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).

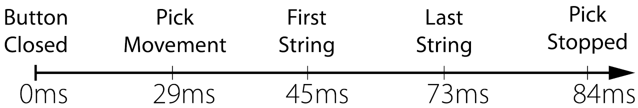

Figure 2: The total amount of time it takes from the button being pressed to the pick moving to the pick movement stopping.

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.

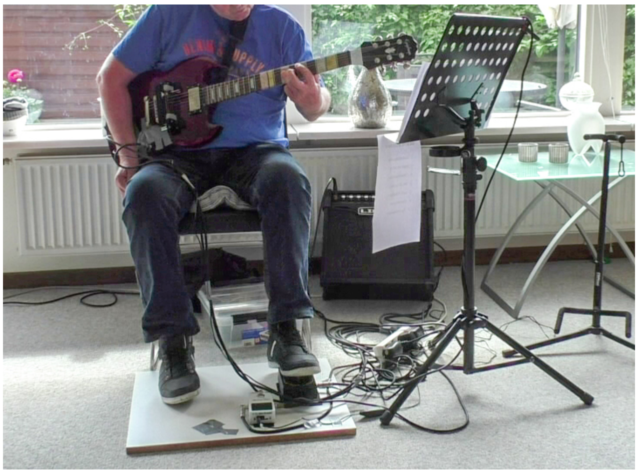

Figure 3: The participant playing the guitar during a free session.

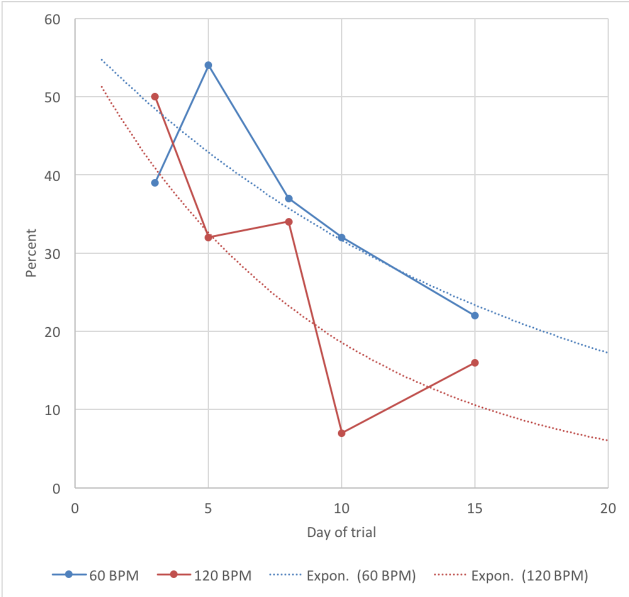

Figure 5: The percentage of synchronisation errors exceeding ±50ms in the mandatory sessions.

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.

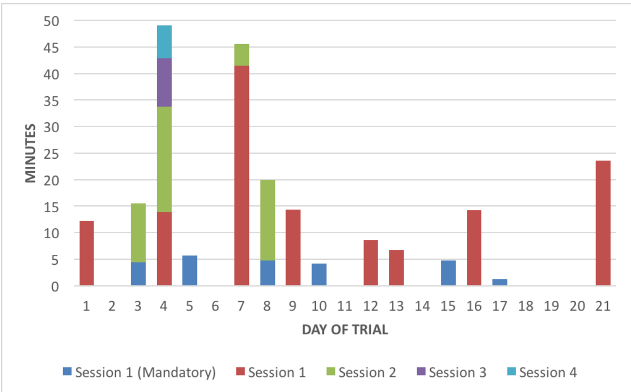

Figure 4: The total time spent per session during the three weeks of the intervention.

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 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.

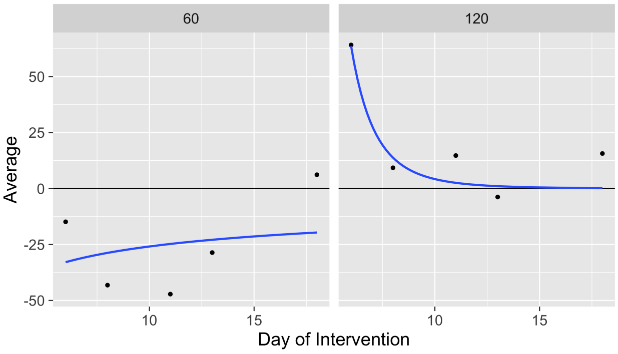

Figure 6: The synchronisation error averages per day in milliseconds from the mandatory sessions at 60 and 120BPM.

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 $\pm$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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