Guitar (16ms). Given the similar interactions of button presses to motor actuation in these two AIMEs, I can expect that the Actuated Guitar's software latency could be reduced to a similar level by simply changing to a micro controller with a faster processor. Using, for example, a Teensy 3.5 micro controller (120 MHz), which is 7.5 times as fast as the Arduino Nano (16 MHz), would at least halve the strumming latency (from button press to reaching the first string) of the Actuated Guitar down to 22ms and most likely even lower.

This reduction in latency would bring the Actuated Guitar's latency significantly under Dahl and Bresin's [40] possible breaking point of between 40 - 55ms conducted on musically trained people. This would likely result in a reduction of synchronisation error spread for all users. Jack et al. [65] compared four latency conditions (0ms, 10ms, 10ms + jitter($\pm$3ms), 20ms) and found that 0ms and 10ms latency were significantly rated more positively than the 10ms + jitter and 20ms latency conditions. The latency did not show any significant difference in mean synchronisation error but was rated more difficult to play, which points to a higher user cost in terms of attention. A latency below 20ms would be favourable for people who start learning to play (non-musically trained) since the aIME would seem easier to play and thereby lower the risk of the user abandoning the aIME. To get the latency from button press to first string even closer or below 20ms the mechanical latency could be lowered. In the case of the Actuated Guitar this is basically the distance from the pick to the string. By moving the end stops closer to the strings the distance travelled before reaching the string would be reduced, which would result in lower mechanical latencies.

5.4 The Actuated Guitar

In the beginning of this section I discuss the 11 design requirements from 4.2, although some were mentioned and argued for in 4.2.

The Actuated Guitar was built around a cheap electric guitar (Epiphone SG), replacing the strumming hand and enabling people with a non-functioning right hand, e.g hemiplegics or amputees, to play the guitar (R11).

The first requirement (R1) for the guitar was that it be inexpensive. The guitar itself cost around 2500 dkr and was fitted with approximately 3000 dkr in other components, adding up to a total of 5500 dkr. This is considered a low cost, if comparing it to the retail price for a Soundbeam 6 'solo' that retails for 2505 GBP or the Magic Flute Starter Pack, which retails for 2125,65 EUR. However, the price of 5500 dkr could still be considered as high for some but compared to the other mentioned products it is inexpensive even if i added additional margins per unit to compensate for the times used to develop the device. The used components are not sourced directly at the manufactures and if they were it would drive the price further down. The second requirement (R2) was that the instrument be light and easy to move for prolonged use. During the longitudinal trial the test participant typically used it for between a half hour and an hour without showing signs of being burdened by the instrument's weight.

The third requirement (R3) was that the guitar be symmetrical so that both right- and left-handed players could play it. It was easy to set up, plug into a normal guitar amplifier using regular jack cables and power on the strumming device (R4)(R5).

The current implementation and components used, in particular, were not capable of prolonged and repetitive use, which became evident from the results reported in the longitudinal field trial (P7). Here the guitar failed the (R6) requirement that it be robust enough for longitudinal use. The switching function of the momentary button, the bearings and the rubber band driving the pick in the motorised fader, were worn down due to extensive use. A higher quality button would have solved the issue of the wear and tear of the momentary button. An even better solution would have been to incorporate MIDI functionality, as was the case with Harrison and McPherson's bass guitar for one handed playing [58], and use of an off-the-shelf MIDI controller for input. A solution to the strumming could be to use a high torque stepper motor and controller that could, with a new custom strumming mechanism, replace the motorised fader.

The system latency of the guitar was not as low as I had hoped, but it was possible to compensate for the latency and play along to e.g. backing track or other people. I discuss possible improvements to the latency in 5.7 Future Work.

In my publications and as mentioned in The Actuated Guitar: A platform enabling alternative interaction methods(P1) [75] Section 2, the Actuated Guitar has focused on simple strumming with an up-down motion. This is the simplest form of playing a guitar and is a good candidate for a proof of concept that shows it is possible to play a real electrical guitar despite being hemiplegic.

The one-dimensional implementation with the one-to-one mapping of button activation and full strum of all strings with the same velocity is slightly limiting when speaking about musical expression. This is similar to Harrison and McPherson [58], who used an off-the-shelf MIDI controller implementing a one-to-one mapping from button to fretted note (8 buttons corresponding to 8 specific fretted notes) on their bass guitar for one handed playing. The implementation of MIDI into the Actuated Guitar could be useful to increase expressiveness. Many off-the-shelf midi controllers have some kind of pressure sensitive pads that could be used as an input device for the Actuated Guitar. Instead of supporting only a one-dimensional strum or trigger like Harrison and McPherson, a controller with pressure sensitivity could be mapped to the velocity of the strum. This would require no modification of the existing strumming mechanism.

When moving into string skipping and string muting the complexity of both input and strumming mechanism increases dramatically. This increase in complexity happens no matter which hand - fretting or strumming - is emulated. When I try to emulate the strumming hand I run into certain problems such as single note playing, muting, strumming of only some of the strings, simultaneous strummed strings like finger picking, and so on. The same is true for the fretting hand where the difficult techniques to emulate include sliding, bending hammer-on and pull-offs, etc.

Mechanical and electronic noise was an issue when developing these systems. Electronic (PWM) noise was a problem when developing the actuated guitar, as it almost stopped the instrument dead in its tracks, but this was solved by changing the PWM frequency of the Arduino Nano (R10). Mechanical noise was problematic when playing the non-amplified actuated guitar, an issue that Harrison and McPherson also mention in their approach [58].

Emulating either the left or right hand is a highly complex task. Each approach has drawbacks that are not easy to solve. However, emulating the fretting hand, as Harrison and McPherson did, presents some additional problems, especially since the horizontal axis simply moves up and down the neck and reaches all 88 positions on a four-string bass guitar or 144 on a six-string guitar.

5.4.1 Perceptual Control of a Button

The different pedal designs developed for controlling the strum, see Figure 4.9a and Figure 4.14a, were very different in terms of their physical dimensions and technological specifications. One had a push button mounted in a casing, while the other had a flat-force sensitive resistor (FSR) taped to a flat board. This caused the interaction and the haptic feedback to differ quite dramatically between the two designs. Oulasvirta et al. discussed the issue of how different button designs altered the perceptual control of a button by comparing linear, tactile, touch and mid-air buttons. They defined a button as a black box where the motor system has no access to the moment the button activates. The perceptual control fails, or yields a high amount of errors, if the distance (time) between the *Expected Perceived Activation* and the *Perceived Activation* is too high and therefore must be kept to a minimum to ensure low error rates [95], for example, when a character is perceived to jump over a platform in a game like Super Mario or an LED light lights up when calling an elevator. This was especially evident during the P6 study, when the latency of the system and the different pedal designs and their feedback confused some of the test participants. Many errors were caused by the click preceding activation in this study, which was a combination of the high audible click coming from the button on top of the big box pedal and the relatively high latency when talking playing music. This frustration was not as evident when using the completely flat FSR-based pedal, but it did present other errors as there were no tactile guides to keep the foot on top of the pedal and many drifted off, causing errors.

5.5 Case Study

I conducted a three week intervention (n=1), which is described in the publication *A Longitudinal Field Trial with a Hemiplegic Guitarist Using The Actuated Guitar* (P7). The aim of the study was to investigate whether it was possible to enable a former guitarist 15 years post-stroke to re-learn to play the guitar in order to increase motivation for self rehabilitation and his quality of life. Kirk et al. [69] ran a similar feasibility study (5 weeks) investigating how a DMI (a forward reaching modular desk with 4 drum-pads triggering percussion sounds) could aid in self management of stroke rehabilitation and improve range of motion in the wrist, arm and shoulder. They used a small number of participants (n=3), as in the Actuated Guitar Field Trial (n=1), and all participants were post-stroke (27 months, 14 years, 11 months), which was comparable to my field trial (15 years). Some of the same arguments used to support the theory that music holds potential in motivating self-rehabilitation in home contexts were made, e.g. that exercising to music results in a reduction in perceived effort [67] and that there are strong links between music and emotions [26]. All participants in Kirk et al's study reported high levels of motivation and enjoyment when playing the digital drum pads. All physical impairment measures (reach, shoulder flexion, wrist extension) improved during the intervention phase and were retained or improved further during the post-intervention phase.

Kirk et al.'s focus and approach differed from that of the Actuated Guitar with their more classic approach to rehabilitation and focus on repeating physical exercises and levels of range of motion. This was evident in the songs they chose and how they implemented them in the two systems. The participants in their system added ten songs of their own choice. All songs were capped at two minutes, regardless of their actual length and the tempo mapped. Four percussion/drum sounds (Tom, snare, hi-hat, woodblock) were mapped to digital drum pads and triggered when by a hit on a drum pad. In the Actuated Guitar, in contrast, the participant was given free choice to play whatever he wanted. Furthermore, the Actuated Guitar is a fully functional electrical guitar, so it allowed for all sonic possibilities that other guitars have.

All participants in Kirk et al.'s study stated that they would not have enjoyed playing songs they had not chosen. Two participants requested a larger selection of songs, which showed that the freedom to choose one's own songs is important for continued motivation.

Kirk et al. provided some anecdotal evidence in their qualitative analysis for transfer of physical gains into tasks of daily living. One participant in their study mentioned that in addition to some physical improvements, he also made cognitive gains during the study. In my field study (P7) this was also evident when looking at the WHOQOL100 scores measuring quality of life, but this was not at all conclusive.

Kirk et al.'s finding of high levels of motivation corresponded with the findings described in the field study (P7). The last mandatory session of the study had to be stopped as the wear and tear had started to affect the performance of the system, the button had be pressed harder and harder, and the bearings in the fader were failing, which made the travel slower and increased latency. The participant was told to leave the guitar alone and that it would be picked up later that week. Nevertheless, the participant kept playing and logged some of the longest sessions of the three week study during this time, which showed an enormous motivation to use the Actuated Guitar despite its suboptimal conditions by that point.

The user showed a high degree of motivation throughout the case study as he incorporated different private items, such as an iPad (chords and YouTube for songs), guitar chords book, metronome, and his old piano and P.A setup for backing tracks (the exact tracks he used before the stroke) into the sessions. He had used the metronome and a chord book when playing guitar before his stroke. He incorporated an iPad into free sessions by using the YouTube app to find songs to play along to, e.g. the mandatory children's song 'Min kat den danser tango' and songs he had played pre-stroke, such as 'Yesterday'. After a while he decided the iPad was not loud enough, so he hooked up the iPad to his old PA system. He also incorporated his old digital piano to play backing tracks he had used previously when playing at parties etc. This behaviour continued to the end of the case study. By the last mandatory test the buttons were starting to wear out and required more than double the force to activate a strum, and the bearings and rubber band pulling the pick were also showing signs of significant wear.

As the study progressed it was clear that the participant was able to factor in the system delay. Although he was not told that the system had a small amount of latency, he did not ask or question it, which could indicate that either he did not notice it or he considered it a result of his condition. The measured results also show that he improved during the three weeks and video recordings make clear that by the end he was playing with ease and commitment. Despite having 20ms higher latency than the breaking point, which has shown to result in difficulties keeping a steady rhythm on drum pads [40], use of the AG was still motivating in the long term.

A lot of information about the overall performance, such as the quality of the chords, cannot be derived by measuring timing alone. All the sessions were video recorded, which made it possible to analyse the participant's movements, posture, and gestures, as well as the audio, which included information like chord quality. Looking at the quality would require a type of taxonomy of chord quality for which timing would be just one parameter. Other important parameters, such as string buzz/rattle, number of notes fretted, muffled/muted strings, etc., could tell something about the quality of the chord. The participant's physical appearance when using the guitar also showed potential improvements in, e.g. how he handled the instrument, how much he struggled, or whether he was just playing and enjoying himself.

5.6 Methods

In this section I discuss the different methods used in the thesis and their potential weaknesses.

5.6.1 Observations and Interviews

The two primary methods used during my studies were semi-structured interviews and observations. Interviews and observations can be labour intensive with large numbers of test participants, especially when results need to be extracted from the gathered data. In this case, with the small number of participants, the amount of data was not an issue. I planned and conducted all of the tests without any assistance. When constructing all of the material, conducting the tests and extracting the results there is always a risk of introducing bias, breaking test protocols, missing important observations, or using leading questions, etc. To avoid these pitfalls I could have established some collaborative research with external partners or hired someone to ensure the objectivity in developing the material and during the tests. This would have freed me to solely focus on conducting the tests and removed any worry while observing the participants' behaviours.

Using video observation can be tricky because the position of the camera is crucial to capturing the essential data needed for either image or sound. Another risk when using video is information overload when both video and sound must be analysed. Many interesting and potentially important aspects can be visible, and choosing what to focus on can be difficult and obscure the important data. To improve the non visible data a think-aloud protocol could be introduced. This would allow the participant to elaborate on how he was experiencing the interaction in the moment [52]. In my case it could have been interesting to implement a think-out-loud protocol during the self-recorded sessions in the longitudinal study (P7). This might have explained seemingly small nuances, e.g. body language that was difficult to decipher, that could have had great significance. To avoid affecting the behaviour or performance of the participants a fly-on-the wall observation could be used [131]. This method, however, requires that it is possible to observe without being noticed.

5.6.2 Questionnaire

Because of the limited size and access to the target group the use of questionnaires was done only once to gather large amounts of standardised information. The questionnaire used in the longitudinal study - the WHOQOL-100 - helped establish a baseline before the intervention and measure potential results after the intervention. The problem with using the WHOQOL-100 in this scenario was that it was designed by the WHO to cover as many different people as possible in order to capture measures of quality of life around the world. This worked and produced some results but it was more or less impossible to conclude whether the use of the guitar was the cause of the changes in some of the parameters. In addition, many of the questions were beyond the scope of this thesis. A custom-designed questionnaire would have been a better approach and a collaboration with the therapists and doctors within the field could have yielded much more usable results.

5.6.3 Quantitative Data and Automatic Data Gathering

In the longitudinal study (P7) the test participant played along to the same backing track to establish improvements in how he adapted the latency from the guitar at every visit. There was no way to compare the two signals automatically and therefore it had to be done by visual inspection of the audio track from the video recording by measuring the difference in milliseconds between the strum and beat signifiers in the backing track. This manual method of comparing peaks in the same audio track is not ideal and can have a potential for errors as it relies on manual assessment. A solution could be to implement MIDI functionality into the logging unit using the possibility from MIDI to send out, e.g. MIDI messages for the metronome beat of the backing track and automatically log the beats at the right tempo. This would eliminate potential error prone evaluation of where the beat is in relation to a strum.

The automatic data logging, developed for P6 and P7, started logging all system data from the moment power was turned on, no matter if the guitar was being played or not. One weakness of this approach was the sheer amount of usable and unusable data generated as it logged once every millisecond with twelve data-points at every logging point. Another challenge when doing automatic data logging this way was the alignment of the data with a particular user and a particular performance as there was not a clear indicator of when a certain person started and what he played, etc. To minimise the amount of data could be to only log when the button was pressed triggering a strum resulting in a lot less data.

5.7 Future Work

It would be interesting to increase the expressiveness of the Actuated Guitar and work on how to map simple input to more complex and expressive gestures in a future study as the simplicity already works well. To continue this research it would also be interesting to see how much of the right hand expressiveness could be transferred to other body parts. This could be by, for example, implementing the ability to play individual strings, string skipping/muting, and/or varying the velocity of strum/pick. Implementing these possibilities would increase the expressiveness of the guitar but would require a way of capturing different kinds of user input to be able to map it correctly to produce the more expressive output. This is a more challenging task.

Looking into the cognitive and psychological aspects of rehabilitation using aIMEs would be highly interesting.

Future studies employing backing tracks should log relevant data e.g.

through MIDI such as tempo and song being played in addition to the already logged push information. This would make it much easier and faster and more reliable to gather, analyse, and compare synchronisation errors. Similar to Kirk et al.'s follow-up, new studies should allow the participants to keep a copy of the guitar either permanently or at least for several months to investigate the participant's long-term motivation.

Harrison and McPherson did a feasibility study [57, 58] investigating the efficacy for future designs and the role of the fretting and plucking hand for playing a bass guitar with one hand. The prototype consisted of a foot-operated MIDI controller with a solenoid-actuated fretting mechanism mounted to the neck of an unmodified bass guitar, somewhat similar to the idea of the Robotar [11]. The foot-operated MIDI controller had two rows of eight pressure sensitive pads where the three first pads on each row were mapped to the actuators fretting the second, third, and fourth fret of the D-string (top row) and the A-String (bottom row). Using a similar foot-operated MIDI controller would be highly interesting as it could be used to expand right hand expression such as velocity from pressure sensitive pads or different strumming patterns where the user then taps the tempo, etc. The implementation of MIDI could help gather important data from both backing tracks and foot-controller, which could make data acquisition a lot faster and more precise. More complex input would require, however, a complete redesign of the current strumming mechanism of the Actuated Guitar.

The actuated fretting mechanism, Mechanical noise, was an issue in Harrison and McPherson's study when playing non-amplified. The fretting mechanism produced hammer-on notes as loud as the plucked notes, which made it difficult to use without an amplifier. This required precise coordination of the fretting mechanism with 50ms latency and plucking of the desired string, which could be a problem with the intended target group. This is important to keep in mind when designing a new string strumming/plucking mechanism for the Actuated Guitar.

The one-handed bass guitar was tested on six non-handicapped bass players playing a rehearsed bass guitar accompaniment for insights on the design of future accessible string instruments. They looked for unexpected facets of bass guitar playing through observations and questionnaires, such as solely muting with the fretting hand, using excessive hammer-ons, tapping etc. Kirk et al.'s study and results followed the same pattern as that found in the literature review in Section 2.6. Their design was not tested on the actual target group of physically disabled, had a heavy focus on the interaction only, used single session tests, and did not consider long term motivation. They found that muting of the strings, which normally are split between both hands, was moved to the plucking hand, which is no surprise. This was the opposite for the Actuated Guitar. All strings were strummed at the same time and all muting was done and had to be done with the fretting hand. Half of the participants in Harrison and McPherson's study used both feet to actuate the eight possible notes using the MIDI controller. This would pose a problem for people with, for example, hemiplagia. Using healthy subjects for a study investigating interactions yields potentially unusable or flawed data about the actual interaction with the MIDI device as the target group might not be able to interact in the same manner. Instructing the participants to use only one foot would have given a better insight into potential problems with the design and interaction as it would mimic the condition of many people with disabilities. This was done during the studies with the actuated guitar and the design itself did not allow for more than a single foot at a time.

A simple solution to decrease the overall latency from activation of the button to a strum would be to use a faster micro controller such as a Teensy 3.5 Board running at 120 MHz instead of the Arduino's 16 MHz. The current implementation has an average system latency of 29ms from activation of the button to when the pick starts moving. By halving that the overall latency would improve by 20%. To evaluate whether the latency should be reduced further than the 29ms it takes for a full strum, future studies could look into how fast the average guitarist strums and where their perception of beat is when strumming a guitar at different tempos.

Chapter 6

Conclusion

Here I revisit the hypothesis and research questions stated in the introduction to the thesis. To recap, the hypothesis and research questions are stated below.

Hypothesis:

Enabling or re-enabling people with disabilities to play an existing musical instrument can serve as a long-term motivator for self-rehabilitation through musical activity and improve their quality of life.

Research Questions:

- *How can an electrical guitar be modified to make it usable for people with hemiplegia?*
- *How does the potential reduction in musical expression through latencies or delayed auditory feedback affect the ability to produce rhythmical music and influence the level of motivation and long term use of the guitar?*

The first research question, *How can an electrical guitar be modified to make it usable for people with hemiplegia?*, was answered in the publications P1, P2 and P7. P1 suggests a potential solution for how an electrical guitar can be modified; it is called the Actuated Guitar. This is a modified, off-the-shelf electrical guitar that allows people with hemiplegia to play one-handed. The device supports both right and left handed players as well as different control sites with potential use of various sensors. Further details about the reasoning for the different design decisions can be read in P1. P2 is a usability study investigating whether the guitar, with a foot pedal as input device, was usable by the target group. Five hemiplegic children between the ages of 11 and 13, from the Helena Elsass Center, were all able to use the Actuated Guitar as intended. The guitar was tuned in a so-called open tuning, making it easier to play cords as the children did not have any experience playing the guitar. P7 is a longitudinal study of a single participant living and rehabilitating at home. The study shows that a hemiplegic with prior musical training on guitar could play the instrument, in contrast to those who had no musical training, as described in P2. The longitudinal study showed that the participant was able to use the guitar as intended since he could press the foot pedal to execute strums at will and fret chords as with a normal electric guitar.

The second research question *How does the potential reduction in musical expression through latencies or delayed auditory feedback affect the ability to produce rhythmical music and influence the level of motivation and long term use of the guitar?*, was answered in publications P6 and P7. The Actuated Guitar has an overall strumming latency or delayed auditory feedback of 45ms, from actuation (button press) to reaching the first string and producing sound. This latency of around 50ms is comparable to findings in similar research including actuators but must be considered high as research shows that some musicians can detect latency as low a 7 - 10 ms. My research shows that it is possible to play the Actuated Guitar as people are able to learn and compensate for the latency. Musically trained people are better at compensating for latency and are even able to factor in much higher latency if it is a subdivision of a tempo. Studies show that there is a breaking point of between 40 - 55ms when musically trained people start having problems compensating for the latency. With small modifications it should be possible to get the Actuated Guitar's latency down below 20ms in order to help non musically trained people play the instrument, as there is no difference in synchronisation errors between 0ms latency and 20ms latency. The current implementation of the Actuated Guitar is limited to a one dimensional input of a button press, resulting in a full strum of all strings at the same velocity. This is a clear limitation on the musical expressiveness of a normal functioning right hand. Implementing a MIDI controller with pressure sensitive pads would extend the guitar with another dimension that could be mapped to the velocity of the strum, increasing expressiveness. However, including string skipping, muting and single string actuation would require a complete redesign and would be much more complex. The same is true for the input part of the guitar: how to capture and map the interaction. Despite the limited expression of the Actuated Guitar, my longitudinal case study showed that playing the instrument yields a high amount of motivation even in the long term, which is crucial in the scope of self rehabilitation.

It was extremely difficult to find literature within my research field of assistive musical instruments (aIME). Either the field is highly fragmented in both outlet and language or not much research has been conducted within the field. Most of the existing literature I found have unfortunate tendencies in their studies. The definition of target groups is extremely broadly defined, using single terms such as *disabled* or *cerebral palsy* but not describing the intended user's actual physical or cognitive disabilities. Loosely defined goals such as *to find new or alternative interactions or potential uses*, often use monophonic digital musical interfaces (DMI) locked into certain scales (the 5 note pentatonic scale). Despite the definition of a target group with disabilities many studies make use of normal functioning people or single session and/or single user studies. None of the instruments went through any longitudinal tests that could demonstrate whether the aIME had potential in a real life scenario. A longitudinal study would have answered some key points like whether the instrument could withstand prolonged use, whether it was motivating to use, or whether it was abandoned.

In answer to the question regarding fragmentation and absence of a common language within the field, I propose a modelling approach to summarise interactions with musical interfaces. The model builds on and extends the ideas of Buxton's original three state model and Hinckley's extension. The model uses text, symbols, and colours to convey the complex nature of an instrument. The current state of the model still lacks the possibilities to visualise the expressiveness and dynamic properties of an instrument. The model is not an 'end all be all' model but a wish that the community would come together to find a common language creating a less fragmented field.

To sum up I will try to answer the hypothesis *Enabling or re-enabling people with disabilities to play an existing musical instrument can serve as a long-term motivator for self-rehabilitation through musical activity and improve their quality of life* from the research questions and the knowledge gathered through my research. Because of the small sample included in my research I cannot conclude that the hypothesis is true, but neither can I reject it. Taking all the results from my research into account and all the people and therapists that have contacted me, even from Germany, to buy an actuated guitar or to be a part of future research, there is clearly something important and interesting here that could be a game changer for many people. In terms of improvements in quality of life I would need to do more studies because I cannot draw concrete conclusions from the limited sample. There are strong indicators, however, based on my research P2 and P7, that the Actuated Guitar can improve quality of life for people with disabilities as the impact music and playing music has on all people is at least as strong on them as it is on regular people.

I hope that my research will convince others to go down this path and look at how we can give access to the world of musical instruments and enrich the lives of people with disabilities.

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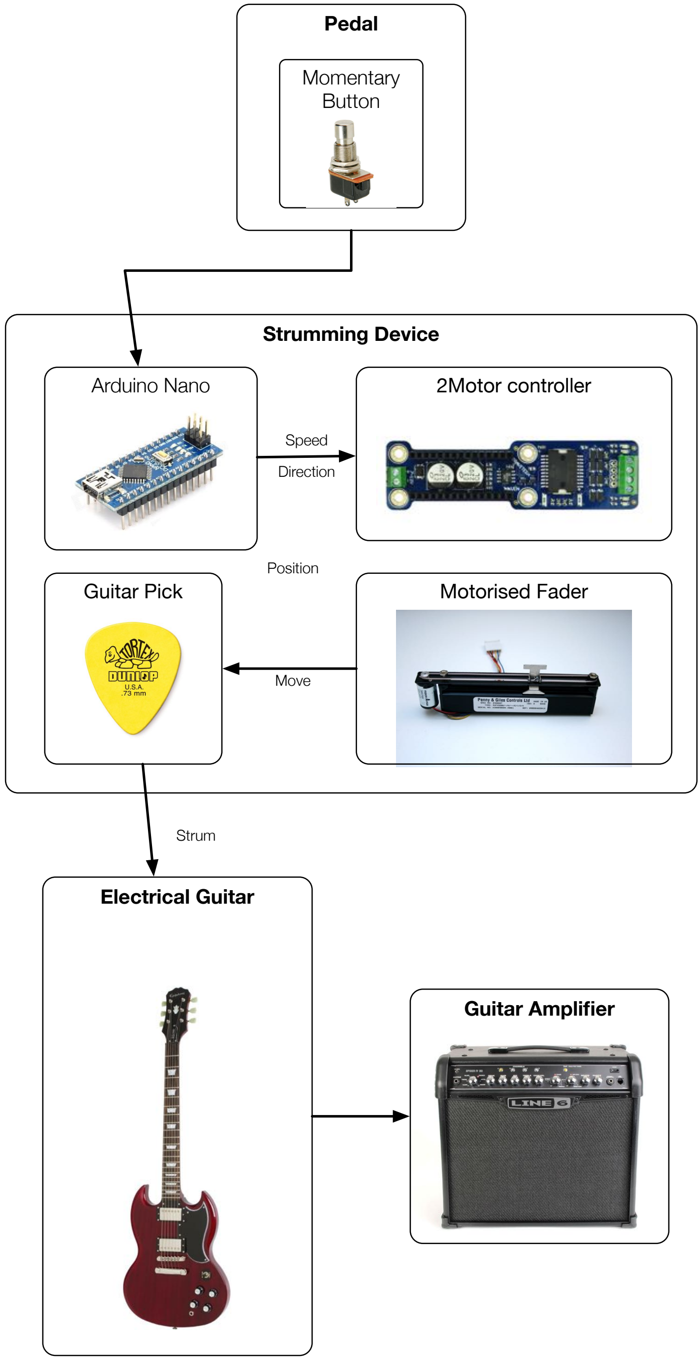
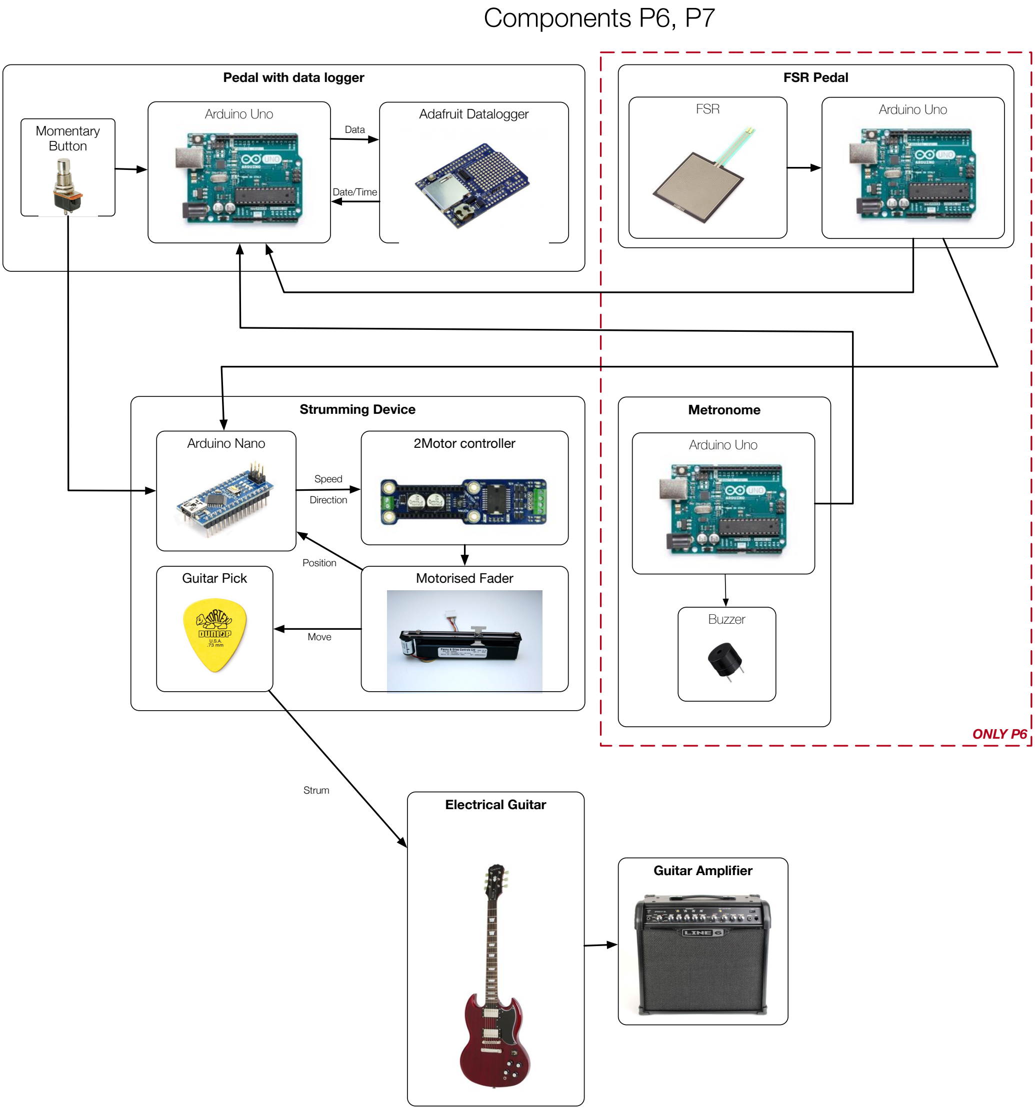
Appendix A

Schematics of Components

Components P1, P2




Components P6, P7
Pedal with data logger
Momentary Button
Arduino Uno
Data
Date/Time
Adafruit Datalogger
FSR Pedal
FSR
Arduino Uno
Strumming Device
Arduino Nano
Speed
Direction
2Motor controller
Position
Guitar Pick
Move
Motorised Fader
Metronome
Arduino Uno
Buzzer
ONLY P6
Strum
Electrical Guitar
Guitar Amplifier

Appendix B

Code for Data Logger

```
//#include <TimerOne.h>
#include <SPI.h>
#include <SD.h>

// Date and time functions using a DS1307 RTC connected via I2C and Wire lib
#include <Wire.h>
#include "RTClib.h"

RTC_DS1307 rtc;

File dataFile;

const byte chipSelect = 10;
unsigned long millisSinceBoot;

int arrayCounter;

//LOGGIN VARIABLES
int force = 0;
int pressureBtnForce = 0;
int buttonState = 0;
int pressureBtnState = 0;
//int beatState = 0;
//int tempoState = 0;
int delayState = 0;
int metronomeBeatAndTempo;

byte buffer0[512];

void setup()
{
  //DO NOT USE DIGITAL PORT 1!!!

  // Open serial communications and wait for port to open:
  Serial.begin(57600);

//METRONOME INPUTS
  pinMode(5, INPUT); //TEMPO
  pinMode(4, INPUT); // BEAT

 //MOMENTRAY BUTTON
  pinMode(2, INPUT_PULLUP); //FOR MOMENTARY BUTTON

//DELAY GUITAR
 pinMode(3, INPUT_PULLUP); //DELAY

  //POWER FOR RED DIODE
  pinMode(6, OUTPUT);
  digitalWrite(6, LOW);

```

```
//PRESSURE BUTTON
 pinMode(7, INPUT); //FOR PRESSURE BUTTON

  //INTERNAL PRESSURE SENSOR
pinMode(8, OUTPUT); //5V
pinMode(9, OUTPUT); //GND
  digitalWrite(8, HIGH); //5V
  digitalWrite(9, LOW); //GND

  Serial.print("Initializing SD card...");

  // see if the card is present and can be initialized:
  if (!SD.begin(chipSelect)) {
    Serial.println("Card failed, or not present");
    // don't do anything more:
    return;
  }
  Serial.println("card initialized.");

  if (! rtc.begin()) {
    Serial.println("Couldn't find RTC");
    while (1);
  }

 if (! rtc.isrunning()) {
    Serial.println("RTC is NOT running!");
    // following line sets the RTC to the date & time this sketch was compiled
    //rtc.adjust(DateTime(F(__DATE__), F(__TIME__)));
    // This line sets the RTC with an explicit date & time, for example to set
    // January 21, 2014 at 3am you would call:
    // rtc.adjust(DateTime(2014, 1, 21, 3, 0, 0));
 }

  dataFile = SD.open("datalog.txt", O_CREAT | O_APPEND | O_WRITE);

}

void loop()
{

  //START MILLIS FOR COUNTING MILLIS SINCE BOOT
  millisSinceBoot = millis();

  //Fetch the current date and time
 DateTime now = rtc.now();

  //GET THE DATA

  //MOMENTARY BUTTON
  buttonState = digitalRead(2); //1 BYTE
  force = analogRead(1); // 2 BYTE
```

```

  //PRESSURE BUTTON
  pressureBtnState = digitalRead(7); //1 BYTE
  pressureBtnForce = analogRead(0); // 2 BYTE

  //METRONOME
  metronomeBeatAndTempo = digitalRead(4) + 2* digitalRead(5); //1 BYTE
  //beatState = digitalRead(4); //1 BYTE
  //tempoState = digitalRead(19); //1 BYTE

  //GUITAR
 delayState = digitalRead(3); // 1 byte


  //ORDER OF DATA
  // (YEAR, MONTH, DAY, HOURS, MINUTES, SECONDS, MILLISBOOT, FORCE, DISTANCE)

  //MILLISECONDS
  //Unsigned Long (4 bytes)
  buffer0[7  + arrayCounter]= millisSinceBoot;
  buffer0[8  + arrayCounter]= millisSinceBoot  >> 8;
  buffer0[9  + arrayCounter]= millisSinceBoot  >> 16;
  buffer0[10  + arrayCounter]= millisSinceBoot >> 24;

  //Force
  //2 bytes (int)
  buffer0[11 + arrayCounter]= force;
  buffer0[12 + arrayCounter]= force >> 8;

  //Pressure Button Pressure
  // 2 bytes
  buffer0[13 + arrayCounter]= pressureBtnForce;
  buffer0[14 + arrayCounter]= pressureBtnForce >> 8;

  //Button
  // 1 byte
  buffer0[15 + arrayCounter]= buttonState;

  arrayCounter +=16;
//Serial.println(arrayCounter);

 if (arrayCounter == 496)
 {

  // if the file is available, write to it:
  if (dataFile) {

  digitalWrite(6, HIGH);

    dataFile.write(buffer0, 512);

```

```
    dataFile.flush();

  }
  // if the file isn't open, pop up an error:
  else {
    Serial.println("error opening datalog.txt");
    delay(500);
    digitalWrite(6, LOW);
    delay(500);
    digitalWrite(6, HIGH);

  }
  arrayCounter = 0;
 }
 //delay(200);
}
```

Appendix C

Code for Guitar Strum

Appendix C. Code for Guitar Strum


```

int dirPin = 4;  // Direction control of Motor A
int PWMpin = 5;  // PWM speed control of Motor A

int potPin = 3;  // for Nano v2.3 and 3.0, this is pin 3
int buttonPin = 3;

int delayStatePin = 2;

int pushed = 0;

bool clickButton = false;

bool delayState;

int delayTime = 177;

unsigned long timeStamp = 0;
unsigned long msEqual;
unsigned long compare = 0;

unsigned long ms;

int potValue;
int buttonVal;
int lastButtonVal;

void setup()
{
//Serial.begin(9600);

// On the Arduino nano, the following code sets the PWM frequency to 31250Hz on pins D5 and D6
// To remove unwanted audible noise from motor
TCCR0B = TCCR0B & 0b11111000 | 0x01;

pinMode (PWMpin, OUTPUT);
analogWrite(PWMpin, 0);
pinMode (dirPin, OUTPUT);
pinMode (potPin, INPUT);
pinMode (buttonPin, INPUT_PULLUP);
pinMode(2, INPUT_PULLUP);//DELAY STATE
pinMode(12, OUTPUT); //SENDING OUT DELAY STATE

}

void loop()
{
delayState = digitalRead(2);
analogWrite(PWMpin, 0);

```

```
if (delayState == HIGH)
{
  buttonVal = digitalRead(buttonPin);
  ms = millis()/64;



  if(buttonVal != lastButtonVal)
  {
    if(buttonVal == LOW)
    {
    timeStamp = millis()/64;
    pushed = 1;
    }
  }
lastButtonVal = buttonVal;
      compare = ms - timeStamp;

 if (compare >= delayTime && pushed == 1)
 {

  if(potValue < 100){
     clickButton = true;

   while(potValue < 175){
     digitalWrite(dirPin, HIGH);
     analogWrite(PWMpin, 255);
     potValue = (analogRead(3) >> 2);
 }
    digitalWrite(PWMpin, 0);
         pushed = 0;

  }
  else if (potValue > 170) {
    clickButton = true;

   while(potValue > 90){
     digitalWrite(dirPin, LOW);
     analogWrite(PWMpin, 255);
     potValue = (analogRead(3) >> 2);
    }
          pushed = 0;

  }
  else if (buttonVal == HIGH) {
    clickButton = false;
    analogWrite(PWMpin, 0);

    pushed = 0;
  }

```

```
  else
  {
    analogWrite(PWMpin, 0);
    pushed = 0;
  }

  //timeStamp = 0;
 }

} else
{
  int potValue;
  int buttonVal;

  potValue = analogRead(potPin);
  potValue = potValue >> 2;

  buttonVal = digitalRead(buttonPin);

  if(buttonVal == LOW && potValue < 100 && clickButton == false){
     clickButton = true;

   while(potValue < 175){
     digitalWrite(dirPin, HIGH);
     analogWrite(PWMpin, 255);
     potValue = (analogRead(3) >> 2);
 }
    digitalWrite(PWMpin, 0);
  }
  else if (buttonVal == LOW && potValue > 170 && clickButton == false) {
    clickButton = true;

   while(potValue > 90){
     digitalWrite(dirPin, LOW);
     analogWrite(PWMpin, 255);
     potValue = (analogRead(3) >> 2);
      }
  }
  else if (buttonVal == HIGH) {
    clickButton = false;
    analogWrite(PWMpin, 0);
  }
  else
  {
    analogWrite(PWMpin, 0);
  }
}
}
```

Appendix D

Code for Metronome

Appendix D. Code for Metronome


```

int tempo = 60;
int tempoDivisor;
int beat;
bool tempoState;

void setup() {
  // put your setup code here, to run once:

 // Serial.begin(9600);
    pinMode(13, OUTPUT);
    pinMode(2, OUTPUT);
    pinMode(3, INPUT);
    digitalWrite(5, INPUT_PULLUP);
    pinMode(10, OUTPUT);
}

void loop() {
  // put your main code here, to run repeatedly:
tempoDivisor = tempo/60;

tempoState = digitalRead(5);

if(tempoState == LOW)
{
  tempo = 60;
  digitalWrite(10, LOW);
}
else if(tempoState == HIGH)
{
  tempo = 120;
  digitalWrite(10, HIGH);
}

if (tempoState == HIGH)
{
//TEMPO 120
//tone(pin, frequency, duration)
  //#1 & #3
  digitalWrite(13, HIGH);
  digitalWrite(2, HIGH);

  tone(8, 2100, 75);
  delay(1000/tempoDivisor);
  digitalWrite(13, LOW);
  digitalWrite(2, LOW);

  tone(8, 1700, 75);
  delay(1000/tempoDivisor);

```

```
}

if (tempoState == LOW)
{
//TEMPO 60
//tone(pin, frequency, duration)
  //#1 & #3
  digitalWrite(13, HIGH);
  digitalWrite(2, HIGH);

  tone(8, 2100, 75);
  delay(500/tempoDivisor);
  digitalWrite(13, LOW);
  digitalWrite(2, LOW);


  tone(8, 1700, 75);
  delay(500/tempoDivisor);

   tone(8, 1700, 75);
  delay(500/tempoDivisor);

   tone(8, 1700, 75);
  delay(500/tempoDivisor);

}

}
```

Part II

Papers

Publications

THE ACTUATED GUITAR: A PLATFORM ENABLING ALTERNATIVE INTERACTION METHODS

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ABSTRACT

Playing a guitar is normally only for people with fully functional hands. In this work we investigate alternative interaction concepts to enable or re-enable people with non-functional right hands or arms to play a guitar via actuated strumming. The functionality and complexity of right hand interaction with the guitar is immense. We therefore divided the right hand techniques into three main areas: Strumming, string picking / skipping, and string muting. This paper explores the first stage, strumming. We have developed an exploratory platform called the Actuated Guitar that utilizes a normal electrical guitar, sensors to capture the rhythmic motion of alternative fully functioning limbs, such as a foot, knee or the head, and a motorized fader moving a pick back and forth across the strings. A microcontroller is utilized for processing sensor data, which allows flexible mapping of user input to the actuation of the motorized fader. Our approach employs the flexibility of a programmable digital system, allowing us to scale and map different ranges of data from various sensors to the motion of the actuator – thereby making it easier adapt to individual users.

Author Keywords: Interactive performance systems; Interfaces for sound and music; Music and robotics; Social interaction in sound and music computing; Actuated instruments; Actuated guitar; Musical instruments for the disabled.

1. INTRODUCTION

Playing a musical instrument can be an interesting and worthwhile pursuit, but in many cases is impossible for someone with a disability. Those of us living without disabilities can just pick and choose an instrument of our liking. We may prefer the sound of a certain instrument, wish to follow in the footsteps of an idol, or learn to play specific songs from the radio. Some people succeed and actually learn to play an instrument, but many give up along the way when they realize what it takes in time and effort to learn to play an instrument well.

What about people with disabilities that wish to play musical instruments? In this work, we begin to address the question via the development of alternative interaction methods for playing the guitar. Disabilities can either be congenital, or caused by illness or accidents in any stage of life. If an arm or hand amputee, or anyone having a medical problem such as cerebral palsy wishes to play a traditional instrument, it is likely that they will be unable to reach the instrument's full potential (or possibly not be able to play an instrument at all). The obstacles while learning to play an instrument designed for those without disabilities can be too large to overcome.

We focus here on the use of technology to enable alternative methods of playing the guitar, specifically for those who have limited or no use of one hand or arm. The use of actuators, feedback systems, and flexible interaction design techniques present a novel design optimized for easy customization. Furthermore, playing music can be a good activity for "Forced Hand Use" training [1]. This method encourages those with cerebral palsy or stroke patients, for example, to use their affected arm, with the aim that they will begin using that arm more in daily life or regain control with the arm or hand.

2. RELATED WORK

Related work has included a wide range of approaches to either customizing existing instruments, or designing entirely new music interfaces. These have ranged from simple mechanical aids [2] (sold by companies such as A Day's Work, LLC[1]), to advanced bioelectric controllers allowing users to produce computer-generated music [3]. An example of a simple tap-pad interface developed for disabled users is the TouchTone [4]. However, we have chosen here to focus on string instruments – specifically the guitar – rather than percussion, wind, or other families of musical instruments.

Most traditional instruments require more than one limb to be used while playing. As there are millions of disabled who lack the use of one or more of their limbs in the world today, these people are excluded from many types of music making. While quite a number of efforts have been undertaken in the past to modify existing instruments for use by the disabled, there have not been many specifically targeting the guitar as an instrument for disabled users.

Our work involves creating a semi-robotic musical instrument. A historical view of robotic musical instru-

[1] http://www.adaysworkmusiceducation.com/

ments is included in [5]. Robotic instruments focused on the guitar include the League of Electronic Musical Urban Robots (LEMUR's) GuitarBot [6], among others. While the GuitarBot is much more capable of completely automating the motions needed to play a guitar than our current work, it discards any affordances of direct human playing skills, due to a design that places each string on a separate 'neck'. We purposefully aim our development at more traditional guitar bodies, thus enabling users to develops skills that are as close to the normal techniques as possible. It follows in some of the author's related work with actuated instruments [8].

3. INTERACTION METHODS

Playing a guitar traditionally requires the use of both hands. The right hand does the strumming and or picking of the strings, and fingers of the left hand are used for fretting the strings. As stated in the introduction, the scope for this research is to enable or re-enable people who are not able (or lost the ability), to play the guitar. Our first approach focuses on the right hand, and how it interacts with the guitar. The common interactions of the right hand have been identified and divided into three stages:

Stage 1: Strumming
Stage 2: String picking and string skipping
Stage 3: String muting

The research is thus divided into the three stages, based on the dexterous complexity of each type of interaction. This paper elucidates only the first stage, strumming. Strumming is the most basic right hand interaction technique, making it a good place to start, as well as a prerequisite for the following stages to build upon (see **Figure 1**). Next we describe and discuss our approaches to strumming a guitar when the user does not have full control of the right hand.

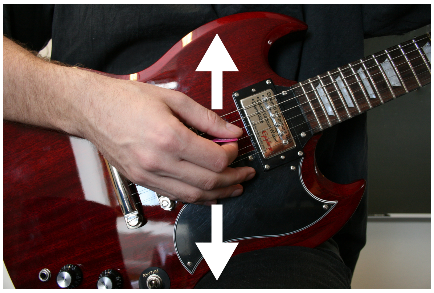


Figure 1. Strumming a guitar is the most basic right interaction possible with a guitar. Strumming is a near-perpendicular rhythmic motion across the strings.

3.1 Candidates for Rhythmic Movement

As the left hand is occupied fretting the strings, possible candidates for control of our motorized strumming actuator include various portions of the legs, the head, or possibly the remaining part an amputated arm, see **Figure 2**. Without mechanical aids, these parts of the body do not offer any realistic means of physically strumming across the strings in a normal playing position. However, the remaining part of an arm, the head or part of a leg (even a foot or toe) do offer the possibility to move in a rhythmic pattern.

Moving the arm or legs in a continuous rhythmic pattern are likely the best options, as humans are accustomed to naturally moving these body parts in rhythmic patters for long periods of time (for example when walking or running). For people with no control of their legs nor right arm, the head can also be used to move in a rhythmic pattern, albeit the muscles in the neck are not normally used for repeated rhythmic movements (and may quickly fatigue). Nevertheless, over shorter periods of time this would still give such individuals the ability to strum the actuated guitar.

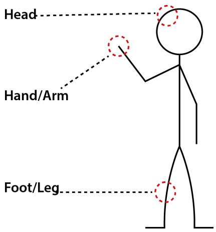


Figure 2. The different body parts that can be used instead of a paralyzed limb to interact with the instrument.

3.2 Gesture Capture and Motion Tracking

Because the rhythmic movement of these alternative parts of the body are not able to physically strum the strings in a normal fashion, our system needs to capture the motions and translate them into control signals for the actuator on the guitar. This can be done through the use of various sensors. The sensors can be mounted several different places on the body in order to optimize the experience for each individual.

Our initial experiments have made use of a simple accelerometer sensor that might be ideal for a person with an amputated right hand. It is fitted with a velcro armband and strapped onto various parts of the body. Many other types of sensors can also work as input for the actuated guitar, such as gyroscope sensors, which capture rotational movements. An individual that can only rotate their head, for example, could use this type of sensor, with the rotational input translated to the actuator's linear output – robotic strumming of the strings via a motorized fader.

The authors have considered many other options as well, such as a full Inertial Measurement Unit (IMU) that combines data from an accelerometer, gyroscope and magnetometer to provide a more precise estimation of orientation and motion, or even commercial options such as the

Leap Motion device[2], which could be mounted in various locations to capture player inputs. In the next phase of this research we plan to incorporate a single-chip IMU, the MPU-9150 released by Invense, Inc. It is a 9-axis motion tracking solution with built-in sensor fusion algorithms combining data from a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer.

3.3 Mapping Sensor Input to Actuation

When customizing the actuated guitar for people with various disabilities, our digital approach attempts to make it easy to perform the necessary mapping of data from various input sensors (simple filtering, scaling and offset operations) to control of the strumming actuator. This is especially true when compared to the wide variety of mechanical approaches that would be needed for different scenarios and users. At the moment, these changes are managed in the firmware of the microcontroller that our system uses, but these parameters could also be changed graphically via a visual programming environment such as MaxMSP[3] or PureData[4]. This approach, based on the FireFader system [8] would likely be preferable for individuals who wish to modify the system themselves.

One example would be a user with a partly paralyzed leg, but who can still stomp their foot. Mounting our sensor on the foot will translate that motion into input for a microcontroller, which can then map the input to fit the actuator's full range of motion. This gives us the possibility of amplifying small motions to move the output actuators an entire strum-length, translate rotation motions into linear motions (if using a gyroscope sensor), etc. Doing this by purely mechanical means will be a highly complex construction and difficult to quickly modify to fit different users with different needs.

4. LIMITATIONS

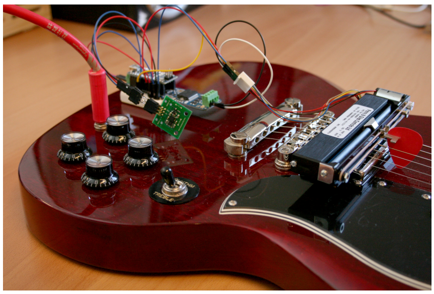
The fine motor control exhibited by a normal human arm, hand and fingers will be difficult if not impossible to replicate via low-cost robotic actuation. A human hand can move in almost a hemispherical fashion at the end of the wrist. Fingers can stretch, bend and move sideways. In addition to the physical movements, we also receive sensory feedback from our hands and fingers. Although we are in the initial stages of this research (focused only on strumming to date), it is already clear that custom actuators would need to be designed, if attempting to truly approach this kind of control and feedback. Therefore, we have so far only researched the types of movements that are the most crucial to maintain, in order to design a substitution for the hand strumming a guitar.

It is worth noting that we are working with an electrical guitar for this prototype, and that the actuator we are using (a small motorized fader) can cause electrical noise to bleed from the motor's electromagnetic field into the guitar's pickups. This occurs due to the proximity of the electrical guitar pickup, be it single coil or humbucker design, near the plucking location on the strings (a position required to best capture the sound). This electromagnetic noise problem can be substantially circumvented by running the pulse-width modulation (PWM) signal that controls the motorized fader at a frequency higher than normal human hearing (more than 20kHz). While an acoustic guitar would not have this problem, the more fragile body makes it somewhat difficult to mount actuators on the guitar's body without damaging or compromising its ability to produce a good acoustic sound.

5. EXPLORATORY PLATFORM

To help us explore the possibilities offered by this research, a proof-of-concept guitar was created as described below (see **Figur 3**). The device consists of an Epiphone SG Standard electrical guitar, Arduino Nano V.3 board with an ATmega328 microcontroller, a "2motor" controller board from Gravitech with an L298 dual H-Bridge driver, an Analog Devices ADXL322 accelerometer, and a Penny+Giles PGFM3200 motorized fader.

The Arduino Nano sits on top of the 2motor board, both of which are plugged into a breadboard that is adhered to the guitar's body. The accelerometer is connected to the microcontroller's analog input ports for processing. A USB cable powers the Arduino, motor board and the motorized slider, and allows for quick data access and easy upload of software to the Arduino during our development process. The system can also be battery powered.



Figur 3. Implementation of the proof-of-concept guitar, which consists of an accelerometer, guitar, microcontroller, motor controller, motorized fader, and a pick.

The data flow throughout the system is shown in **Figure 4**. A user interacts with the accelerometer, which sends a signal to the Arduino. The ADXL322 is capable of sensing two independent axes, but as seen on **Figure 1** the type of movement we are most interested in when approximating traditional playing technique is just a single axis of motion. We therefore omit one axis entirely. The axis in use is averaged over 30 samples, as the sensor produces somewhat noisy data, and we are primarily interested in lower frequency information. The microcon-

[2] Leap Motion, http://www.leapmotion.com/
[3] MaxMSP, http://cycling74.com/
[4] PureData, http://puredata.info/

troller also reads the current position from the fader's potentiometer.

The feedback from the fader position in combination with the target value from the low-pass filtered accelerometer data determines what control data to send to the motor controller, for example in which direction and how fast to move. To avoid jitter while the fader is idle, the micro-controller only commands it to move when a sufficient G-force threshold is applied to the accelerometer in a given direction. The motor controller then turns on the motor in the given direction, and the fader strums the guitar. This is similar to the 'Real-Time Feed-Forward Control paradigm' outlined in [9].

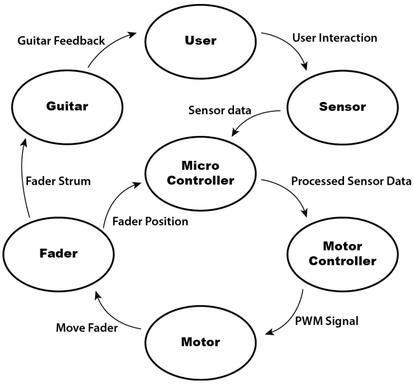


Figure 4. The data flow throughout the system. The user interacts with the sensor, which allows them to 'remote control' the position of the actuator – via internal feedback in the microcontroller that steers the system's output – thereby producing sound perceived by the user, completing the outer (interaction) feedback loop.

6. FUTURE WORK

There are many avenues of future work that would be interesting to pursue. For example, the initial studies shows that using a single accelerometer brings limitations. The constant pull of gravity of 1G is impossible to remove from such a sensor's output, making it difficult to get the same reading when strumming up and down (lateral motions are therefore preferable). The IMU mentioned in section 3.2 will help to resolve this issue, by allowing us to remove gravity effects through a calculation of the residual accelerations after subtracting the gravity vector. It should also enable us to explore much more detailed interaction due to the greater number of sensor types.

Trying completely different types of sensors, as mentioned in section 3.2, is also something we plan to pursue. Standard 'sip and puff' or simple force-sensitive resistor types of sensors would facilitate entirely different types of input, and could be interesting helps for more severely disabled people to strum the guitar.

7. CONCLUSIONS

We have shown that it is possible to enable or re-enable people to strum a guitar using an accelerometer as input controlling an actuated guitar using different body parts. Drawing on a range of inspiration we have shown that disabilities does not need to stop people to explore and experience normal instruments made for people without disabilities.

Acknowledgments
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The Actuated Guitar: Implementation and User Test on Children with Hemiplegia

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ABSTRACT
People with a physical handicap are often not able to engage and embrace the world of music on the same terms as normal functioning people. Traditional musical instruments have been refined over the last centuries, developing highly specialized and powerful interfaces; but nearly all require two functioning hands. In this study we try to enable people with Hemiplegia to play a real electrical guitar, by modifying it in a way that allows people with Hemiplegia able to actually use the instrument. We developed a guitar platform utilizing sensors to capture the rhythmic motion of alternate fully functioning limbs, such as a foot, knee or the head to activate a motorized fader moving a pick back and forth across the strings. This approach employs the flexibility of a programmable digital system which allows us to scale and map different ranges of data from various sensors to the motion of the actuator, thereby making it easier to adapt to individual users. To validate and test the instrument platform we collaborated with the Helena Elsass Center in Copenhagen, Denmark during their 2013 Summer Camp, to see if we actually succeeded in creating an electrical guitar that children with Hemiplegia could play. The initial user studies showed that children with Hemiplegia were able to play the actuated guitar by producing rhythmical movement across the strings, enabling them to enter a world of music they so often see as closed.

Keywords
Interactive performance systems; Interfaces for sound and music; Music and robotics; Social interaction in sound and music computing; Actuated instruments; Actuated guitar; Musical instruments for the disabled.

1. INTRODUCTION
Music is a big part of human culture. Music is consumed, performed and enjoyed by nearly everyone in every layer of society. But the feat of performing music is more of a challenge to some than others. Those of us living without disabilities can just pick and choose an instrument of our liking and start learning. Some people succeed and actually learn to play an instrument, but many give up along the way when they realize what it takes in time and effort to actually learn to play a musical instrument well. People with disabilities might not be able to use an arm or a leg, and thereby are unable to use the instrument.

In this work, we continue the development of the Actuated Guitar [1] that began to address these issues via development of a solution for people with one side of their body paralyzed – for example, those with Cerebral Palsy Hemiplegia or stroke victims – to start learning to play the guitar or regain the ability to play. While it is still likely that they will be unable to reach the instrument's full potential, just enabling them to actually play a guitar that otherwise would be out of reach is viewed as a huge accomplishment.

The focus of this research is to use technology in combination with existing instruments to enable alternative methods of playing the guitar for people with cerebra Palsy Hemiplegia. By using small linear actuators, feedback systems, and flexible / adaptive interaction design techniques, we present a novel design optimized for easy customization.

In terms of therapy, playing music can be a good activity for "Forced Hand Use" training [2]. This method encourages those with Cerebral Palsy or stroke patients, for example, to use their affected arm, with the aim that they will begin using that arm more in daily life or regain control with the arm or hand.

1.1 Related Work
A wide range of approaches to either customizing existing instruments, or designing entirely new music interfaces exists. These range from simple mechanical aids [3] to advanced bioelectric controllers allowing users to produce computer-generated music [4]. Many of the customized instruments focus on percussion-like input modalities, such as simple tap-pad interfaces developed for disabled users. One such example is the TouchTone [5]. However, our research focuses on stringed instruments, in this case the electric guitar, not percussion, wind, or other families of musical instruments.

The work described here involves creating a semi-robotic musical instrument. A historical view of robotic musical instruments is included in [6]. Robotic instruments focused on the guitar include the League of Electronic Musical Urban Robots (LEMUR's) GuitarBot [7], among others. While the GuitarBot is much more capable of completely automating the motions needed to play a guitar than our current work, it discards any affordances of direct human playing skills, due to a design that places each string on a separate 'neck'. We purposefully aim our development at traditional guitar bodies, thus enabling users to develops skills that are as close to the normal techniques as possible. This also follows in some of the author's related past work with actuated instruments [8].

2. METHODS
Playing a guitar traditionally requires the use of both hands. The right hand does the strumming and the fingers of the left hand are used for fretting the strings. As stated in the introduction, the scope for this research is to enable or re-enable people who are not able (or lost the ability), to play the

guitar. This approach focuses on the right hand's strumming motion, and how it interacts with the guitar. The are some common and complex interactions of the right hand that have been divided into three stages:

Stage 1: Simple strumming up and down movement
Stage 2: Individual string picking and string skipping
Stage 3: String muting both multiple and individual strings

The research approach has been divided into the above stages, based on their complexity where *stage 1* is the simplest form of interaction and *stage 3* the most difficult. We have focused on the strumming as the best candidate for a proof of concept to investigate the possibilities, before including the other types of right hand interaction. Next we describe and discuss our approaches to strumming a guitar when the user does not have full control of the right hand.

2.1 Suited Body parts for Rhythmic Movement

As one hand, right or left depending on the user, is occupied fretting the strings, possible limbs for control of our actuated strumming include the legs, feet, head or neck. These parts of the body do not offer any realistic means of physically strumming the strings in a normal playing position. One of the simpler main tasks of the strumming hand is moving in a continuous rhythmic pattern. While most limbs can offer a similar type of motion, the feet or legs are likely the best options, as humans are accustomed to naturally moving these body parts in rhythmic patters for long periods of time (e.g. when walking, running or dancing). For people with no control of their legs nor right arm, the head could also be used to move in a rhythmic pattern, but as the muscles in the neck are made for stabilizing the head and not for prolonged rhythmic movements, this is not optimal due to possible fatigue or injury. Nevertheless, over shorter periods of time this could still give such individuals the ability to strum the guitar.

2.2 Interpreting Rhythmic Motion

Because rhythmic movement of the suited parts of the body is not able to physically strum the strings in a conventional fashion, the system somehow needs to capture and interpret the motions. This can be done through the use of various sensors that can be mounted on the desired parts of the body, in order to capture the rhythmic moment made by the user. One example would be a user with a partially paralyzed leg, but who can still stomp their foot. Mounting a sensor on the foot will translate that motion into input for a microcontroller, which can then map this input to control the actuator's full range of motion. This gives us the possibility of amplifying small motions to move the output actuators an entire strum-length, translate rotation motions into linear motions (if using angular sensors such as a gyroscope), etc. Doing such by purely mechanical means would require highly complex constructions and be difficult to quickly modify to fit different users with different needs. Therefore electronic sensors and actuators prove very useful when combined with programmable microcontrollers in this eontext.

2.3 Implementation of Development Platform

One of the most important aspects when working with any form of interaction design is latency. This is even more important when you need to control the sound produced by your interactions. To determine which sensor was the best fit for realizing the construction and playability of the guitar, we ran a series of prototype development iterations with each sensor. The three initial candidates were an infrared distance sensor from Sharp (GP2D12), an accelerometer from Analog Devices (ADXL322) and a simple momentary push button, see Figure 1.

For prototyping, sensors can be fitted, with e.g. a velcro armband and strapped onto various parts of the body. Many other types of sensors can also work as input for the actuated guitar, such as Inertial Measurement Units (IMUs), which capture orientation changes, sensors to capture blinking, etc.. An individual that can only rotate their head, for example, could use an IMU, with the orientation data translated to the actuator's linear output. However, the chosen candidates were used because of availability and time constraints in this initial prototype implementation.

To interpret the sensor signals an Arduino Nano V.3 board with an ATmega328 microcontroller was used, because of its small form factor and simple usage. To drive the actuator, we used a '2motor' controller board from Gravitech, Inc., which has an L298 dual H-Bridge driver on-board. For the actuator, we chose a Penny+Giles PGFM3200 motorized fader due to it's specification with the strongest linear force we could find. The firmware used on the Arduino in order to drive the motorized fader was inspired by the FireFader project [3].

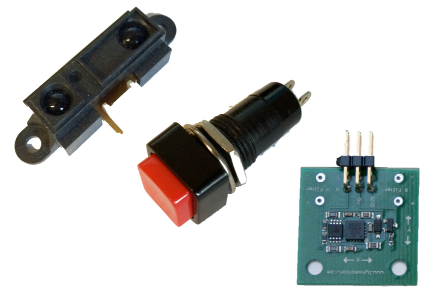

Figure 1: The three candidates for acquiring motion information from the user. To the left a Sharp GP2d12 IR Distance sensor, in the middle a momentary pushbutton and to the right the ADXL322 tilt sensor from Analog Devices.

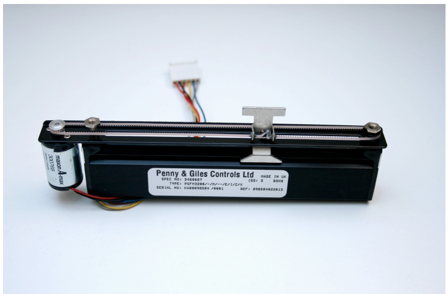

Figure 2: Motorized fader used as the actuator for driving the pick back and forth over the strings of the guitar.

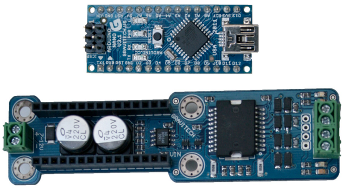

Figure 3: Top, the Arduino Nano V. 3. Bottom, the 2Motor controller.

2.3.1 Linear Mapping and sensor selection

The accelerometer (see Figure 1) was tested in a first iteration with a simple linear mapping between its tilted position and the fader's position. When the accelerometer pointed straight up, the actuator was at one of its extremes and when the accelerometer pointed straight down the actuator was at its other extreme. A problem became apparent right away, which is the inability of an accelerometer to separate accelerations due to dynamic motion from accelerations due to gravity (tilt angle). While an IMU would have solved this issue, we did not have easy access to one – so we moved on to the next prototype iteration, even though filtering of the raw sensor data was attempted. Filtering did solve the problem partially, but it also introduced a slight latency. This was still playable, but at the same time noticeable and annoying. As mentioned above, this is not optimal considering the context of its use in a musical application.

The first tests using the distance sensor (see Figure 1) showed that it had less initial problems when compared to the accelerometer, but still had some needed of filtering. A simple linear mapping was applied but the filtering again introduced a noticeable latency, so it turned out to be difficult to do a difficult to play with.

A solution instead of the linear approach to mapping, would be to set a threshold for actuation. This was tried with both of the above described sensors. It worked in such a way that when e.g., the accelerometer exceeded a certain g force it would trigger the motor to run the fader to the opposite extreme, thereby strumming the strings. The same was applied to the distance sensor. This worked a lot better in terms of playing, and seemed a lot more stable. However, these two sensors were still prone for accidental activation of the fader, which resulted in unwanted output. This threshold approach is really similar to a simple binary trigger, which led us to consider the next sensor type..

The last prototyping test used a simple push button. There are of course two types of buttons, latching and momentary. The latching type hold its state until changed again and momentary only changes state while being pressed. Momentary behavior is appropriate in this context, as there is simply no need for latching

The motorized fader itself is driven by a rubber band to pull the fader back and forth. However, the rubber band is able to stretch a bit, which results in a small overshoot of the fader's position on the linear potentiometer. This feedback is what tells the microcontroller its current position, so this needs to be taken in to consideration in the final implementation.

2.3.2 Final Development Platform

The final development platform ended up consisting of an Epiphone SG Standard electrical guitar, the Arduino Nano V.3 board, "2motor" controller board from Gravitech as described in section 2.3, a 3D printed foot pedal pushing a momentary button, see Figure 9 and a 3D printed mount used for mounting the Penny+Giles PGFM3200 motorized fader, see **Figure 5**.

Figure 4: The guitar used for this project is an Epiphone SG. [12]

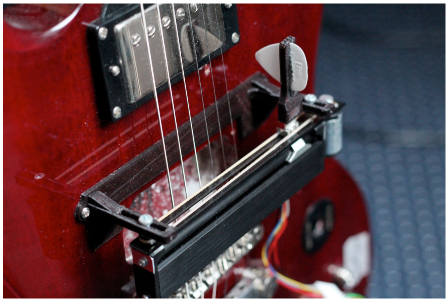

Figure 5: The finished system with the actuator mounted in the customized mount on top of the guitar body.

The Arduino Nano sits on top of the 2motor board, both of which are plugged into a simple breadboard that is adhered inside the guitar's body (part of the control cavity). The foot controller is connected to the microcontroller's input pin via connectors mounted in the existing holes (where the volume and tone knobs sat). An external power supply is plugged into the guitar body, again through one of the spare holes, which powers the Arduino, motor board and the motorized slider. The USB port on the Arduino is still accessible and allows for quick data access and easy upload of software to the Arduino during development. With a few simple modifications, the system could also be battery powered. The electronics are all protected by covering them with the original backplate on the guitar. This makes the system robust enough for testing purposes.

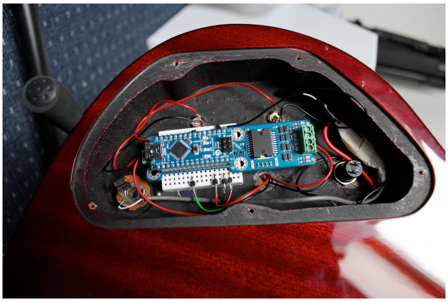

Figure 6: The Arduino and motorcontroller mounted on a breadboard inside the guitar's empty control cavity for protection (but still providing easy access to the electronics).

2.3.3 Dataflow

When a user presses the foot pedal's momentary button, the signal is sent to the Arduino. The microcontroller then reads the current position of the pick by checking the value of the fader's potentiometer. Depending on the position, it reverses the direction of the motor and drives the pick the opposite direction across the strings. The microcontroller continues reading the potentiometer's value as it moves, and stops the motor when it reaches the other end. Once there, it waits on further messages via interaction from the user. An illustration of the data flow throughout the system is shown in **Figure 7**.

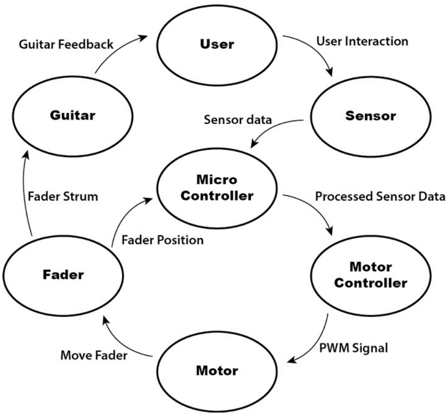

Figure 7: Simple dataflow throughout the system.

2.4 Test method

The user test was conducted at the Helena Elsass Center in Charlottenlund, Copenhagen, during the 2013 Summer Camp. This is an annual week-long camp for children with Cerebral Palsy. The goal of the summer camp is for the kids to challenge themselves through various activities, proving that they can be more physically capable than they might think. The test was not an actual part of the summer camp, but was conducted when the staff and children could find enough time in the busy schedule.

The test tried to investigate if children with Hemiplegia Cerebral Palsy were able to play the actuated guitar. It was expected that the children have no previous experience with playing traditional musical instruments; this was of course verified by asking them as well. The success criteria was two fold. The first success criteria was if they could sit with the guitar, position their hand and fingers of their non-paralyzed side on the guitar neck, fret a chord and press the foot switch producing some sound (it was not needed or expected to be pristine sounding). The second and more demanding criteria was if they were able to take it a step further and produce a continuous rhythmic motion, which might indicate an inherent musicality.

For testing these criteria, a qualitative method was used. It included observations using video and sound recordings for later in-depth observation and analyses. The observations were followed by semi-structured interviews that were used to investigate the children's familiarity and use of music. E.g., have they taken guitar or piano lessons, or if and how they listen to and use music, or if they have ever imagined/dreamed of themselves performing music and if so, what song they would like to perform.

The guitar was tuned in an open-G tuning for easier fretting of chords. This means that if you do not fret any strings and strum all strings you play a G-Major chord, and if you want to fret another Major chord you simply press all the strings on the same fret. Further simplify chording and fretboard navigation, the neck was color-coded with stickers beneath the strings to indicate certain chords. The color-coding was combined with a sheet of paper telling the children how to play "Sweet Home Alabama" by Lynyrd Skynyrd, which was chosen because of its simplicity. It only contains three Major Chords: D, C and G.

3. RESULTS

The children attending the Summer Camp were between 11 and 13 years old. They had different types of Cerebral Palsy, but mainly Hemiplegia. Because of the tight schedule and planning of the summer camp, there was only enough time for testing with five children, from ages 11-13, all with Hemiplegia, but in different sides of the body and severity stages. The semi-structured interview focused on three main areas: The children's knowledge about their own condition, their musical experience, and their own and their family's use of music in their every day life. All of the children except for one didn't know what type of paralysis they had but simply responded: "I just know I have Cerebral Palsy." This was a bit problematic, because then they were not able to answer on what level they were according to the Gross Motor Function Classification System – Expanded and Revised (GMFCS - E&R) that ranges from Level 1, best functioning to Level 5, worst functioning [11]. Based on observations during the Camp and the user tests, the children attending the Summer Camp and the test were either level 1 or 2.

None of the children had attended any prior instrument lessons, besides the mandatory music lesson at their schools. Four of the children had a desire to start learning to play an instrument, and when asked what type it ranged from guitar, piano, and drums to tambourine. None of the test participants came from homes where their parents or siblings played any instruments. Only one had a mother that had attended some piano lessons when she was younger. When asked if they listened to music, they all responded 'yes', and two said that they listened to music quite a lot. When asked how they used the music (to see if it was something that the whole family used), most answers were "just in my room, on my iPad, on youtube," etc. Only one said "on the radio and in the car".

The children were introduced to the actuated gjuitar with a brief explanation on how the instrument worked, and how they could operate the it. They got the sheet music showing the simplified view of how many times they should play a color to play Sweet home Alabama (1 x Green, 1 x Yellow, 2 x Blue) The instrument was placed so that their good side operated the guitar's neck for fretting the strings and pressing the pedal. One of the children insisted on doing the opposite and using his weakened side. He was also by far the least affected child in the test, and had nearly the same strength in both sides.

From notes during the test and review of the recordings, it became clear that all of the test participants are able to interact with the guitar. They could fret the guitar and press the foot pedal to produce sound. It was obvious that it would take time to gain speed along the fret board and foot, hand and eye coordination (to lower the time between fretting and striking the strings, etc.), but nothing more substantial than normal children have when they interact with a new and unfamiliar instrument. One child stood out in the test. He was actually the most severely paralyzed. He had never played a normal instrument before, but was able to play Sweet Home Alabama by following the color-coded chart. After the test he said his mind was blown. In his wildest fantasies, he had never imagined that he would be able to play guitar and even actually able to play a song. Compared to the others rhythmic tendencies, he seemed to have an inherent musicality or talent. This does not mean that the other children couldn't maintain consistent rhythms, but that they maybe needed a bit more convincing. Overall, the test has shown that these children are able to produce rhythmic motion, and would be able to start learning basic chords by going to regular guitar lessons like normal children.

Figure 8: A user with Hemiplegia Cerebral Palsy playing the guitar for the first time. It can be seen that the user is partially paralyzed in his right side.

4. DISCUSSION

There are many possible directions for future work that would be interesting to pursue, following this initial research. One example would be to experiment further with different types of sensors. It is likely worth pursuing Inertial Measurement Units (IMUs) that combines data from an accelerometer, gyroscope and magnetometer to provide a more precise estimation of orientation and motion. This would allow us to remove the coupling effects between gravity and dynamic motion experienced in the initial test with the accelerometer. Commercial sensor options such as e.g. the Leap Motion device, could also be interesting. This could be mounted in various locations, because if its small size, to capture player inputs.

The current implementation of the guitar foot pedal, using the momentary push button, does not facilitate coarse motor control exercises of paralysed limbs (unless it happens to be that leg). Using the pushbutton approach also limits the range of motion which might be unwanted in a rehabilitation perspective. In fact, therapeutic use may purposefully require larger motions for successful interaction. However, the system at this stage is very flexible and can easily be adjusted to accommodate many diiferent styles of interaction that might be more focused on training and rehabilitation of the paralysed or affected limb. This could e.g. be done with the alternative sensors as suggested in the interaction methods in section 2.3 or above.

When customizing the actuated guitar for people with various disabilities, our digital approach attempts to make it easy to perform the necessary mapping of data from various input sensors (simple filtering, scaling and offset operations) to give control of the strumming actuator. This is especially true when compared to the wide variety of mechanical approaches that would be needed for different scenarios and users. At the moment, these changes are managed in the firmware of the micro-controller that our system uses, but these parameters could also be changed graphically via a simple GUI presented via a small screen or a laptop running visual programming environments such as MaxMSP or PureData . This approach, which could easily be based on the FireFader system [9] would likely be preferable for individuals who wish to modify the system themselves.

Figure 9: The 3D printed foot pedal used to activate the actuator strumming the strings of the guitar. The print is fitted with a momentary button that is connected through wires to the Arduino inside the guitar.

4.1 Limitations

The fine motor control of a normal functioning human arm, hand and fingers will be extremely difficult if not impossible to replicate via this low-cost approach. A human hand can move in almost every direction of the wrist. Fingers can stretch, bend and move sideways and the hand can bend and rotate at the wrist. Furthermore, we receive sensory feedback from our hands and fingers that help immensely when touching or operating objects. As we are still in the initial stages of this research, and in this installment only focuses on strumming (coarse movements), it is clear that custom actuators would need to be designed and implemented, if more advanced and hand-like interaction should be possible (finger-picking or other playing styles).

It is also worth noting that we are working with an electrical guitar for this prototype, and that the actuator we are using can cause electrical noise in form of a electromagnetic field and audible motor noise to bleed from the motor into the guitar's pickups. This occurs due to the proximity of the electrical guitar pickup, be it single coil or humbucker design, near the plucking location on the strings (a position required to best capture the sound). This noise problem can be substantially circumvented by running the pulse-width modulation (PWM) signal that controls the motorized fader at a frequency higher than normal human hearing (more than 20kHz). While an acoustic guitar would not have this problem, the more fragile body makes it somewhat difficult to mount actuators on the guitar's body without damaging it, or compromising its ability to produce a good acoustic sound.

5. CONCLUSION

The results clearly points in a direction that children or adults with Hemiplegia can play an actuated guitar, potentially even bringing it to a traditional guitar teacher and start learning basic chord shapes with their good hand (with standard tuning). In the prototype's current state – where string skipping and muting is not possible – it has to be limited to things possible only with strumming. Nonetheless, is it a huge step for people with disabilities to simply be able to play a real guitar. It is also possible to use it as a training and rehabilitation instrument for the affected arm as a therapeutic tool with a few more iterations of prototype development. Using the motivating factor that playing guitar and learning new tunes can be fun possibly leads to more consistent training the affected arm, and thereby hopefully increase the dexterity of the affected limb more quickly.

6. ACKNOWLEDGMENTS

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Exercising the Tibialis Anterior Muscle of Children with Cerebral Palsy for Improved Neuroplasticity using an Electrical Guitar

Jeppe V. Larsen, Thomas B. Moeslund and Dan Overholt

Abstract— **This paper is a suggestion on how to improve or extend a known method of exercising the tibialis anterior muscle for improved mobility for children with cerebral palsy through neuroplasticity. We suggest that by using slightly altered existing devices, in this case the Actuated Guitar, it is possible to motivate children to do functional activities as regular exercises and that it will provide better results when compared to traditional exercises.**

Keywords: Rehabilitation, Musical Instrument, Neuroplasticity, Motivation, Cerebral Palsy.

I. INTRODUCTION

People with Cerebral Palsy often have lowered functionality of the tibialis anterior muscle, which is the front facing muscle on the lower leg covering the length of the shin. Having problems to activate the tibialis anterior muscle results in difficulty doing dorsiflexion of the foot, that is, lifting the tip of the foot upwards. Normally dorsiflexion is working in tandem with plantarflexion, that is stretching the foot away from the knee. This is for example used when walking, and help positioning the foot in the right angle producing a smooth and normal gait cycle. Lack of control or strength in the tibialis anterior muscle can results in the characteristic tiptoe gait often seen on children with cerebral palsy. What happens is that following a planterflexion the tibialis anterior muscle is not strong enough or not activated properly and a full dorsiflexion is not executed causing the toe to touch the ground first when walking. This makes it difficult to walk and even more difficult to walk in rough or non flat terrain. This uneven gait makes it extra tiring for children with cerebral palsy to follow along in the tempo of normal children. Therefor rehabilitation of children with cerebral palsy has often focus on training the tibialis muscle to improve gait and mobility.

II. METHODS

A. Traditional Training of the Tibialis Anterior Muscle

A common technique used to strengthen the tibialis anterior muscle is a simple repetitive exercise of the isolated muscle using a device designed for the purpose, see figure 1. You simply put weight on the front of the foot and the user lifts the foot as high and as many times he or she can. The device is often used in combination with other exercises such as long walks or walking in different and difficult terrains.

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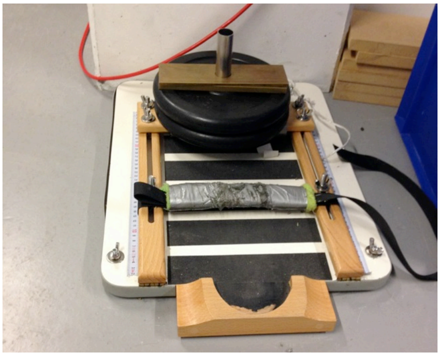

Figure 1: An example of a device used to train the tibialis anterior muscle. The heel is placed in the cutout and the tip of the foot under the strap. Weight and size can be customized. - *Image provided by Jakob Lorentzen from the Helena Elsass Centret*

B. Rehabilitation and neuroplasticity

Neuroplasticity refers to the brain's remarkable ability to rearrange areas in the brain previously used for other specific tasks. The idea is that if an area of the brain has been damaged that information or functionality can relocate to an undamaged area of the brain. Advances within this area will be extremely important and helpful for people with brain injuries like cerebral palsy or stroke victims. Studies show that by doing 400 – 600 repetitions a day exercise can lead to structural neurological changes [1][2][3]. There is still a lot to discover regarding neuroplasticity and how to optimize and target specific areas and functionality of the brain.

The type of repetition used in rehabilitation is also important. *Passive exercise* is where a therapist is performing or aids the patient in moving a limb opposed to an *active exercise* where the patient performs a conscious action himself. When talking neuroplasticity active exercise is the only type that have showed any results. [1].

C. Motivation through functional activity

For children repetition without any apparent goal is quickly becoming a boring task. The best rehabilitation is the exercises that the child will do by itself in his or her own context and by own free will. As stated in the section above a high number of repetitions every day is needed to achieve the desired results and therefor motivation is the key for a positive result. An indirect way to accomplish this is by functional activity exercise [1]. A functional activity is an exercise that has a purpose e.g. picking up a glass. If the active exercises can be either replaced or supported by functional activities in their everyday lives and interests or hobbies of the child the chances for self supported continuous rehabilitation will be a lot higher.

D. The Actuated Guitar

Musicians' brains have often been used as models for neuroplasticity because the plasticity is rather extreme in the brains of musicians [5]. One of the reasons why the changes are more pronounced can be because music performance requires, that a high number of areas of the brain are working simultaneous to coordinate the body and on the same time interpreting what it is hearing and reacting accordingly [5].

An example of a device that can be used to do functional exercise in a musical context is the Actuated guitar [4], see figure 2. The actuated guitar was developed to give people with hemiplegia cerebral palsy, stroke victims or similar disabilities the ability to play on a real electrical guitar. User studies were conducted during the 2013 Summer Camp at the Helena Elsass Center[6] and showed that children with no prior musical training were able to produce rhythmic strumming patterns using their non affected foot and thereby over time be able to operate and play the instrument.

The system allows for a wide variety of input devices that make an expandable and divers rehabilitation tool that can be used in many different areas.

Figure 2: The Actuated Guitar. The actuator pulling the pick across the strings is a motorised fader from a mixing console. The motor is controlled via a Arduino microcontroller and a 2Motor motor controller mounted inside the guitar's body.

E. Functional Activity-Based Training of the Tibialis Anterior Muscle

Our hypothesis is that, using a foot pedal as input to control the Actuated Guitar, see figure 3, it is possible to setup at functional activity that will facilitate the same movement patterns as the traditional exercise. The goal is to compare if the functional activity's effect on neuroplasticity is greater than the traditional exercise, not the muscle building capabilities.

The studies should be longitudinal when dealing with neuroplasticity networks because it is time consuming, probably 3 – 6 months. First part of the evaluation will be a qualitative evaluation focusing on how the different exercises motivate the children. Are the guitar and its possibilities more motivating over time compared to the traditional exercise? The second part will be a series of test to determine if the children's has gained better control of the tibialis anterior muscle.

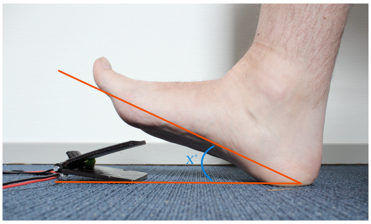

Figure 3: The pedal used for strumming the guitar. The height of the pedal will increase or decrease the angle X and thereby alter the difficulty and the intensity of the exercise.

III. DISCUSSION

The idea of using existing or slightly altered technologies to replace or improve existing rehabilitation has numerous benefits. First of all, making people able to rehabilitate through existing devises and initiatives can significantly cut down costs. Enabling people with e.g. CP to play a real guitar opens up a world of opportunities they would otherwise not be able to explore. If they got a one of a kind custom made instrument, there will be no one to teach them how to play the custom made instrument. They will not be able to identify with artists playing that instrument, they will not be able to identify their instrument in popular music, they will not be able to find inspiration, sheet music or watch videos of performances the internet. It will be more or less impossible to keep up a long-term motivation. With a solution like the Actuated Guitar, people can use all the initiatives like every normal child. By doing just enough scaffolding long-term motivation is possible and will be fed by the children's own desire for learning and through that continuous exercise with a high number of repetitions which will increase the benefits of neuroplasticity.

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The Prospects of Musical Instruments For People with Physical Disabilities

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ABSTRACT
Many forms of enabling technologies exist today. While technologies aimed at enabling basic tasks in everyday life (locomotion, eating, etc.) are more common, musical instruments for people with disabilities can provide a chance for emotional enjoyment, as well as improve physical conditions through therapeutic use. The field of musical instruments for people with physical disabilities, however, is still an emerging area of research. In this article, we look at the current state of developments, including a survey of custom designed instruments, augmentations / modifications of existing instruments, music-supported therapy, and recent trends in the area. The overview is extrapolated to look at where the research is headed, providing insights for potential future work.

Author Keywords
Interactive performance systems; Interfaces for sound and music; Music and robotics; Social interaction in sound and music computing; Actuated instruments; Actuated guitar; Musical instruments for the disabled.

ACM Classification
H.5.2 [Information Interfaces and Presentation] User Interfaces --- Haptic I/O. H.5.5 [Information Interfaces and Presentation] Sound and Music Computing. K.4.2 [Social Issues] Assistive technologies for persons with disabilities.

1. INTRODUCTION
Many countries in the world today face an aging population, meaning an increase in the average age of the population in the coming years. Old age brings with it the risk of diseases and general decline in health. Therefore, rehabilitation methods are quickly becoming increasingly important. We focus here on therapy and rehabilitation methods for those affected by physical disabilities, using music as a motivational factor to incentivize user engagement with the process. Our approach has been described in [33, 34], but here we focus on the field in general – as an emerging set of techniques and technologies enabling those with physical disabilities to improve their condition, both physically and psychologically.

2. PHYSICAL DISABILITIES
A physical disability can be caused by a number of different things. It can be inherent, acquired, disease-born, or caused by an accident. We start by examining the most common causes for physical disabilities within Denmark. Here we focus only on Denmark as a sample population, due to the local availability of statistics and information available to us as researchers.

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2.1.1 Cerebral Palsy
In Denmark (population 5.6 million), about 10,000 people have been diagnosed with Cerebral Palsy (CP), with approximately 33% under 18 years old. These numbers suggest that around 2 percent every year are confirmed CP patients, or around 180 children every year [1].
Cerebral Palsy is a type of brain damage, and 90% of the cases are caused by damage or disorders to the immature brain during pregnancy. However, precisely what causes the brain damage is not clear. It can be caused by many different complications, such as infection during pregnancy, lack of oxygen, small blood clots or cerebral hemorrhages. In 10% of cases, it is estimated that injuries during birth or shortly thereafter were the cause.
There are three primary types of CP: spastic, dyskinesia, and ataxia. There is a fourth category as well, in which there is a mix of the three primary types. Spastic Cerebral Palsy is by far the most dominant type, covering 75 – 80% of the cases. In this type of CP, increased muscle tone causes stiffness in the muscles, making movements with the affected body part(s) awkward. Spastic CP is categorized by what body parts are affected. Monoplegia is when a single arm or leg is affected, diplegia is when mainly both legs are affected, hemiplegia is when one side of the body is affected, and quadriplegia, which is the most severe, means the entire body is affected. Dyskinesia CP causes uncontrollable movements, which can be either slow or rapid. Finally, ataxic CP causes problems with the coordination of the limbs.
Aside from difficulties in controlling limbs or other affected body parts, CP can also (depending of the severity or the damage) have a great impact on cognitive abilities.

2.1.2 Stroke
In Denmark, about 12,000 people per year have strokes, and about 75,000 people live with complications caused by strokes [2]. Worldwide, it is estimated that one in six people will suffer a stroke in their lifetime [3]. The term stroke covers two types of strokes, both causing damage to the brain. The most common comes from blood clots that block vessels and prevent blood from reaching the brain, thereby causing brain damage. The other type is a cerebral hemorrhage, in which an aneurism bursts or a weak blood vessel leaks, and the pressure from the blood causes damage to areas of the brain. For those who survive a stroke, some of the most common physical effects include:

- Hemiparesis (Weakness on one side of the body)
- Hemiplegia (Paralysis on one side of the body)

- Dysarthria (Slurred speech or difficulty swallowing)

Along side any physical effects, there are many times cognitive and behavioral changes as well [4].

2.1.3 Disease, Accidents and Amputation

Accidents at home, in traffic or at work with trauma to the head (and /or severe damages to the extremities) can lead to physical disabilities as well. Diseases may also cause amputation, or brain damages that can lead to physical disabilities. Whatever the cause – be it Cerebral Palsy, a stroke, or anything else – the possibilities of improving and enjoying ones life with a physical disability are not static, and can potentially be enhanced through music.

3. BRAIN PLASTICITY AND MUSIC

Our brains are capable of continual change via plasticity, which is a fundamental (re)organizational function of the human brain. Throughout our lifespan, the brain responds and changes its functional and structural organization [5] through events like maturation, learning and memory, adopting physical skills, recovery form injury, or coping with loss of sensory input like auditory or visual input, and much more [6]. This amazing function is extremely important throughout life, both when growing up and learning, but also following a brain injury.
Medical knowledge about plasticity is used in many different ways in rehabilitation, following strokes or accidents. Several studies have shown that intensive practice with e.g. constraint-induced therapy (CIT) [7] [8] with an impaired limb, can result in further recovery, even after reaching a plateau with less rapid progress in rehabilitation [7]. A change in the paradigms used within Music Therapy came from research in the mid-1990s focused on the relationship between brain functioning and music, demonstrating the experience-dependent plasticity [9] [10], and suggesting that music stimulates complex, cognitive, affective and sensorimotor processes in the brain [11] [12].

Why is music interesting when talking about plasticity? Music performance is one of the most demanding cognitive challenges that the human brain can endure. Music performance requires a number of advanced and precise skills involving auditory-motor interactions, activating areas in the brain such as the Motor Cortex, Dorsal and Ventral Premotor Cortex, Frontal Cortex, Superior Temporal Gyrus, and the Audio Cortex [13]. This broad exercise of the brain is why musicians are often used as examples of brain plasticity, with clear differences between a musicians and non-musicians brain. G. Schlaug et al. [14] compares the brain and cognitive effects on young children who had instrumental music training with children without any prior training. The research shows that certain transfer effects start to emerge in an early age, and get more and more pronounced as training continues. It comes as no surprise that structural changes appear in the areas linked to musical training, however very interesting structural differences occur outside these areas as well. This is an indication of transfer effects, which may indicate that playing a musical instrument would benefit other areas as well. Such research shows that playing music could be important for general cognitive rehabilitation purposes, as well as pure enjoyment and physical rehabilitation.

4. MUSIC-SUPPORTED THERAPY

The increased interest and research within the field of neuroscience and plasticity has altered the perspectives of traditional music therapy, that usually is connected with topics like well-being, emotional response and relationship building – to a new model called Neurologic Music Therapy [9]. NMT has its focus on rehabilitation following e.g. strokes, and has grown rapidly over the last 20 years. In a series of papers [15][16][17] S. Schneider et al. compares a widely used rehabilitation method to improve motor skill recovery following a stroke, with a music-oriented approach. The method often used in rehabilitation is called CIT, which stand for Constraint-Induced Therapy. CIT is a standardized intensive rehabilitation intervention where the healthy extremity is in constraint several hours a day, thereby forcing the person to increase the use of the impaired extremity. The goal is through a high increase in use and thereby repetitive usage trying to cause plastic reorganization of neural networks in the brain [8].
Schneider et al. suggest a method they call Music-Supported Therapy (MST), which still builds on repetition but at the same time draws upon the additional benefits of active music making. They designed a training program according to the following principles:

- *Repetition:* Repetitive exercising of simple finger and arm movements.
- *Auditory Feedback:* Reinforcement of movement effect due to immediate auditory feedback supporting the precise timing control of movements.
- *Shaping:* Adapting the complexity of the required movements according to the individual progress.
- *Emotion:* Increased motivation of the patients due to the playfulness and emotional impact of making music and acquiring a new skill.

Their results compare conventional (CG), functional (FG) and music-supported therapy (MG) in a variety of tests. The results show MG as a substantial improvement in most test parameters pre- and post-test, when compared to CG and FG. However, their results are not conclusive as single variables need to be identified and further test will show which are significant, but there are clearly some aspect of music creation that yield far better results than conventional CG and FG rehabilitation methods [17].

5. MUSICAL INSTRUMENTS FOR PEOPLE WITH PHYSICAL IMPAIRMENTS

The musical instruments used in S. Schneider et al.'s research are two commercially available products. One is a standard MIDI keyboard, and the other an electric drum set. The position of these devices was altered to fit the disabilities of the individual users in the test, but the devices themselves were not altered or modified in any way.

5.1 Example of Custom Instruments

S. Schneider et al. uses existing products for their research, which can work in certain cases. But it is also possible to create custom musical instruments designed for people with physical disabilities. Historically speaking, there have been a small number of such musical instruments targeting users with physical disabilities. We exclude instruments for those with cognitive disabilities, as it can often be the case that cognitively impaired users still have good enough motor skills to physically engage and play normal musical instrument as intended. Instruments for physically disabled users have come from either researchers or commercial vendors, as described below (in order of publication/release date).

Soundbeam (1989) [18] is a well known and well established commercial product for music creation for people with disabilities. It is also called 'the invisible expanding keyboard in space'. The soundbeam can use up to four beams that each consist of a housing containing an ultrasonic range sensor. The beams are connected to a hub that interprets the signals and extracts note and velocity for each beam and converts to MIDI. MIDI signals are then sent to a DAW or other music software that can playback samples. The beams have a range from 15 cm to 6 meters and can be divided in 64 notes.

EyeMusic (2004) [19] is both a performance and a playback instrument. EyeMusic uses an eyetracker that output the gaze position (x, y) 60 times pr. Second. Max/MSP is used for grabbing the eyetracker data. It operates with eye fixation, that has two parameters, deviation and duration. An obvious target group is people with severe disabilities or spinal injury, who may not able to move their body at all.

Movement-to-music computer technology: a developmental play experience for children with severe physical disabilities (2007) [20]. The MTM system consist of a web camera, screen and speakers connected to a computer. The camera captures the movement of the user. Tiny movements such as raising an eyebrow, to big movements such as waiving the arms are captured alike by the system. The screen shows the user, with colored shapes superimposed around their silhouette. These shapes correspond to a region of physical space surrounding the user, and a note is triggered when part of the body penetrates the boundary of one of the coloured shapes. This gives a visible and auditory feedback to the user, indicating that the shape has been activated. This adaptive approach is highly useful for a broad range of users.

Skoog (2008) [21] is an musical interface that where you can push 5 pads, hit it, squeeze it and twist it. It can play sounds using its own software or hook up to other software using its MIDI capabilities. It can expressively play five pre-defined notes that can be changed using the following software.

Beamz (2009) [22] is a controller consisting of four IR-beams. Each beam can be set to send a MIDI signal, thereby triggering any music software or hardware that supports MIDI. As the Beamz design only catches users interrupting the IR-beams, it is only trigger events that are generated (no velocity), and is also not able to take advantage of e.g. modulation that MIDI offers. However, Beamz is rather inexpensive, and targets schools for beginners to start experimenting with music, or as a tool for therapy and rehabilitation to inspire to movement and the enjoyment of music creation.

Computer Assisted Music Therapy: a Case Study of an Augmented Reality Musical System for Children with Cerebral Rehabilitation (2009) [23] uses an augmented reality system where coloured markers in front of a webcam represent a certain instrument and a particular note of that instrument. A note is played when a hand is in the centre of the marker. The use of the augmented graphics of the system is somewhat unclear from the publication, and the system is tested on a single individual, a child with CP of an unknown age, in a music therapy session. However, is suggested that he system could be used in daily sessions and clinical use.

TouchTone (2010) [24] is design for children with hemiplegic cerebral palsy. The unaffected hand triggers pitches using pressure sensitive pads, and the affected hand is used to shift pitches by invoking a momentary switch. The pressure pads are arranged in two rows of five where one row is a pentatonic scale and the other row can ad a note there has a pitch difference of a 3rd or a 5th of a corresponding pad. There is a LED on each pad to signal if it is active. This can be used as a learning mode, that allow the user to follow the LEDs. It was tested as an individual instrument with 6 children between 8 and 12 years of age, for 15 minutes each, as well as a group instrument with 12 children accompanying a music therapist.

Tongue Music (2010) [25] uses Hall sensors placed on a custom headset which acts as receiver for a magnet affixed to the tip of the tongue. The changing magnetic field is used as input. Moving the tongue creates different magnetic fields, which are interpreted by a microprocessor before being sent to a computer for sound creation. The instrument can play 10 minor and major notes as well as ambient sound, as designed. Tongue Music was demonstrated and 25 couples participated in what seems to be an unstructured test.

EyeGuitar (2010) [26] uses Eye Gaze as a mean of simplified input to play a guitar hero style game for people with disabilities. It is not a true musical instrument, as it can only play the selected song. However, it is a showcase of how to approach eye gaze/tracking for people with disabilities.

MusEEGk: A Brain Computer Musical Interface (2011) [27] creates a BCI using EEG to measure the P300 response. The BCI controls a sequencer, where the user can select notes on a matrix on a screen and position them in the sequencer grid. The sequencer itself has no latency, but current BCI technologies have a high latency. This leads to a limitation that the user at most can select or change 3 notes per minute with an average accuracy of 86%.

Robot-Assisted Guitar Hero for Finger Rehabilitation after Stroke (2012) [28] is a lightweight robot assisting the user in a naturalistic grasping movement of individual fingers. As the title states, a variant of the guitar hero theme was used to test the robot.

Rhyme: Musiking for All (2012) [29]. The RHYME project is a project that investigates the term musicking through Participatory Design and Design for All. The project has made two prototypes called ORFI and WAVE. "ORFI is a set of co-creative tangibles: The ORFI modules, or cushions, communicate wirelessly with each other. They can be freely built, thrown, played in and with as the user like. ORFI responds with changeable graphics, light, and music when the wings of the modules are bent, or the microphone is activated."[29].

Brainfingers (2013) [30] is a hands-free computer control developed by Brain Actuated Technologies Inc. A headband fitted with sensors detects electrical signals from facial muscles, eye movement and brain waves. Brainfingers does not directly target music creation, as it can solve many tasks such as simple clicking, to complex combinations of controls. It is software that converts all the sensor input data into controls termed Brainfingers. This software is useful for a broad range of users, especially people with severe disabilities.

"Musical co-creation"? Exploring health-promoting potentials on the use of musical and interactive tangibles for families with children with disabilities (2013) [31] is an article building upon the RHYME project. The article focuses on actual interaction with ORFI and co-creative tangibles. It has a primary focus on two users, a boy and a girl, and it discusses the theories behind the project, and how the children with their cognitive and physical disabilities interact with the system. The focus is on how users can benefit, but the article also discusses what might need to be changed in a future context.

The Actuated Guitar: A platform enabling alternative interaction methods (2013) [33], The Actuated Guitar: Implementation and User Test on Children with Hemiplegia (2014) [34]and Exercising the Tibialis Anterior Muscle of Children with Cerebral Palsy for Improved Neuroplasticity Using an Electrical Guitar (2014) [35] is a series of papers describing a project with focus on enabling or re-enabling people to play a real electric guitar. The guitar is a fully functional guitar that can be hooked up to a guitar amplifier. The system uses a linear actuator for strumming the strings, and the neck is operated as usual by forming normal chords. In its current state, it is not able to mute individual strings or skip strings. The idea of modifying existing instruments is to open up the existing musical world for people who are not able to use their strumming hand, either as beginners or people who have played all their life and after a stroke or similar, are not able to play normally any more.

RoboTar (2013) [36] started as a kick-starter project, but was cancelled because of the low interest in the project. The device was finished anyway and is now a product you can by from the inventors' site. RoboTar is a device you strap on the neck of the guitar that can press down notes on all six strings along the first four frets. It is replacing the fretting hand/left arm for people with injuries and or disabilities. The device can be programmed from an app and you can cycle through pre-programmed chords via a foot pedal.

6. CONCLUSTION / DISCUSSION

Performing music may or may not be inspiring for a particular person, no matter if it is during rehabilitation or not. However, it has enough potential benefits to justify that music-focused rehabilitation should be offered to those who would be interested in music-based therapy. That said, some are more into football, biking or running – and the broader the support within rehabilitation, the better. In the long run, it should be whatever motivates the individual to keep them on the path to rehabilitation.

The main criteria of Schneider et al. [15][16][17] was that the patients should have residual function of the affected extremity above a certain threshold, before they could contribute to the research. This makes sense, as the goal was to investigate if MST would improve the dexterity and motor function of an effected extremity, compared to traditional methods.

Using existing musical instruments for people with residual function in one or more extremities is an interesting approach, and opens up for a broad range of possibilities. Taking a drum kit as an example, this could be well suited for people with residual function in both upper and lower extremities, since they need to use both hands and feet when playing a drum kit. Drums could also be a good place to start for exercising coarse motor skills, rhythm, memory and timing. For exercising fine motor skill in the upper extremities (hands and fingers), piano or keyboard may be a good choice, as it gives the same benefits such as motor skills, rhythm, memory and timing.

But what is equally important is motivation and goal-setting [37]. It is well known that for improvement, practice is key. Practice without motivation is difficult and often results in skipping practice, meaning users will not reach their goals. By using (potentially modified) existing musical instruments, however, the benefit of constant inspiration from music on the radio, songs played in TV or on the Internet becomes present.

In addition, existing musical instruments can potentially open up for social activities more easily than entirely new instruments. When using existing musical instruments (modified or not), one can bring their instrument to normal instrument lessons, or even join a band. Socializing is a crucial part of music, and is highly motivational (just as playing in team sports is for some).

But what about people with no residual movement in the effected extremities? What options do they have for exploring the joys of playing a real musical instrument, and gaining some of the same benefits as described above? Looking at the review of instruments designed specifically for people with disabilities, there are not a lot of existing / modified musical instruments. The development of instruments for people with disabilities often follows the trend of technological advances, which of course make sense to explore the new frontier technologically, and see if that can solve what other technologies before could not. But there is a remarkable lack of interest in making existing musical instruments accessible for people with moderate physical disabilities, who are well functioning enough to still have a social life and do self rehabilitation. People who have played music their whole life, but are then hit by a stroke end up from one day to the next e.g., not being able to move one arm. Only three papers in this survey, and one commercial product focus on an existing musical instrument.

If one follows the newest technological solutions, it might be argued that the "Holy Grail" within musical instruments for people with physical disabilities, would be a 100% adaptive instrument. Such an instrument would always fit the user, and give them the degrees of freedom and expression that people without disabilities would have. However, it is our suspicion that after an initial honeymoon with such an instrument, most would lose interest in it. People often learn by imitating other people like their parents, siblings, friends, teachers or coworkers. But an adaptive instrument would give different gestures for a given sound for different users, meaning that it will never be able to be replicated in the same way as another user. This isolates players, making it impossible to learn from each other directly. One of the most exiting and challenging parts of playing a musical instrument is to learn from others playing the same instrument.

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States and Sound: Modelling User Interactions with Musical Interfaces

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ABSTRACT

Musical instruments and musical user interfaces provide rich input and feedback through mostly tangible interactions, resulting in complex behavior. However, publications of novel interfaces often lack the required detail due to the complexity or the focus on a specific part of the interfaces and absence of a specific template or structure to describe these interactions. Drawing on and synthesizing models from interaction design and music making we propose a way for modeling musical interfaces by providing a scheme and visual language to describe, design, analyze, and compare interfaces for music making. To illustrate its capabilities we apply the proposed model to a range of assistive musical instruments, which often draw on multi-modal in- and output, resulting in complex designs and descriptions thereof.

Author Keywords

Sound; Assistive Musical Instruments; ADSR; Three-State-Model; Modeling; Gestures.

ACM Classification

H.5.5 [Information Interfaces and Presentation] Sound and Music Computing, I.6.5. [Simulation and Modeling] Modeling Methodologies

1. INTRODUCTION

The unambiguous and complete description of interactions with and feedback from musical interfaces is important for 1) designers to analyze and publish their designs, and 2) researchers intending to compare different designs and reproduce results from interactions with these interfaces. Frameworks and taxonomies for musical interface design have been proposed before [2, 7, 12, 14]. However, publications of novel interfaces still lack the required detail due to the complexity of the focus on a specific part of the interface and the absence of specific templates or structures to describe these interactions for easier comprehension and visual comparison. The interactions and feedback the musical interface provide can be difficult to describe with the existing vocabulary, which prompted Buxton to formulate his three-state model of interaction for input devices. However, musical instruments include a temporal course of sound that cannot be described by Buxton's model and its extensions alone; rather, it requires a temporal notion. We suggest a way of modeling musical instruments that draws on and synthesizes models from interaction design and music making. We apply the proposed model to a range of examples in the domain of assistive musical instruments, which often draws on multi-modal in- and output that complicates designs and their descriptions. All of these IMEs lack interaction/feedback details in their respective publications, which are representative of publications/descriptions of IMEs in general. The analysis of the resulting model allows for a visual comparison of the interfaces in terms of where and how input can manipulate the expressive parameters of sound and which feedback modalities the system employs when transitioning between states.

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2. BACKGROUND

Buxton's Three-State Model of Graphical Input [3] introduced a vocabulary and modeling template to better describe interactive techniques vis-a-vis the technologies that implement a graphical user interface. His model draws on the notion of finite state machines consisting of labeled states (circles) and transitions (arrows) between them that describe how user input (labels on the transitions) from one input device changes the state of a system (see Figure 1). State 0 denotes an out-of-range state in which the user has not acquired the input device or control, state 1 allows for movement of a cursor (tracking), and state 2 allows the manipulation of objects (dragging). The transitions between states model discrete events, whereas the self-loop transitions model continuous input or non-input (in state 0).

Many instruments involve more than one input device or extremity. Hinckley et al. extended Buxton's model to

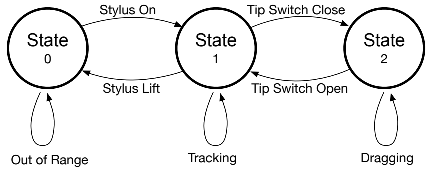

Figure 1: Buxton's Three-State Model with stylus and a tablet.

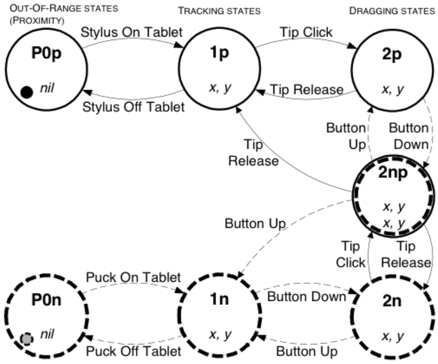

Figure 2: Hinckley et al.'s two-handed input example of stylus and o puck on a tablet.

address a wider range of design problems, multiple effectors through input devices, and interaction technologies [8] by drawing on Petri net representations [15] and including continuous properties. Hinckley's model uses tokens (represented as circles inside states in Figure 2) to express which state the system is in. The tokens can move along through the transitions to states that have the same outline (solid or dashed). Instead of Buxton's self-loops, (see arrows under each state in Figure 1), the model relies on the notion of sensing continuous input, like position, angle, force, or torque, within a state expressed through a named *italicized* property in the lower half of the state in Figure 2. Hinckley further added a prefix to state 0 to distinguish between the two out-of-reach states - touch (T0) and proximity (P0). Different formatting (dashed or solid lines Figure 2) of the states, tokens, and transitions indicate the devices. A state name postfix distinguishes between the respective effectors, i.e. input hands (p for the preferred and n for the non-preferred hand in Figure 2).

Apart from providing a language and notation for user interface interaction concepts, state modeling allows for visually inspecting the model and spotting asymmetries in the design in case certain states exhibit different behaviours [20]. Figure 1 is a case in point of symmetry, and Figure 2 illustrates that state 2np is special in terms of the larger number of transitions to and from it and its overlap.

Obrenovic and Starcevic created a modeling framework for specifying multimodal systems. Their model draws on the Unified Modeling Language (UML) and focuses on the inner workings and effectors of the system and its modalities [13]. Our work focuses on modeling the states the system can be in, how user input affects transitioning between states, and the feedback they receive from the system while doing so.

Birnbaum et al. suggest a dimension space for musical devices using a spider web representation [2]. The axes in the spider web have different representations, e.g. required expertise, musical control, feedback modalities. The axis values vary, e.g. high/low, none/extensive, few/many, etc., depending on what they are describing. Hattwick and Wanderlay further expand the dimension space for evaluating collaborative music [7]. Vertegaal and Ungvary investigate the relationship between body parts, transducers, and feedback modalities [21] in music controllers. Overholt presents the Musical Interface Technology Design Space (MITDS), which provides a theoretical conceptual framework and guidelines for describing, analysing, designing, and extending the interfaces, mappings, synthesis algorithms, and performance techniques for interactive musical instruments [14]. Morreale et al. also present a conceptual model called MINUET, which offers a way to understand the elements involved in musical interface design [12]. Most of these frameworks, however, do not provide a sufficient graphical representation of the musical interfaces and do not model different states and feedback to user interactions. MIDI, for example, does not concern itself with how users actuate sounds and what feedback the system provides apart from the generated sound.

2.1 Musical Control and Expression

A number of major components are used to describe musical control and expression. For music making, the *attack*, *decay*, *sustain*, and *release* (ADSR) envelope [16] describes the volume of a generated sound over time (c.f. Figure 3). We draw on Swink's visual depictions of these ADSR parts (the arrows) in our musical interface models. Goldstein [5] used a state transition diagram to model both sustaining and percussive instruments. The diagram describes how an instrument produces sounds and the different modes of control. Francoise et al. [4] also used ADSR to decompose gestures into four phases of sound control: *preparation* (P), *attack* (A), *sustain* (S), and *release* (R). Levetin et al. described musical control through more explicitly detailed steps called: *beginning*, *middle*, *ending*, and *terminus* [10]. These steps roughly map to the ADSR envelope. The *beginning* combines ADSR's *attack* and *decay*, the *middle* maps to *sustain*, and the *ending* paired with *terminus* makes up *release*. Levitin's beginning distinguishes how energy enters into the system through either *continuous excitation* (CE) or *impulsive excitation* (IE). Continuous excitation stems from continuously, e.g. bowing or blowing. Plucking a guitar string or pressing a key on a piano yields impulsive excitation. Levitin further classified instruments into two types of middle: the non-excited middle (NEM), e.g. a guitar, and the continuous excited middle (CEM), e.g. an organ. During *middle* (*sustain*) CEM instruments allow for gestures to control expressive parameters such as pitch, loudness, and timbre. NEM instruments usually do not support these manipulations during this step since the musician cannot manipulate the energy source. NEM and CEM instruments further differ in how a note can end. Musicians of NEM instruments, e.g. a guitar, can either let the impulse energy reach *terminus* (no sound) through *gradual decay* or actively *terminate* the note by muting the string. CEM musicians cannot employ *gradual decay* as the energy abruptly ends when the musician stops bowing or blowing.

2.2 Assistive Musical Instruments

Advances in technology have created opportunities for new assistive interfaces that make musical instruments accessible to people with impairments. Such assistive musical instruments have to overcome different challenges depending on the type of impairments [6, 9, 11]. Obrenovic classified constraints that hamper accessibility as user, device, environment, and social constraints. Users can be impaired in terms of their senses, perception, motor or linguistic skills, and cognition [13].

Designing musical interfaces for people with impairments requires design tools and a language to ensure the best solution and to convey the design in a clear and detailed fashion. We follow Buxton's lead and argue that state models are a

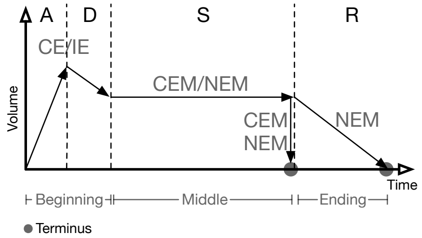

Figure 3: The ADSR Model (black text and arrows) overlaid with Levetin's stages (gray text labels) below and on the ADSR arrows.

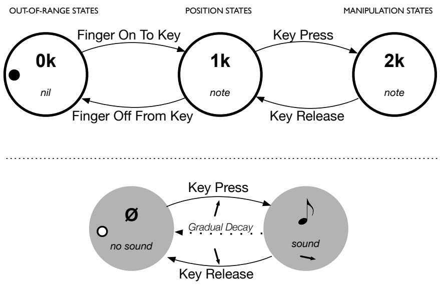

Figure 4: A piano key (CEM instrument) with sound states.

good basis to start from in this case. While our proposed model can be applied to any instrument, we believe that designing for impaired users, which requires attention to detail about which modalities are employed as input and feedback, can benefit especially from a tractable tool and the rigorous approach it promotes.

3. MODELING MUSICAL USER INTERFACES

The model in Figure 4 shows the physical properties of a piano key, but due to the temporal quality of music - specifically for NEM instruments - the model needs to be able to express time. If we imagine an organ instead of a piano we would have a continuous excited middle and thereby infinite sustain. When the organ key is pressed down we have the attack of the note and transition to *state 2k*. As long as the model is in state 2 we have sound, but on release, i.e. once we lift our finger off the key, there is no sound as we transition back to state 1 or state 0k. Just as with the organ, after the attack the piano is in state 2k but with a piano we have a non-excited middle. This results in a *gradually decaying* sustain, which will eventually fully decay while the key is still down. In that case, we would end up with no sound but still be in state 2k. Timed Petri nets [22] model time in the transitions, but this does not align with the temporal behaviors in music making such as preempting a current guitar chord with a new strum. Therefore, we propose to model the temporal course of a generated sound in states and transitions in a separate sub-model for sound. We will from hereon refer to the sub-models for sound and the interactions as the sound model and interaction model.

In the sound model, based on and-states [20], we reuse the transition labels from the interaction model to make explicit how user input changes sound. To visually distinguish between the two sub-models we include a dotted line between the models and a gray fill for the sound model states. To specify the temporal properties of sound we incorporate the ADSR stages on the transitions together with the labels. We use attack ($\nearrow$) for the onset of the note, sustain ($\rightarrow$) for the length of the note, and release ($\searrow$) for the end of the note. These are not used on the interaction model as that would be redundant information that would bloat the model. Sustain is a special case when trying to model a musical instrument. The white token indicates what state the sound model is in. On *key press* and ($\nearrow$) we transition from *no sound* to *sound*. When in *sound* there are two ways to transition to *no sound* depending on Levitin's type of middle. The first is to release a key, dampening a string or stop bowing. This would cause a ($\searrow$) and stop the sound moving us back to *no sound*. The second possibility is through *gradual decay* when a key or a string is pressed down until the sound decays fully, see Figure 4. To describe what type of middle or sustain the musical interface or modelled instrument has, a horizontal arrow is used for CEM interfaces and a slightly tilted arrow is used for NEM instruments. Preempting chords and gestures are shown with a curled arrow returning to the same state just as the loops in Buxton's original model. The loops use the same type of line and color as the effector to which they belong.

3.1 Logical and Relational Conditions

To better explain and control the flow and transitions in our model we draw on logical and relational conditions to express exceptions and special cases throughout the interaction with a given musical interface. We also add a new effector so that our model consists of a single piano key, a sustain pedal, and the sound states. When playing a piano releasing the key dampens the sound, but a sustain key can avoid stopping the sound when releasing the key. To be able to model this we have used *if* and *NOT* to express when we get a release and transition to *no sound*.

3.2 Feedback

In Figure 5 we have added information about the type of auditory, haptic, and visual feedback the system provides in states (at the bottom) and during transitions (on the inside of the arc). Assistive devices can often benefit by improving or adding additional feedback to better signal when certain interactions occur that otherwise would be missed or cause the user to doubt. We focus on the auditory (illustrated through an ear), haptic (hand), and visual feedback (eye) shown as icons.

4. ANALYSIS OF ASSISTIVE MUSICAL DEVICES

In this section we apply our suggested model to analyze five assistive musical interfaces to illustrate its expressive capabilities. We highlight both the value in the design stages of a musical interface and in the analytical or comparative stages to ensure a complete description of a MUI.

4.1 Soundbeam

Soundbeam (SB) is a commercially available assistive musical (NEM) instrument using an ultra-sonic range finder

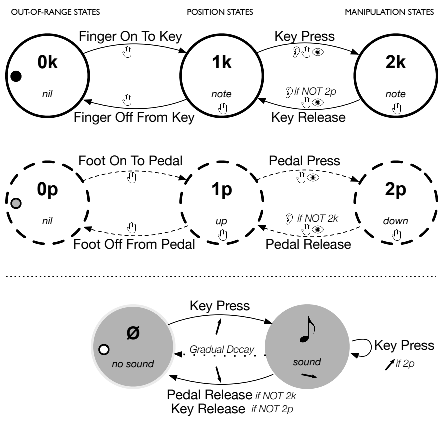

Figure 5: A model of a piano key and a sustain pedal with the use of logical, relational conditions and icons for type of feedback.

(range between 23 cm and 6 meters with a conical shape of diameter of 90 cm and height of 4 meters) to expand an area in front with virtual notes [18, 17]. By interrupting the invisible beam, e.g. with a body part, the user triggers a note, the discrete pitch of which depends on the distance to the range finder. We have modeled SoundBeam in one of its nine settings called multi, and Figure 6 illustrates the absence of a state 1.

As a touch-less device using an ultra sonic range finder it plays one note when breaking the beam at a given distance to the sensor and a different note at discrete distances as it moves closer to or farther away from the sensor. There is no intermediate or positioning state like the piano key and sustain pedal in Figure 5 and therefore no state 1. Soundbeam gives only auditory feedback at the attack/onset of a note; it uses no other modalities or feedback. The sound states in Soundbeam are different from other instruments. It provides no gesture for stopping a sound, so the only way to stop a sound is to let the note decay fully. It has no resting (position) state but is either on or out of range.

4.2 Movement-To-Music

The movement-to-music (MTM) prototype [19] - a CEM instrument - combines exercising and music making. It uses computer vision to capture body movement, renders the user's body on a screen, and superimposes a number of colored shapes around the user. When the rendered body intersects with the shapes, they change transparency and trigger a musical note.

The Movement-To-Music Instrument is like the SoundBeam - a touch-less device without any haptic feedback. MTM can track more than one limb, but every limb would have an identical but independent model. So we only model one effector here as an example. Unlike Soundbeam, MTM has a state 1, which tracks the coordinates of the user, see Figure 11. In state 1 the instrument gives visual feedback when tracking the user and when entering and exiting the predefined trigger regions. The sound state illustrates a continuous instrument where the attack and onset of the sound start when entering the region and stop when exiting.

4.3 The Actuated Guitar

The Actuated Guitar (AG) [9] allows people with hemiplegia to play a real electric guitar. The fretting hand takes regular chords, and a foot pedal, when pressed down, triggers an actuator to strum the strings. The actuated guitar has multiple effectors that interact with one another. The instrument consists of seven effectors, six strings, and a pedal-controlled strum actuator. However, Figure 8 only consists of two effectors, one exemplary string, and the foot pedal because the strings are independent and identical in behaviour. To distinguish between the two effectors we color the string blue and the pedal red.

When looking at the string effector the feedback is primarily tactile. When sound is present in the system we have auditory feedback when sliding or bending the string in state 2 or transitioning to state 1, which dampens the string and stops the sound. The pedal effector offers primarily haptic feedback except at Pedal Down, which also gives visual and auditory feedback. When the pedal is en-

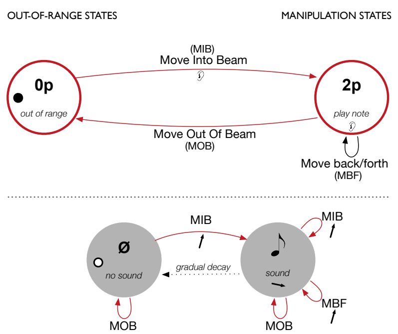

Figure 6: In Soundbeam (NEM) there is no state 1 and therefore no resting position.

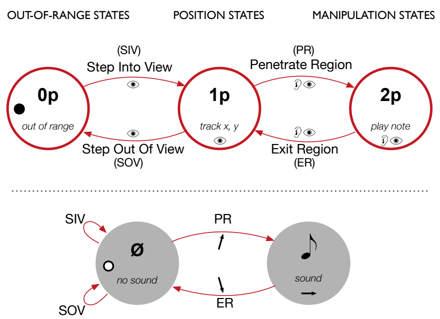

Figure 7: The Movement-To-Music instrument uses computer vision to capture the movement of the user.

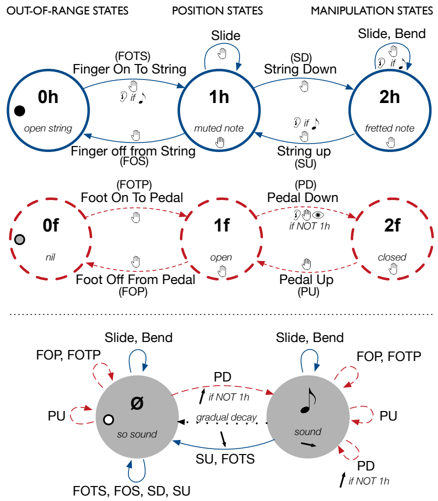

Figure 8: Model of the Actuated Guitar with a single string and a foot pedal.

gaged the actuator drags the pick across the string/s, giving clear visual and auditory feedback. The sound states illustrate an impulse (NEM) instrument in which the attack occurs when pressing the pedal down (PD). Gestures such as sliding or bending can manipulate the sound but the exact mappings of gestures to sound modification are outside the scope of our interaction model. The sound can either decay fully over time, be actively stopped by String Up, or be renewed when the string is strummed again (PD).

4.4 TouchTone

TouchTone (TT) lets children with cerebral palsy engage in musical composition [1]. The instrument consists of 10 pressure sensitive pads, in two rows of five, with associated LED indicators for the unaffected hand and a momentary switch for the affected hand. The pads allow for playing a note while the switch modulates the pitch frequency by one octave up when pressed. Figure 9 shows the model of a multi-effector interface with a single pad and a switch. What is noticeable right away is the shared state **2ps** - the combined solid and a dashed circle. A shared state shows that when both effectors are in state 2 they manipulate the same note. This results in a note playback raised by an octave. This shared state gives some more explicit connections between the states instead of using conditions like *if* and *if NOT*. The pad effector has haptic and auditory feedback. The switch effector is purely haptic unless we move into the shared state when sound is present. The sound states illustrate the creation of sound by putting pressure on the pad (PP). The instrument has continuous (CEM) non-decaying sound as long as the pad is pressed, requiring a release of the pad (RP) to stop the sound.

5. COMPARISON & DISCUSSION

A visual comparison shows a big difference between the modeled instruments from simple (SoundBeam) to more

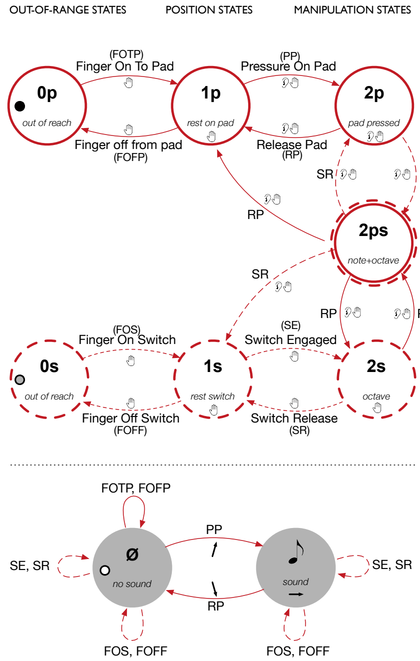

Figure 9: Touch Tone has a shared state shown as the two states overlap.

complex (Actuated Guitar). A visual comparison is much faster than reading through and comprehending large amounts of text. It is quick and easy to compare the different models and it unveils differences and similarities.

But all models describe all meaningful interactions, presence of sound, and feedback. The actuated guitar is the only system that is a hybrid of assistive and existing instruments evident from the different colors of the model effectors. Simple asymmetries, in TT's sound model in Figure 9, allow for verification that the actions FOTP and FOFP can only occur when there is no sound in the system. This is due to the fact that the user releases the pad (RP) prior to taking their finger off the pad (FOFP) and RP stops the sound. A designer pondering whether to add some auditory feedback in response to Finger onto Pad (FOTP) can thereby verify that this does not conflict with sound from the system. The sound model allows for checking completeness as all transitions should either be represented and emanate from each state or not be possible. Take Figure 8 as an example. The only transitions from the interaction model missing from the sound state are FOS and SD. Both transitions originate from state 1h (muted note), which, by definition, does not allow for sound. The absence of self-loops in the sound state for AR and MTM illustrate that these MUIs do not allow for further manipulation or pre-empting of sounds through gestures unlike SB, TT, and AG. Manipulation using gestures would be particularly interesting for assistive musical interfaces that need to be tailored to perceptual, cognitive, and motor abilities of their users. Preconception would also be interesting to add to the model as remote sensing technologies completely remove the tactile feedback channel; however, proprioception are indirectly shown in our model by the absence of tactile feedback (the hand symbol).

Designers can harness the model as a design tool to help identify requirements, incorporate desired gestures, and manipulate expressive parameters (pitch, timbre, and loudness) of the musical interface. It can be used for documenting, discussing, and publishing new musical interfaces and gives a birds eye view of the current design and facilitate a much more efficient and less error prone design process as discussed. Further benefits are easier checks for completion, e.g. by checking that in each state we have all eligible actions represented in transitions. We can use visual asymmetries to verify and potentially re-think design choices. For the merits of state diagrams for modeling we refer the reader to e.g. Thimbleby's work [20]. Using conditional logic helps control the flow of the model, but it could be further extended to include a weighting factor to state transitions to quantify cognitive and motor costs of actions as suggested by Hinckley et al. [8]. Researchers can more easily establish an overview and compare a range of instruments allowing for a faithful reproduction of research results. In further research we would like to explore if the model might require further extensions to incorporate more gestures to capture the expressiveness of musical devices from velocity, vibration, tempo, etc. In the current state of the model we cannot tell if certain interactions in *sound state* actually manipulate sound and, if so, how. Such information could be included by further enhancing the self-loops of the sound states with additional modifiers. Including these could help when comparing the different devices and evaluating whether the chosen interaction comes with an expressiveness cost.

6. CONCLUSION

We have described a novel way of modeling musical interfaces and provided a visual vocabulary and method for systematically describing and analyzing existing musical interfaces in terms of their actions and feedback, as well as how they manipulate sound. The modelling framework provides a quick overview that allows for easier collaboration when designing or analyzing musical interfaces. The model has been shown to work on CEM and NEM instruments in general and, more specifically, on a wide range of different assistive musical instruments. It allows for a complete description of the individual instrument's interaction possibilities with respect to sound.

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Hear You Later Alligator: How delayed auditory feedback affects non-musically trained people's strumming

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ABSTRACT

Many musical instruments exhibit an inherent latency or *delayed auditory feedback* (DAF) between actuator activation and the occurrence of sound. We investigated how DAF (73ms and 250ms) affects *musically trained* (MT) and *non-musically trained* (NMT) people's ability to synchronize the audible strum of an actuated guitar to a metronome at 60bpm and 120bpm. The long DAF matched a subdivision of the overall tempo. We compared their performance using two different input devices with feedback before or on activation. While 250ms DAF hardly affected musically trained participants, non-musically trained participants' performance declined substantially both in mean synchronization error and its spread. Neither tempo nor input devices affected performance.

Author Keywords

Latency, compensation, music, guitar, assistive technology

ACM Classification

H.5.5 [Information Interfaces and Presentation] Sound and Music Computing H.5.2 [Information Interfaces and Presentation] User Interfaces — Prototyping

1. INTRODUCTION

Delayed auditory feedback (DAF) between activation of controls and production of sound can be disruptive, and reduce expressiveness and synchronization performance. DAF increases synchronization errors but musicians can use subdivisions of the overall tempo to reduce synchronization errors. Regardless of musical training, slow tempos reduce synchronization performance with an increased bias to tap before the beat. Studies conducted until now have focused mostly on how DAF affects musically trained people. The synchronization performance of people with no musical training under DAF and at different tempos is unknown. It is also unclear whether actuator feedback can help to cope with DAF. This is particularly important for assistive interfaces for musical expression (aIMEs), which often incur additional latencies, e.g. from filtering or verifying gestures to improve accessibility, and are used by people with less musical training, e.g. in musical therapy.

2. BACKGROUND

Many instruments exhibit an inherent latency or *delayed auditory feedback* (DAF) between actuator activation and the occurrence of sound. For example, by moderating velocity a pianist can manipulate the latency by pressing (activating) a piano key to the audible onset of a soft note by as as much as 100ms [2]. While some musicians can detect latencies as low as 7-10ms [5], people tapping along to a beat on average have a tendency to tap before the actual beat. This *anticipation bias* amounts to around 50ms for non-musically trained people and about 14ms for musically trained people [1]. This bias, however, does not affect the ability to keep a continuous and steady beat. Highly skilled musicians can deviate from inter-tap intervals as little as 4ms [11]. Increased DAF can lead to note errors (sequencing of notes), prolonged play time, erratic changes in key stroke velocity, and errors in inter-hand coordination. This disruption increases with delay and its effect peaks at 200ms, after which it decreases again [5, 9]. DAF can degrade the perceived quality of an instrument [6]. Pfordresher and Palmer showed that DAF disruption in a rhythmical sequence using professional pianists could be lowered if the DAF was close to a subdivision of the overall tempo [9].

The average flutter, i.e. the differences between adjacent *Inter-Onset-Intervals* (IOI), of the hits by a professional percussionist playing along to a metronome ranged between 10 and 40ms or between 2-8% of the associated tempo in relative terms [4], suggesting that tempo moderated anticipation bias. Takano defined *synchronization error* (SE) as the difference between the point in time from a metronome beat and the activation of a note [12].

Asynchronies of 50ms or more between different orchestra members are common already from the spatial arrangements, e.g. a distance of 10 meters adds 30ms due to the speed of sound [10].

Interfaces for musical expression (IMEs) can provide primary feedback such as visual, auditive (instrument noise), tactile, and kinesthetic or secondary feedback (the generated sound). Bongers described *passive feedback* as the feedback produced by the physical characteristics of the system (clicking noise of a button etc.) or as active feedback produced in response to a certain gesture [3].

3. STUDY

The test investigated how precisely *musically trained* (MT) (regardless of instrument) and *non-musically trained* (NMT) people could synchronize the audible strum of the actuated

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guitar [7] to a metronome given either a small (73ms) *inherent system delay* (from triggering the input device to sound) or a large *delay* of 250ms. We compared two foot pedals providing different haptic feedback to investigate if earlier haptic pre-activation feedback could help the participants to better synchronize the strum to the metronome beat.

3.1 The Strumming Device

The aIME used was the Actuated Guitar [7], which is an off-the-shelf electrical guitar (Epiphone SG) fitted with a strumming device operated by a foot pedal for improved accessibility. The strumming device was made from a motorised mixing desk fader positioned above the bridge pickup (see Figure 1) to drive a glued-on pick across the strings. Foam stoppers at each end of the fader shortened the distance the pick had to travel, lowering latency and reducing noise when the pick hit the end of the fader. An Arduino controlled motor managed the speed and direction of the pick. Two different foot pedals activated a strum of all strings. The first consisted of a momentary button mounted in a plastic housing, which raised the button 5.5cm above the ground. The button provided haptic feedback (resistance) from the time it was first touched to when it was fully depressed taking typically around 30ms. The second input device, made from a *force sensitive resistor* (FSR) taped flush to a surface board, only provided haptic feedback when the foot hit the wooden backboard, see Figure 2.

3.2 Data Logging

The momentary button, FSR and metronome were all connected to their own separate Arduino to avoid increasing the computations on the Arduino in the guitar and thereby increasing the latency of the guitar strum. An Adafruit Data Logging Shield with a built in clock and SD-card reader logged timestamps, metronome, sensor, and button data with millisecond precision. These components were built into the casing that held the momentary button.

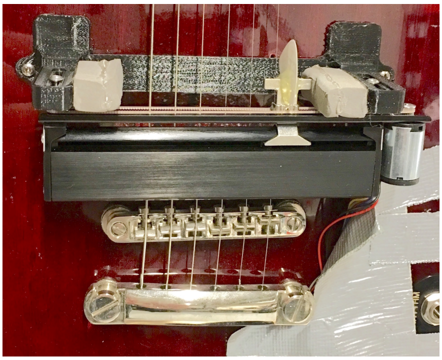

Figure 1: The motorised fader mounted above the bridge pickup. Gray foam stoppers on each side reduced noise and the pick's travel distance.

A custom-built Arduino-based metronome generated primary beats at 2.1kHz and the supporting beats at 1.7kHz with a buzzer at either 60bpm or 120bpm. It provided no visual indication of the beat. Each high beat was sent to the data logger that allowed for the computation of synchronization errors between the generated beats and the push

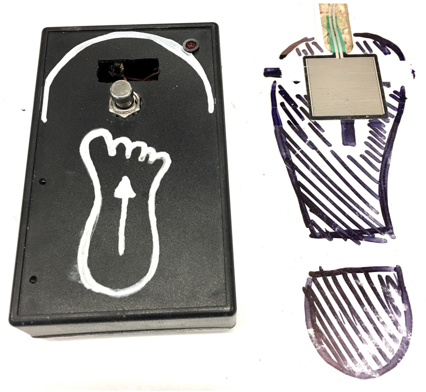

Figure 2: A momentary button in a plastic casing containing the data logger (left) and a force sensitive resistor button mounted flush on a board (right) to trigger strums

data from the two input devices.

Using a 240 frames per second GoPro camera we determined a 45ms system latency between activation of the momentary button and the plectrum picking the first string and 73ms for the pick to reach the last string. For more precise alignment and verification of activations a camera recorded an LED that lit up when the button closed the circuit. The participants had no access to this visual feedback.

At both 60bpm and 120bpm, 250ms was the subdivision closest to Finney and Pfordresher's most disruptive delay (200ms). To yield a 250ms delay between activation and strum the Arduino controlling the motor added 177ms to the system's inherent 73ms delay.

3.3 Participants

We recruited twelve participants (n=12, age= 39.9 years, from 16 to 65 years old, four women) - three from campus and nine without ties to higher education. Half of the participants had at least five years of musical training or experience from paid tuition or regular band practice - referred to as musically trained (MT) - the other half had no musical training or experience - referred to as as non-musically trained (NMT). All participants wore flat soled shoes. Guitar play experience was not required as the participants merely strummed through foot activations and did not 'play' the guitar, e.g. fretting chords.

3.4 Procedure

The test participants were divided into two groups, each of which consisted of three participants with musical training and three without musical training. The first group played at a *tempo* of 60bpm and the second at a *tempo* of 120bpm - the between subjects factor. Each participant played in four conditions of both *delays* (73ms, 250ms) combined with each *input device* (momentary button, FSR) as within subject factors. The orders of the *input device* and *delay* were counterbalanced. At 60bpm the participants played four minutes and at 120bpm two minutes at each condition to ensure that each participant got the same amount of training, i.e. the number of times they triggered the input device.

We observed, video recorded, timed, and helped change input devices and delays during each session. Before starting in each condition, the participants were allowed a few strums on the input device. The delay condition was not disclosed to the participants, who had to adapt their timing to synchronize to the metronome beat in each condition.

For each participant and condition we computed the median synchronization error (SE) - the time difference between the audible strum (derived from the activation times tamp plus the system latency) and the metronome beat. Negative values indicate strums before and positive values indicate strums after the metronome beat. We computed the SE spread as the difference between the third and the first quartile of the synchronization errors. The participants' median synchronization errors and synchronization error spreads - our dependent variables - were subjected to four-way ANOVA tests with *delay* and *input type* as within and *musical training* and *tempo* as between subject factors.

4. RESULTS

We found a significant main effect for *delay*, F(1, 36)=26.7, p≪0.001, and an interaction between *musical training* and *delay*, F(1, 36)=27.3, p≪0.001 on synchronization error.

While the mean synchronization error of musically trained participants was close to constant, irrespective of delay, the non-musically trained participants' mean synchronization error increased from −8.5ms for short (73ms) to 51ms for long (250ms) delay, see Figure 3.

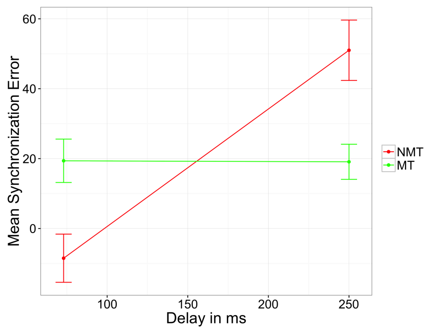

Figure 3: The mean synchronization error of musically trained (MT) and non-musically trained (NMT) participants (N=6+6) by delay including 0.95 confidence interval error bars.

Similarly, the ANOVA test of the spread of the participants' *synchronization error* found the same effects - for *delay*, F(1, 36)=21.7, p≪0.001, and the interaction (see Figure 4) between *musical training* and *delay*, F(1, 36)=10.6, p=0.002. While musically trained participants had an increased synchronization spread from 44ms to 55ms, this difference was not significant according to a t-test (t(5)=0.71, p=0.51). In comparison to the low delay, the high delay almost doubled the mean spread of the synchronization error (from 73ms to 137ms) of the non-musically trained participants. The density plots in Figure 5 for 60bpm, momentary button, 73ms and 250ms delay illustrate the bigger spread for the non-musically trained participants.

For *tempo* we found no effect on the mean synchronization error but the ANOVA on its spread bordered significance F(1, 36)=3.57, p=0.067. At 120bpm the spread of synchronization errors was larger (88ms) than at 60bpm (67ms). Neither on synchronization error nor on its spread did we find significant effects for *input type*. Regarding input devices all participants mentioned the lack of primary feedback (haptic, visual, auditive) [8] when using the FSR, which made correct positioning of the foot difficult. This lack of feedback prompted them to bend down and lift their foot to use the eyes for guidance. Three users lost the position during the test and struggled to quickly find the resting position again before continuing the test.

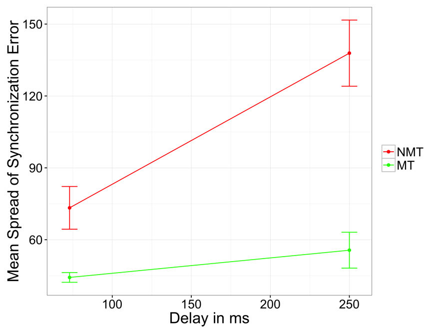

Figure 4: The mean spread of synchronization errors of musically trained (MT) and non-musically trained (NMT) participants (N=6+6) by delay including 0.95 confidence interval error bars.

Moreover, seven participants (all male) with bigger feet initially needed some time to find a comfortable foot position on the enclosure with the momentary button as the physical dimensions in height and length of the casing containing the momentary button made it difficult to quickly find a good pivot position. Four participants found that the passive feedback [3] (clicking sound) from the momentary button distracted them from focusing on the metronome. The height of the momentary button, combined with the short length of the housing, made it impossible to rest the heel on the floor while pushing the button, which forced the participants to position their foot on the edge of the housing to get a good pivot point. That caused some starting issues, but after a few minutes it was not an issue. Four participants (mixed) complained that it was difficult to focus on the metronome as some felt it was drifting, others locked on to an off-beat, and some felt the passive feedback from the momentary button was distracting.

5. DISCUSSION

Figure 3 shows that NMT participants performed better (with smaller synchronization errors) than MT participants with the short delay (73ms). At first glance this seems to contradict that musicians tend to have smaller synchronization errors (in the form of a small negative anticipation bias) compared to non-musically trained. However, remember that the synchronization error was computed as the distance from the strumming of the last string to the metronome beat. If we computed the synchronization error from the first string (45ms) the mean synchronization error would be -36ms for NMT and -10ms for MT. These values are a lot closer to what previous research has found [1, 4]. This shows that the participants were, in fact, trying to synchro-

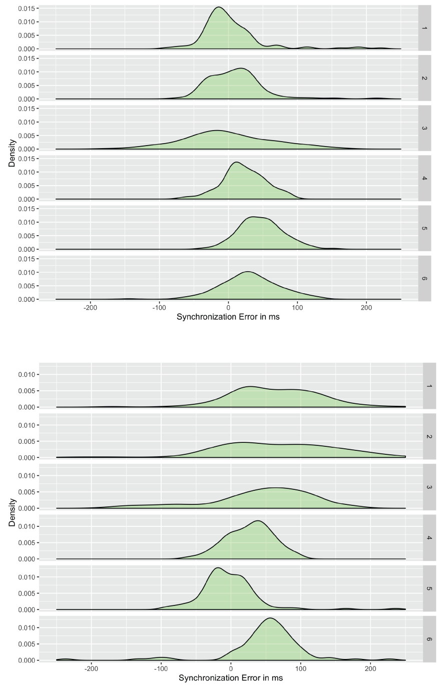

Figure 5: Density plots of six participants playing at 60bpm using the momentary button. Participant (1-3) non-musically trained and participant (4-6) musically trained with 73ms delay (top) and 250ms delay (bottom).

nize to the beginning of the strum and could factor in the system delay (45ms to first string). The results indicate MT participants were not affected by the large delay, but NMT participants' synchronization error was increased by 60ms. While the NMT's mean synchronization error of 50ms seems low, as these are common in musical performances [10], the actual spread of their synchronization errors at 250ms DAF was rather large (138ms) (see Figure 4 and 5), which shows that NMT participants were struggling to reliably synchronize to the beat. The MT participants performed equally well under both delays with a small increase in spread, suggesting that they could time their activations consistently, unaffected by the 250ms DAF. Asked about their strategy for coping with the long DAF, two MT participants explicitly mentioned recognising hitting the subdivision of the beat in this setting - in line with Pfordresher's findings. The two tempos used in our study did not affect synchronization error spread substantially (11ms difference), but the trend was in the opposite direction of previous findings by Dahl [4]. Her participants, however, did not play along to a metronome, played at faster tempo, and experienced no DAF. Future research needs to address this further.

While the input devices had some notable differences and participants struggled to a small degree with them, this did not affect the participants' performance. They performed equally well using the momentary button and the FSR to control the strumming. The qualitative feedback highlighted confusions stemming from the auditory pre–activation feedback that might have negated the tactile feedback benefits of the momentary button before activation.

6. CONCLUSION

Delayed auditory feedback has detrimental effects on synchronization performance of non-musically trained people. Unlike for musically trained people this cannot be overcome by increasing system delays to subdivisions of the overall tempo. When building assistive instruments for rehabilitation purposes designers should strive to minimize system latency. While our healthy participants' synchronization performance did not benefit from an input device with pre-activation feedback, this might not hold in musical therapy due to other benefits these controls provide. Musically trained people can be subjected to longer DAF if they are close to subdivisions of the overall tempo, which implies that aIMEs should allow for adjusting activation latency.

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A Longitudinal Field Trial with a Hemiplegic Guitarist Using The Actuated Guitar

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ABSTRACT

Common emotional effects following a stroke include depression, apathy and lack of motivation. We conducted a longitudinal case study to investigate if enabling a post-stroke former guitarist re-learn to play guitar would help increase motivation for self rehabilitation and quality of life after suffering a stroke. The intervention lasted three weeks during which the participant had a fully functional electrical guitar fitted with a strumming device controlled by a foot pedal at his free disposal. The device replaced right strumming of the strings, and the study showed that the participant, who was highly motivated, played 20 sessions despite system latency and reduced musical expression. He incorporated his own literature and equipment into his playing routine and improved greatly as the study progressed. He was able to play alone and keep a steady rhythm in time with backing tracks that went as fast as 120bpm. During the study he was able to lower his error rate to 33% and his average flutter decreased.

Author Keywords

Motivation, Stroke, Hemiplegia, Re-enabling, Music, Guitar, Actuation, Assistive Technology

CCS Concepts

•**Applied computing** → *Sound and music computing;* Performing arts; •**Hardware** → **Sensors and Actuators;**

1. INTRODUCTION

Every year 15 million people worldwide suffer strokes, of whom 33% survive with permanent disabilities. Demographic projections show a likely increase in this trend. Common emotional effects following a stroke include depression, apathy and lack of motivation [34, 9], which are a major problem in the later stages of home-based rehabilitation. An increasing amount of research has been dedicated to the potential role of music and music performance in helping people cope with the physical and emotional effects of a stroke. Performing music exercises the brain, increases quality of life through a sense of agency, empowerment, and belonging [27], and provides intrinsic motivation [33] to engage in the activity. The intrinsic motivation is an important factor to help stroke survivors stay motivated in order to encourage to self-rehabilitation and combat the life-long physical and emotional effects of a stroke.

Musicians hit by a stroke find themselves suddenly unable to play a musical instrument with one side of their body. While their musical knowledge remains intact, they can no longer use it to play an instrument. Enabling former musicians to play their instrument by making their instrument accessible would likely improve their motivation. However, it is unclear how the reduced musical expression in *assistive interfaces for musical expression* (aIME) from e.g., added latency, the simplification of input gestures, custom-made interfaces, and change in feedback modalities, affects long-term motivation as aIME research typically focuses on short-term proof of concept evaluations [6, 30, 35, 20].

This paper investigates how latency, delayed auditory feedback and reduced expressiveness affects long term motivation using the Actuated Guitar [15, 16].

2. BACKGROUND

2.1 Musical Benefits in Rehabilitation

People who listen to or perform music use several mental registers that trigger a coordinated action of multiple mechanisms [1], including the motor cortex, cerebellum, sensory cortex, visual cortex and the audio cortex [17]. In gait training acute stroke patients using simple Rhythmic Auditory Stimuli (RAS) (prerecorded music with metronome overlay) showed significant improvements in gait velocity, stride length and stride symmetry compared to normal gait training for stroke victims [31]. In addition to listening or moving to music, performing music is one of the most challenging and complex tasks for the brain as it requires precise timing, hierarchically organised actions, precise pitch interval control, and rhythm [38]. Studies with stroke patients suffering from a moderate impairment of motor function of the upper extremities show that playing an instrument for three weeks results in more improved motor function than with conventional therapies [28]. This music-supported therapy builds on repetition and draws on the additional benefits of the playfulness and emotional impact of active music making, which increases the participant's motivation. Besides the physical and motivational benefits, performing music has also positive effects on memory, attention, neglect, executive function, and emotional adjustment [32]. Even in short interventions music reduces depression, anxiety, and hostility [32].

2.2 Gestures and Mapping

The separation of the sound source from the control interface gives more possibilities when designing Digital Musical Interfaces (DMI) than with traditional acoustic instruments whose sound source is an integrated part of the in-

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terface [23, 22]. However, designing musical instruments - whether acoustic or DMI - is still a lesson in how to avoid frustration and boredom. If the instrument is too simple it might not provide rich musical expression and result in boredom, but if it is too complex it could cause frustration and scare away the user before they were able to achieve any rich musical expression [36][21].

A gesture is a human action used to generate sounds [22] and a common DMI model [22] splits the instrument into two parts: a gestural controller and a sound generator. A gesture when referring to DMI is a human action used to generate sounds [22]. The gestural controller takes these gestures as inputs. The gestural interface does not emit any sound besides what is called primary feedback (visual, auditive i.e., instrument noise, tactile, kinesthetic). The gestures are mapped to the sound generator, which can facilitate outcomes that would otherwise be impossible with existing acoustic instruments either because of user limitations or because of the instrument itself. The sound generator outputs the sound of the DMI, also called secondary feedback. Bongers further expands the description of feedback with passive feedback that is produced by the physical characteristics of the system (i.e., clicking noise of a button) or active feedback that is produced in response to a certain gesture [7]. The acquisition of gestures can be accomplished by six different types of interfaces [11]: distance sensing interfaces (DSI), motion tracking interfaces (MTI), tangible interfaces (TI), biometric interfaces (BI), touch screen interfaces(TSI), and wind controller interfaces (WCI) each or in combination allowing for certain interactions.

2.3 Musical Expression

Levitin et al. describe gestures, and hence musical expression, through what they call the *musical control space* where the performer can control the temporal stages - the beginning, middle and end of a musical event [18]. During the three stages the performer can, depending on musical instrument or DMI, vary the expressiveness through pitch (selected note, vibrato, slide etc.), loudness (attack, tremolo, bowing etc.) and timbre (bow or pick angle, bow or pick position, palm muting, etc.).

2.4 Latency and Synchronisation

Many instruments exhibit an inherent latency between actuator activation and the occurrence of sound. For example, by moderating the velocity a pianist can increase the latency from pressing a piano key to the audible onset of a soft note by as as much as 100ms [4].

While musicians detected latencies as low as 7-10ms [12], people tapping along to a beat had, on average, more tendency to tap before the beat. This *anticipation bias* amounted to around 50ms for people without musical training and about 14ms for musically trained people [2]. This bias does not affect the ability to keep a continuous and steady beat where variation in inter-tap intervals can be as low as 4ms [26]. Increased delayed auditory feedback from activation causes disruption and leads to note errors (sequencing of notes), elapsed time, key stroke velocity, and inter-hand coordination. It peaks at 200ms whereupon it diminishes again [12, 24].

In terms of evaluating temporal accuracy Pfordresher [24] used the coefficient of variation (CV) and the standard deviation of inter-onset-intervals (IOIs/mean IOI) computed for each trial as the primary measure of timing variability. The average flutter (differences between adjacent Inter-Onset-Intervals) of the hits from a professional percussionist ranged from 10 to 40ms between 2-8% of the associated tempo [10], suggesting that tempo affects the anticipation bias. The relative size of the flutter increased with smaller tempos, which suggests that the inter-onset-intervals of the consecutive onsets varied substantially. Flutter resulted in an offset or difference between the inter stimulus onset interval (ISI), e.g. a metronome beat, and the IOI, e.g. hit on a drum, resulting in synchronisation errors (SE) [29].

People are more sensitive to *auditory advance* than *auditory delay* as they can detect auditory advance asynchronies between video and sound at around 20 - 75ms and auditory delays from 100 - 188ms [3]. Asynchronies of 50ms or more between different orchestra members are common in musical performances due to, e.g. flutter, but even the spatial arrangements increase asynchronies, e.g. a distance of 10 meters adds 30ms delay to the sound because of travel time [25].

2.5 Function allocation and Control Site

A general Human Factors design approach is *Human-Machine Function Allocation* in which the functions are divided between the human user and the machine [19]. Bailey [5] defines several approaches to function allocation where the *leftover allocation* in aIME design is interesting. In leftover allocation as many functions as possible are given to the user to emphasise the natural movements of the user, and the leftovers are to be handled by the technology. When designing aIMEs the human body offers several different control sites that can be used for controlling a device. Webster et al. identify commonly used sites for controlling assistive devices: hand/finger, arm, head, forehead, eye, leg, knee, foot and mouth [37]. The control sites for aIMEs should have precise rhythmical motion within the latency limits. In addition, the control site should be suited to prolonged used.

3. STUDY METHOD AND aIME DESIGN

We planned a three week case study using a mixed methods approach to allow for an in-depth and long-term investigation. The methods used were observations, interviews, and detailed data logging of the participants usage of the Actuated Guitar. Before the intervention we conducted a pre-intervention interview to collect general health and background information about the participant. We used the World Health Organisation Quality of Life questionnaire (WHOQOL-100) on both the participant and his wife before and after the intervention to compare the Quality of Life scores and to see if there are any increase in QOL or if any crossover QOL effects happened during the intervention. The domains within Physical Health, Psychological, Level of Independence and Social Relationships were of particular interest. We determined that it was the Psychological Domain where the study might have the biggest impact as the participant could become more positive as he gained or re-gained functions and abilities, experienced greater self-esteem, and saw an increase in thinking, learning, memory, and concentration because of repeated practice.

The Functional Independence Measure (FIM) questionnaire is a widely used questionnaire for determining a person's performance of self-care, bowel-bladder control, transfer, locomotion, communication, and cognition to indicate how independent and well functioning the person is in a given setting [13]. We used this to get a more thorough understanding of the participant's general level of function and Independence at the start of the intervention.

3.1 The participant

A 64-year-old male former school teacher participated in the study. At the time of the intervention he was 15 years post-stroke and a right-side hemiplegic with complete paralysis of his right arm. He was still able to walk using an ankle bracelet and shoes but had a significant limp. He lived at home with his retired wife who was the primary care taker. Before the stroke he had been a avid organ, piano, and guitar player in different semi-professional bands since his teens. After the stroke he was unable to play any instruments but had relearned to some extent how to play melody on the piano with the left hand instead of the normally used right hand. The aIME had to take into account his disabilities as well as his remaining abilities. Using the principle of leftover allocation the full functioning left hand could fret chords as usual, but the assistive part had to substitute the typical gestures of the strumming hand.

3.2 aIME Design

The study used the Actuated Guitar [15, 16, 14] there is a regular off-the-shelf electrical guitar (Epiphone SG) fitted with a motorised fader that strums the guitar when a pedal is pressed. The current implementation of the Actuated Guitar only allow for the simplest right hand gesture on a guitar, (strumming of all strings), as it requires lower precision than, e.g. picking or plucking, but still allows the player to play most chords. The actuator is placed above the strings and drive a pick across the strings to strum the strings when a footpedal is pressed, see Figure 1.

3.2.1 Modifications and Data Logging

A few important changes were made to the Actuated Guitar before the the longitudinal field trial began.

A new foot pedal was developed as the original 3D-printed prototype was worn out from previous tests showing that the current components and design was too fragile for longitudinal use. To ensure that the pedal could withstand prolonged use we installed a rugged momentary button in a hard plastic enclosure, see Figure 1. The plastic enclosure also served as enclosure for additional components for collecting data from the user during use of the Actuated Guitar.

For registering button pushes the existing momentary button was used. We measured how hard the button was pushed with a force sensor sandwiched between the button and the casing. We also fitted a distance sensor in front of the button to measure how high the participant lifted his foot from the button, if he did so at all. All the sensors were connected to their own Arduino to avoid increasing the latency of the guitar strum. An Adafruit Data Logging Shield with a built in clock and SD-card reader was used to log the date, sensor and button data at each millisecond for the highest precision.

The change to the foot pedal did not alter how the guitar performed and a button press still resulted in a strum of all strings.

Two foam stoppers were installed at each end of the fader to shorten the distance the pick had to travel, which lowered latency, and to reduce noise when the pick hit each end of the fader.

The new footpedal and the motorised fader with foam block can be seen on Figure 1.

3.3 System Latency

By using a GoPro camera that recorded 240 frames per second we found a 45ms system latency between the closing of the pedal button and the plectrum picking the first string. For more precise alignment the camera recorded an LED that lit up when the button closed the circuit. The complete six string strum (from hitting the first to leaving the last string) took 28ms. See Figure 2.

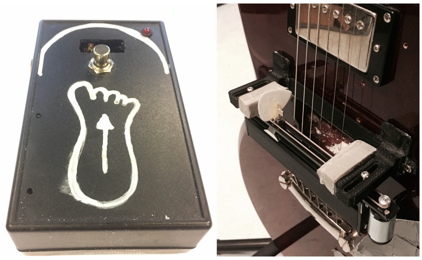

Figure 1: The pedal with the momentary button and built-in datalogger (left) and the electrical guitar with the motorised pick (right).

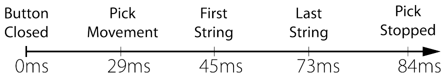

Figure 2: The total amount of time it takes from the button being pressed to the pick moving to the pick movement stopping.

4. THE INTERVENTION

The intervention lasted three weeks, throughout which the participant had the guitar at his home to play whenever he chose. The set-up consisted of the Actuated Guitar, guitar amplifier, guitar tuner, the pedal, a note stand, clear instructions and a video camera to record all sessions. The pedal and tuner were attached to a wooden board with Velcro for fastening and easy re-positioning. The equipment was set up in the living room and was able to remain there for the entire intervention without being moving or disassembled.

The questions going into the intervention centred on whether the participant could do the following despite the inherent system delay and reduced expressiveness:

- play a song without support?
- play along to a slow backing track with bigger anticipation bias?
- play along to a fast backing track?
- stay motivated and play during the free session?

During the intervention the participant could play voluntarily, while twice a week he played in a researcher-led mandatory session. During the mandatory sessions he played the same song of his own choosing at his own tempo, and then played along to a simple four chord backing track first at 60 beats per minute (bpm) and then at 120bpm. The researcher, who observed the sessions, noted down any interesting observations. The remaining time was a so-called free session without any restrictions during which he could play whatever and whenever he wanted. During the free sessions his wife helped equip the guitar, since the soft guitar strap prohibited the participant from equipping the guitar himself, and turned the video camera on and off. The regular strap was replaced with a strap with clips at each end, which made it easier for her to help equip the guitar.

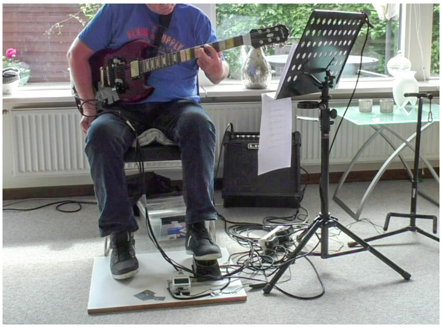

Figure 3: The participant playing the guitar during a free session.

5. RESULTS

During the three-week intervention the participant played a total of 20 sessions (14 free, 6 mandatory). We counted the duration of a session from the point at which the participant was ready to play in the chair with an equipped guitar to the moment he put the guitar down again,

see Figure 5. On average, a mandatory sessions lasted 14 minutes and the free sessions 31 minutes.

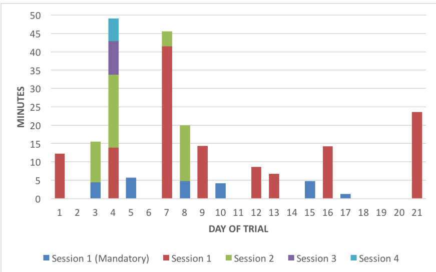

Figure 4: The total time spent per session during the three weeks of the intervention.

During the first few days the participant investigated the guitar and its potential by playing different chords up and down the fretboard.

From the third day he included an iPad running YouTube for backing track support for the mandatory children's song. Around the same time he started to include his own musical tools - an old metronome and old books about guitar chords - and continued to challenge himself and expand his musical repertoire.

He used his piano playing ability to create supporting backing tracks, which gave him drum and bass to play along to. The backing tracks were not random chords but actual full-length songs he had played along to on the piano before he had the stroke. He played entirely from memory. The chords he played included extended, major and minor chords.

Based on both the logged data and observations the general design of the guitar and pedal worked well for a long-term study, and the delay and reduced musical expression

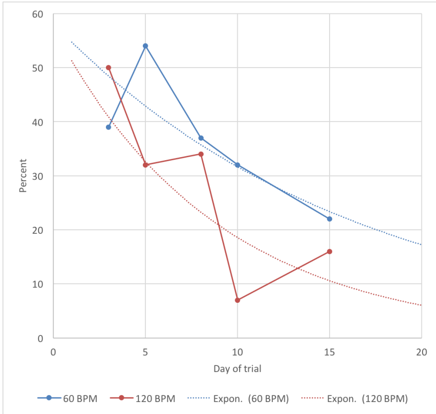

Figure 5: The percentage of synchronisation errors exceeding ±50ms in the mandatory sessions.

were not a problem. The momentary button itself got worn out because of the extended use. This required the participant to press harder and harder to strum the guitar. However it did not alter his motivation to play the guitar.

We visually inspected the audio wave to determine the error rate during the intervention. The flutter or beat offset were evaluated by comparing the beat to the actual strumming of the strings.

According to [25] we labelled strums that occurred more than 50ms before or after the backing track beat as errors. We obtained the onsets from visual inspection of the audio wave form. This was done by inspecting the audio wave form the video recordings of the participant playing along to the 60bpm and 120bpm backing track and comparing the peaks. The error threshold was set to a flutter of 50ms [2, 10], see Figure 5.

Figure 5 shows the percentage of synchronisation errors exceeding the threshold of ±50ms for each mandatory session and tempo. We reviewed the video of six strum outliers exceeding 200ms and excluded these from the data set. The outliers we removed were caused by small readjustments to the guitar position (n2), button interaction error (n2), or lack of concentration during play, e.g. looking at the researcher (n2). The synchronisation errors showed a steady decline during the intervention from 39 to 22% for 60bpm and from 51 to 17% for 120bpm, which conforms to the power law of learning [8].

The participant generally strummed later when playing to the 120bpm track than when playing to the 60bpm track, see Figure 6. The first session average from the 60bpm actually shows that he was also late compared to the following averages, and with anticipation bias in mind it is clear that this was not a sign of better performance. On day 17 of the intervention the final mandatory session had to be stopped as the participant struggled to activate the button to strum the guitar and gave up on finishing the session. It was decided that he could stop using the guitar and pick it up 5 days later when the intervention was scheduled to end. However, his motivation to play the guitar was so strong that he kept playing despite the failing button, see Figure 4. Logged data from the force sensor shows that the force required to activate a strum slowly increased during the intervention and during the sixth mandatory session required more than three times the force.

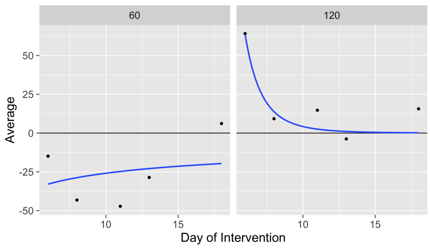

Figure 6: The synchronisation error averages per day in milliseconds from the mandatory sessions at 60 and 120BPM.

The QOL questionnaire showed a small QOL improvement in *Pain and Discomfort*, *Positive Feelings*, *Thinking, Learning, Memory and Concentration*, no change in *Sleep and Rest* and *Self-Esteem*, and a small QOL decrease in *Energy and Fatigue*, *Bodily Image* and *Negative Feelings*.

The results of the FIM test (108 out of 123) placed the participant on step 6 as a person having 'modified independence' on a scale going from 1 (Total Assistance) to 7 (Complete Independence). The score matched the participant's inability to use his right arm. He needed assistance with such tasks as buttering bread, cutting up meat, and putting on a t-shirt. The cognitive sub-part of the FIM test focusing on problem solving and memory showed that he needed supervision or assistance less than 10% of the time and that he often used an iPad or similar device to solve cognitive challenges.

6. DISCUSSION

The participant showed strong motivation to play the guitar long-term despite the inherent delay and reduced expressiveness as he played 14 free sessions over a total of 7.2 hours spread out across the three-week intervention. In addition to the time spent playing the guitar he also incorporated his former backing tracks stored in his old keyboard setup, which showed an even higher degree of motivation. We used a Synchronisation Error (SE) threshold of 50ms which was rather strict, as normal anticipation bias can be ±50ms. The participant learned to incorporate the inherent delay of the system as the SE showed a clear decline throughout the intervention. Fewer SE during the 120bpm backing track can partly be explained by the fact that the relative size of flutter increases with slower tempos [10] and thereby produces more SE when playing along to the 60bpm backing track. The SE average also supports the conclusion that he gradually learned the interface and the built-in delay, see Figure 6. The figure also reveals that he struggled more with the 120bpm tempo since the averages are higher (later) overall. According to anticipation bias [2], they should be around -14 to -50ms early.

In the future the data logger should be able to log the MIDI tempo data to get more precise and extensive data.

We did not consider the quality of the chords played, which could potentially tell a lot about how the participant coordinated the strum and chords. Any mismatch could affect rhythm and timing if the participant experienced it as disruptive and might have lost focus, which would affect the results. A visual and auditive comparison of the recorded video from the beginning and the end of the intervention reveal that his ability to coordinate the strum and and the fretting of chords improves immensely. Despite the profound latency of the system and the worn out button.

According to the power law of learning the SE should continue to decline based on the amount of practice/learning, but as seen in Figure 6 the SE average increased a lot during the fifth and last mandatory session. Figure 5 also shows an increase from 7 to 16% in the 120bpm tempo in SE percentage, exceeds the threshold. The increased force needed to activate the button most likely affected the data and could explain why the averages in both 60bpm and 120bpm increased in the last mandatory session.

The QOL questionnaire showed an increase in positive feelings, which fits well with how the participant used the guitar during the intervention and indicates that he was highly motivated and enjoying himself. Thinking, learning, memory and concentration also increased, which also fits well with the many sessions and hours played. Bodily Appearance and Negative Feelings decreased, which can seem contradictory as he was able to perform a task that he could not do before. The lower scores might indicate an increased awareness of his own situation and limitations. The QOL questionnaire did not have the sensitivity to reveal any conclusive improvements or changes in quality of life. In coming studies a more suitable questionnaire should be used.

While the current design was good for short-term use longer term trials would need to resort to higher quality to avoid wear.

7. CONCLUSION

The participant was able to play the guitar without support and only needed help for equip the guitar as it used a regular guitar strap. The mandatory session showed that the participant was able to play along to both the slow and fast backing track lowering his synchronisation errors with 17% at 60bpm and 34% at 120bpm. This showed that the participant was able to learn and compensate for the system delay of 45ms from pushing the foot pedal to the pick reaching the first string. Playing 14 free sessions for a combined total of more than 7 hours is a clear indication of the participant's motivation to use the Actuated Guitar despite the latency and limited expressive possibilities. Other indicators of a high degree of motivation was how the participant incorporated his own devices into the study. He used his iPad to find tunes on YouTube to play along too and used his old piano setup and P.A. with the backing tracks from the time before his stroke.

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