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Musical Instrument based on Visual Feedback of Left/Right-Hand Motor Imagery

Bachelor thesis



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STATUTORY DECLARATION

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ABSTRACT

A musical instrument was created using left- and right-hand motor imagery and visual feedback to control a virtual piano. The capabilities of brain computer interfaces as musical instruments were investigated with this device. Therefore, progression of performance and subjective opinions of users were analyzed over the course of two weeks. The foundation for the presented work was the idea of the Encephalophone of Deuel (2017). EEG of ten electrodes was recorded in order to measure motor cortex activity. Power of mu rhythm (10-13Hz) was calculated for electrodes C3 and C4 and the difference was used as control signal for a cursor moving across the white keys of a virtual piano. Every second the key under the cursor was played. Five volunteers worked with the instrument for six sessions each. One session consisted of a calibration phase (5 minutes), a free play phase (10 minutes) and an evaluation phase (5-15 minutes). After the experiments, the subjects answered questions to provide some insight into their experience and personal opinions. The evaluation of the accessible control signal range, the classification accuracy of left versus right and the number of errors while trying to play presented notes shows an initial decrease in performance, followed by an increase in performance after the third session. Three out of five subjects made significantly less errors than random in some sessions. In agreement with literature, two of the five subjects did not seem to have any control at all, so the device may not be suitable for everyone. Nevertheless, all users enjoyed playing the instrument and had a good time. Although the data indicated some training effects, there has to be further investigation for clarification. Some evidence suggested that proper instructions and proper understanding of the motor imagery task are crucial for success. The practicality of the instrument would benefit enormously from EEG electrodes that are easy and fast to mount. Common spatial patterns algorithm and linear discriminant analysis is proposed for improving control signal quality. Although there is still much work to do, the technology looks promising particularly for disabled people.

Keywords: brain-computer interface, music, motor imagery, neurofeedback, electroencephalogram

INTRODUCTION

As brain computer interfaces (BCIs) are becoming better, the question arises if they can be used for doing art. Especially for disabled people a new form of expression could be beneficial. But also healthy people could train their concentration ability or explore the functioning of their brain. A playful approach to bring BCI technology to broad society could lead to faster acceptance in the field. Music is great for exploring the artistic possibilities of BCI technology, because it can be reduced to very simple components. Rhythm and a few different notes is all it takes to make music worth listening to. Nevertheless all sorts of different and interesting sounds can be produced using virtual synthesizers. Here we want to answer the question, how well people are able to make music with BCIs. Therefore, a musical instrument based on the ideas of the Encephalophone (Deuel 2017) was created and tested with subjects over the course of two weeks. One critical characteristic of musical instruments is that people get better with training. So when performance increases over many training sessions, we are one step closer to prove the capability of BCIs as full-fledged musical instruments. We expect some increases in the capability to hit presented notes as people get more experience with the BCI.

Since data rates of simple BCIs do typically not exceed 15 bits per minute (Pfurtscheller 2001; McFarland 2003), thoughtful design must go with the development of a musical instrument. The user should enjoy the experience from the beginning but not get discouraged by errors. Deuel has found a solution for this issue with the Encephalophone. The instrument allows the user to play just notes of one musical scale. Most musical scales consist of notes with mostly small integer frequency ratios, which tend to sound pleasant when played together or soon after another. Therefore, using only one scale at a time, unintended notes usually do not sound unpleasant. Thus the subjective performance is less affected by errors.

The Encephalophone is a device which uses EEG signals for the generation of scalar music. To control the device, the user thinks about either the movement of his right hand or the clouds in the sky (Deuel, pers. comm.). This is a form of motor imagery which affects the mu rhythm (Pfurtscheller 2006). For electrode C3, which is nearest to the left motor cortex, the power of the 8-12Hz band is averaged over 500

milliseconds and used as control signal. The control signal range is divided into eight equally sized classes, each of them representing a note of a musical scale. This musical scale is configurable, the operator can choose between major, minor and various other scales. Every 500 milliseconds the note assigned to the class which is hit by the control signal is played. Rhythm cannot be controlled by EEG so far, but it can be provided by some external trigger. For evaluation the user has to hit the lowest or highest note or its nearest neighbour three times consecutively in about ten seconds.

Although the Encephalophone provides a good foundation, some modifications were made for this study. The Encephalophone distinguishes between motor imagery versus non motor imagery (clouds in the sky). Not thinking about anything is a form of meditation, which is powerful brain training. But it is also difficult and unintuitive and therefore not practical for control. We decided to use left versus right hand motor imagery as it is intuitive for playing the piano and easy to comprehend. We also chose to provide visual feedback, in order to further simplify the instrument. Visual feedback is superior to auditory feedback in training of control sensorimotor rhythms (Nijboer 2008). A group of subjects provided with auditory feedback learned slower, but reached about the same performance as the visual feedback group. Nijboer suggests that auditory feedback could be as efficient as visual feedback, with only enough training time. Well-designed continuous auditory feedback could theoretically replace the visual feedback without much performance loss.

For evaluation, we look at the objective performance of five people and their personal opinions over the course two weeks (six training sessions of about 30 minutes per person). Personal opinions are collected to get a feeling what people want and how they like the instrument. Since the subjects train with the instrument over a period of two weeks, change in performance can be investigated, but also some suggestions for improvement should come up. We decided on evaluating at least five people, because performance of different subjects is expected to differ quite a lot.

The distribution of interpersonal differences tends to be linear in BCI (Blankertz 2010), with some people doing really well and about 20 percent not having any control at all (Allison 2010). To observe some training effects, one session

should last at the very least 30 minutes. (Müller-Putz, pers. comm.). With the mounting and demounting of electrodes, one session takes about one hour, which is the maximal time we wanted to ask of our volunteers.

METHODS

EEG Recording

For EEG recording eleven Ag/AgCl electrodes were mounted with EASYCAP ABRALYT 2000 abrasive electrolyte-gel (EASYCAP GmbH, DE-82211) using the International 10-20 system (American Electroencephalographic Society 1994). A g.tec g.USBamp biosignal amplifier (g.tec medical engineering GmbH, AUT-4521) with a sampling frequency of 128Hz was used to collect the data. Reference and ground were both connected to the electrode Fz. To record activity of the motor cortex, electrodes C3, C4 and their surrounding electrodes C1, C2, C5, C6, FC3, FC4, CP3 and CP4 were connected. Data of these electrodes were streamed to lab streaming layer (<https://github.com/sccn/labstreaminglayer>) with the g.USBamp connector program.

Instrument and Signal Processing

The software for the instrument was programmed in Python 3.6 (Python Software Foundation), it connects to the provided lab streaming layer (LSL) stream. It interacted via MIDI with Synthesia 10.4 (Synthesia LLC, <https://www.synthesiagame.com/>), which is a software for learning the piano. The virtual MIDI cable LoopBe1 (Daniel Schmitt, DE-60327, <https://www.nerds.de>) was used for this connection. In order to estimate motor cortex activity for each side, power of mu rhythm was calculated for electrodes C3 and C4. For artifact reduction a spatial Laplace filter was used. Band-pass filter (10-13Hz) was applied and then the power was calculated. The average of the last two seconds was computed. Then the logarithm was calculated. The two signals were subtracted and used as control signal. For visual feedback, the signal value was displayed as a little brain moving over the white keys of Synthesia. The white keys on the piano correspond to the musical scale C major, consisting of notes C, D, E, F, G, A, B (excluding Notes C#, D#, F#, G#, A#). The lower and upper limits of this control signal which represent the left side of the lower C and the right side of the upper C were determined in a calibration phase. Every second the note under the brain was played via the MIDI interface. Synthesia also provides functionality to present target notes flying from the top down to the piano keys (figure 1).



Figure 1: Graphical user interface with Synthesia and Brain-Cursor

Study

Five subjects were tested over the course of two weeks. Each of them took part in six sessions. Before the experiments were started, they had been informed about the risks of EEG. The participation was voluntary and the subjects knew that they could end their participation at any time. They also agreed that the recorded data may be published anonymously. All procedures were in accordance with the Helsinki Declaration (World Medical Association 2013). At the end of the study all subjects were handed out a questionnaire about their experience and their opinions.

Before each session the subjects got instructions on motor imagery. The importance of relaxation and concentration was communicated. The elementary instruction was to think about the movement of the left or right hand without actually moving. The users should imagine movement of their left hand for low notes and his right hand for high notes. They were instructed to concentrate on the feeling of the particular hand, but not on the mental image of their hands moving. In order to make instructions more tangible they were given a lemon which they should gently squeeze once every second. They should imagine the same movement and feeling during the experiments, but also find out what exactly works best for them. At last they got instructions on the phases of each session. A session consists of three stages: calibration phase (5 minutes), free play phase (10 minutes) and evaluation phase (5-15 minutes).

In the calibration phase the subjects had to do motor imagery of each hand alternately. Every eight seconds the hand had to be switched. The built-in functionality of Synthesia, which presents target notes, was used to indicate the side. The low C was the hint for left hand, the high C was the hint for right hand. There wasn't any feedback provided in the calibration phase. All achieved signal values were sorted after the calibration phase. The lowest and highest three percent were discarded. The lowest and the highest of the remaining values were used as boundaries for the note mapping and the visual feedback. These boundary values were subtracted to get the control signal range for evaluation purposes.

In the free play phase the subjects could play freely to get a feeling for the instrument.

In the evaluation phase participants had to hit target notes. There were 310 notes to hit one after the other. After three misses the note was played automatically to prevent discouragement. The subject had three chances to hit a note. Every skipped note was counted.

Evaluation

For the evaluation of the study, the progress of several parameters throughout the sessions was observed. These parameters are the control signal range, the calibration accuracy and the total skips in the evaluation phase. The control signal range is calculated after the calibration phase. In order to calculate the calibration accuracy, the signal processing was applied to the control signal of the calibration phase with an averaging time of one second. The inner six seconds of the eight seconds of each hand were used as training data for LDA classification. With 10 times 10 fold cross validation the classification accuracy was estimated. To get an estimate of how many total skips the device would produce with random inputs, the control signal of the evaluation phase was randomly permuted in time and fed into the instrument again. For each of the 30 sessions this was done 1000 times. The highest and lowest 2.5 percent of the resulting 30000 values were discarded. The random interval was considered to be between the lowest and highest of the remaining values. The questionnaires were analyzed and summarized. The precise wording of all questions (in German) can be found in Appendix I.

RESULTS

Control Signal Range

The accessible range of control signal (maximal difference in band power of C3 and C4) was evaluated first. A clear negative trend at the beginning, followed by a positive trend towards the end is observable in the averaged data (figure 2). There are big interpersonal differences and the progression is not steady for single subjects (figure 3). At the last session, there is a prominent increase in range for subjects 3 and 4.

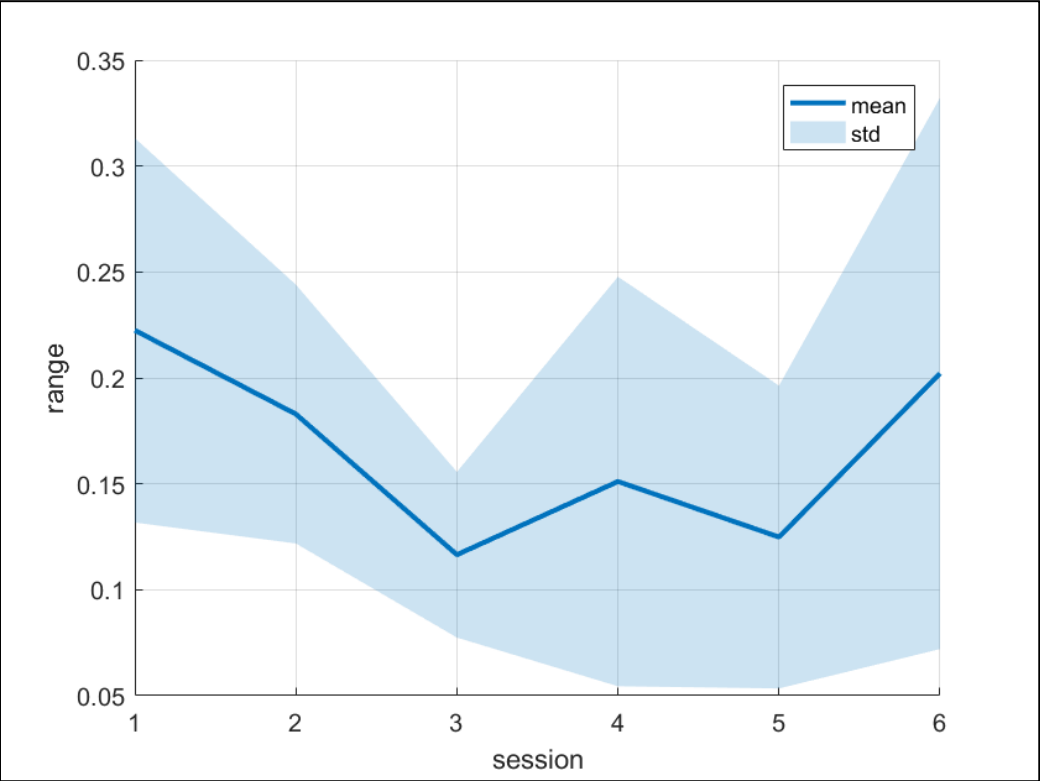


Figure 2: Normalized progression of range

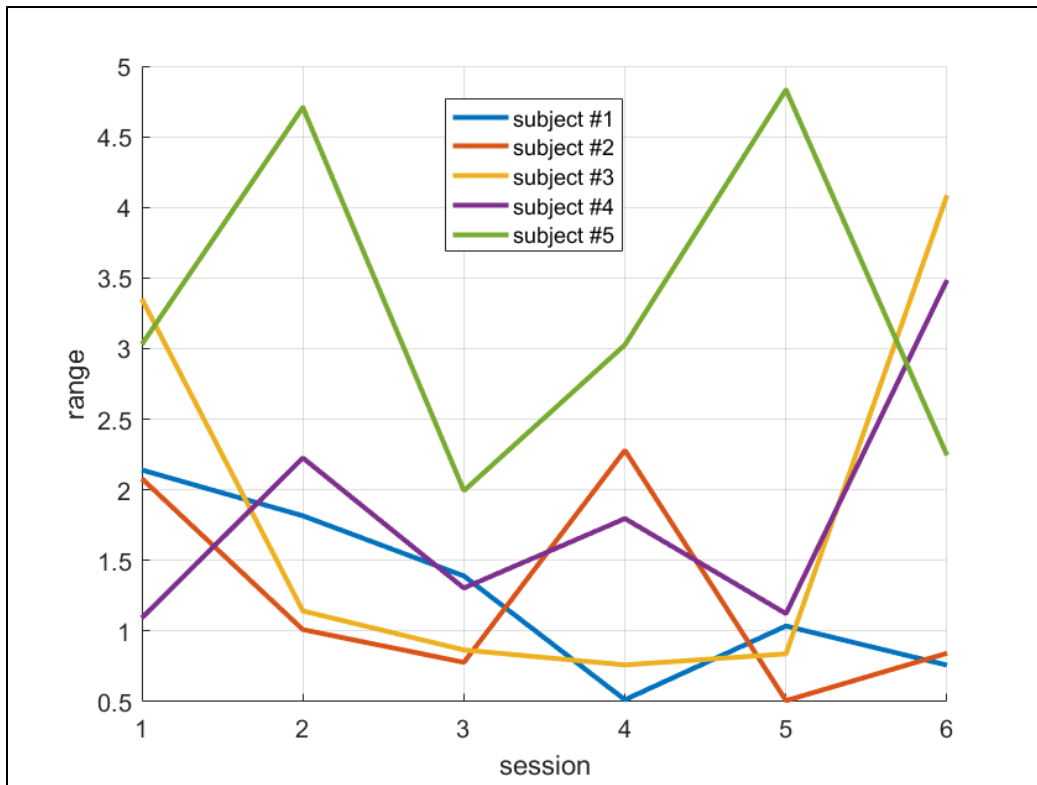


Figure 3: Progression of ranges for each subject individually

Calibration Accuracy

Evaluation of the progression of averaged calibration accuracy shows a decrease in performance at the second and third session, followed by an increase at the last three sessions (figure 4). Averaged calibration accuracy is higher at the end than at the beginning. Subject 3 shows a noteworthy increase in accuracy from 65% to 91% at the last session (figure 5).

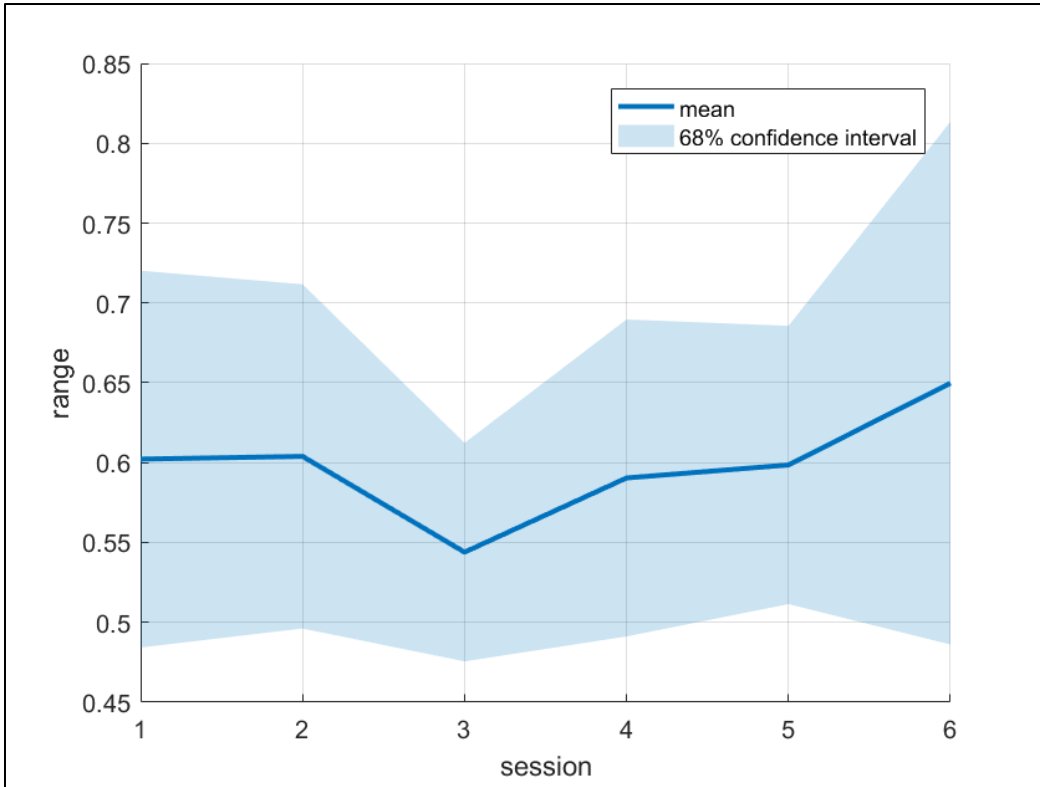


Figure 4: Progression of calibration accuracy

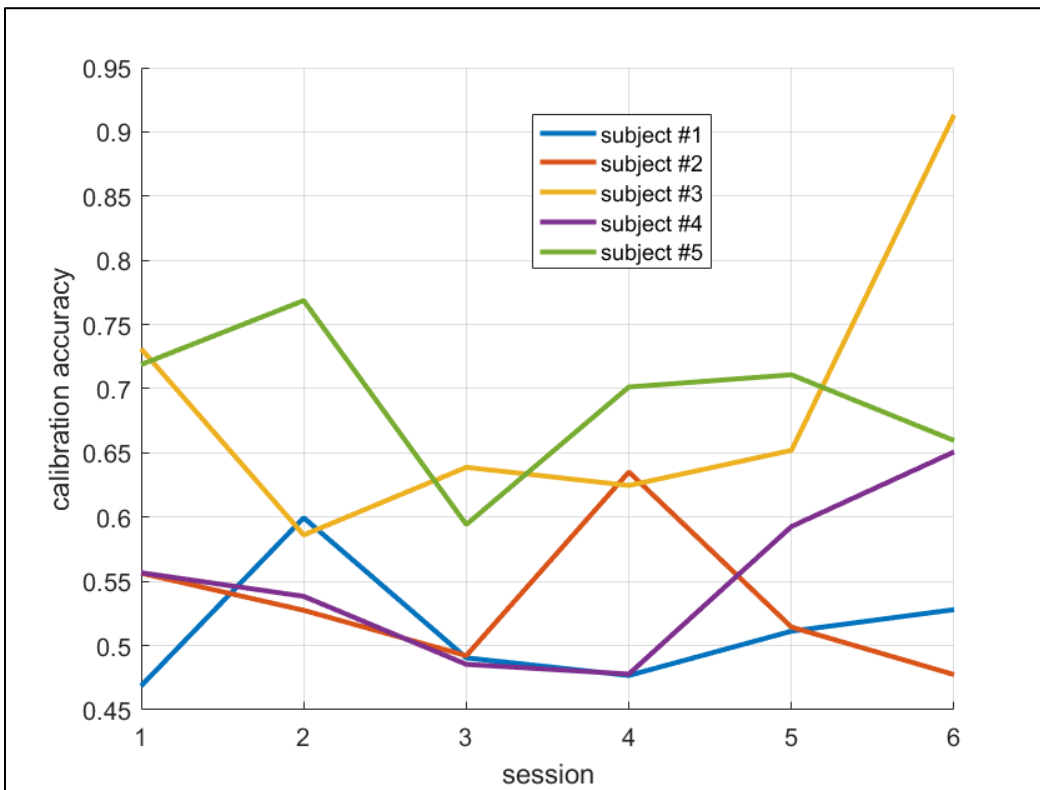


Figure 5: Progression of calibration accuracy for each subject individually

Skips

For good performance the number of skips should be as low as possible. Average skips show an increase at the beginning and a decrease after three sessions (figure 6). The average of skips is never below random, but the standard deviation drops below random at the first two sessions and at the last session. At the sixth session two out of five subjects are better than random. At the last session subject 3 skips less than half of the notes (figure 7). The simulation with permuted control signal values resulted in a random interval between 184 and 219.

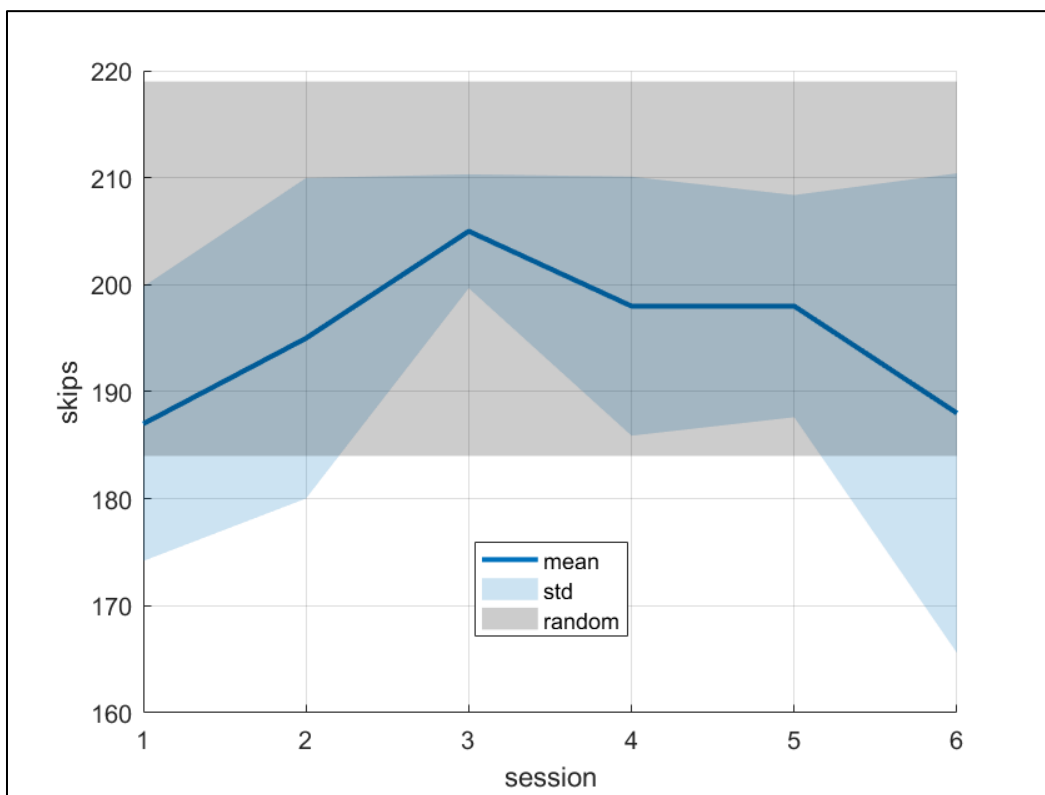


Figure 6: Progression of skips

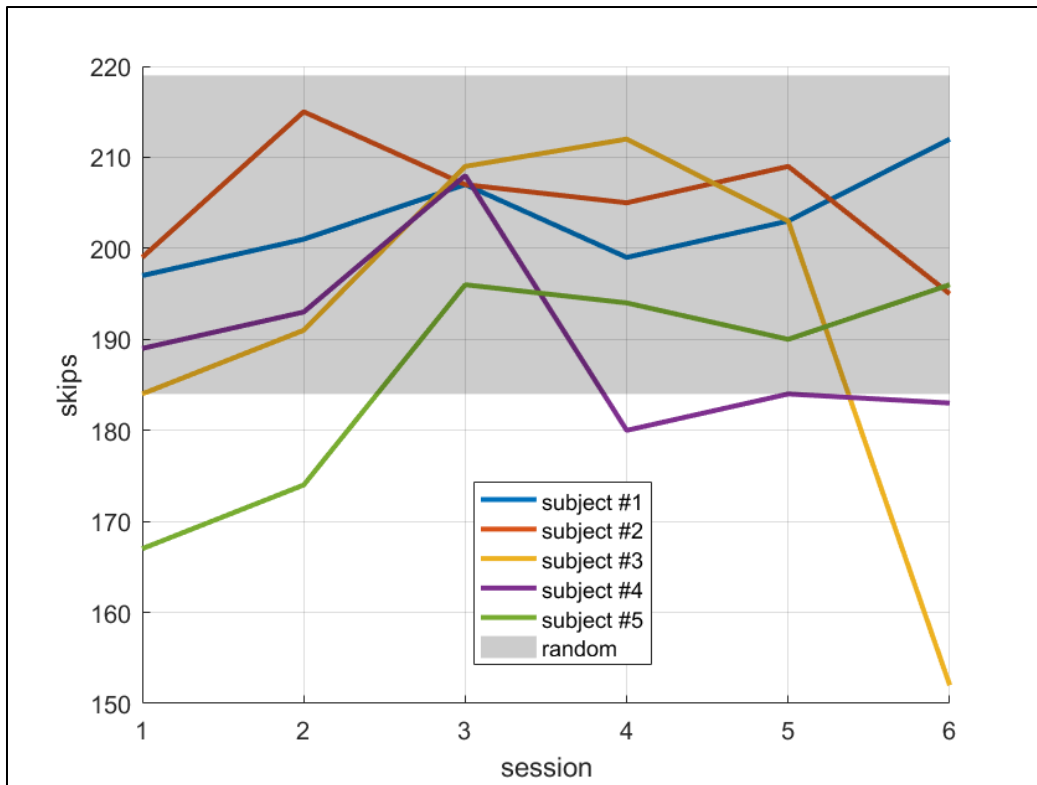


Figure 7: Progression of skips for each subject individually

Questionnaires

One questionnaire was received for each of the five subjects. All subjects enjoyed playing the instrument and had a feeling that they would train their ability to concentrate. One subject additionally mentioned that the more relaxed he was the better he could play. The subjects had the feeling of control in 0-2 sessions. Their subjective performance was not steady. Nevertheless, three subjects could sense a training effect. For three subjects the duration of a session was too long.

Some Ideas for improvement came up: to have breaks in between, make the scales and the delay adjustable, show feedback in the calibration phase and decrease free play time after some sessions. For healthy customers the instrument has to be cheap, easy to use and the cap has to be dry and fast to mount. The device should be versatile and able to control not only a piano, but also other instruments, games etc.

DISCUSSION

Progression of Performance

The evaluation shows an initial decrease in performance, followed by an increase after the third session. Maybe performance tends to decrease before improvement in learning takes place. The decrease could also be due to confusion of motor imagery in the beginning. Only before sessions one, five and six, briefings on motor imagery were given, so maybe the subjects forgot the correct instructions in the meantime. Instructions should have been consistent throughout the sessions. The increases in performance after session 3 could be interpreted as learning effects, but further studies are required for verification and clarification. In order to investigate the progression of performance sufficiently, some more sessions will be necessary.

Possible Improvements

The biggest obstacle to making the device utilizable for making interesting music is lack of rhythm. As long as there is not any rhythm, the instrument will always sound boring. It is difficult to provide the rhythm directly by the BCI, because it will never achieve the necessary timing accuracy. The simplest way to provide simple rhythm is through pauses. That means a second two-class BCI control signal could be used to switch between a predefined rhythm and silence. The instrument can also be controlled by more than one person, for example one controls rhythm and the other controls pitch. If people would use BCIs together they could share their experience and also compete with each other. This could result in more interest and pleasure.

The wet electrode system with abrasive gel is unhandy as it took about 15 minutes to mount ten electrodes. As long as electrodes take longer than a few seconds to mount or require washing hair afterwards, healthy people will not be very interested in the device.

The control signal was averaged over two seconds. This was too long and also the biggest mistake in the study, because people lose the sense of direct feedback, thus making it extremely difficult to control the cursor. One second would be better. With continuous feedback there comes also the possibility of controlling the speed of the cursor instead of the position of the cursor with an averaging time of only about

250 milliseconds. With this setup the position of the cursor represents the integral of the control signal. Advantages are very fast feedback without much wobbling, unlimited number of accessible notes, easily customizable control with a speed-factor, more intuitive user experience and the utilization of the own control capability of the brain.

In order to get good results regarding learning, there should be more time for the users to practice with the device. Roughly the first four sessions were necessary for some of the users to properly understand motor imagery. Feedback in the calibration phase and proper instructions could improve this. Using pauses and a dry electrode system, one session could be extended to one full hour without asking too much time of the volunteers. Five minutes of relaxation or meditation before the start of each session should positively affect the performance.

Common spatial patterns (CSP) algorithm could be used instead of Laplace filter. This is useful especially for people whose motor cortex activity does not project exactly onto C3 and C4. BCI performance is optimized for each individual. Electrodes can also be placed arbitrarily and the spacing between them could be increased. Linear discriminant analysis (LDA) could be used in regression mode instead of simply subtracting the two signals. A prototype with CSP, LDA and cursor speed control was already built with promising first results.

Conclusion

The device trains relaxation and concentration and brings awareness to body sensations. Rhythm has to be implemented and the device should also be tested with electrode systems that are easier and more comfortable to use. There has to be further investigation with all proposed improvements, but the technology looks promising particularly for disabled people. Maybe sometime even healthy people will benefit from this device, using it for amusement, mental training or to learn about brain computer interfaces.

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APPENDIX I

Hat Ihnen das Spielen am Instrument gefallen? Welche Aspekte besonders?
Was hat Ihnen am Instrument bzw. der Studie nicht gefallen? Was hat Sie gestört?
Hatten Sie das Gefühl selbst Musik zu machen?
Hatten Sie das Gefühl das kleine Gehirn mit Ihren Gedanken steuern zu können?
Hatten Sie das Gefühl einen Lernfortschritt zu machen? Beschreiben Sie den Lernfortschritt genauer.
Hatten Sie das Gefühl Ihre Konzentration zu trainieren?
Hatten Sie das Gefühl Ihre Fähigkeit zur bewussten Entspannung zu trainieren?
Glauben Sie das Instrument könnte Kindern gefallen?
Hat das Instrument Ihrer Meinung nach Potenzial für Menschen mit Behinderung des Bewegungsapparats (Locked In Syndrom, Querschnittslähmung, ...)? Wo sehen Sie den Nutzen und welche Verbesserungen sind noch nötig?
Hat das Instrument Ihrer Meinung nach Potenzial für gesunde Menschen? Wo sehen Sie den Nutzen und welche Verbesserungen sind noch nötig?
Haben Sie Ideen/Verbesserungsvorschläge? Welche?
Haben Sie eine Idee wie man durch ähnliche Steuerung nicht ein Piano sondern eine Trommel steuern könnte? Man müsste also den Rythmus steuern können. Bei dieser Studie war der Rythmus ja immer gleich.
Stellen Sie sich das Instrument als Produkt (EEG-Kappe + Software) vor. Unter welchen Voraussetzungen würden Sie in Erwägung ziehen es zu kaufen (Funktion, Benutzerfreundlichkeit, Preis, ...)?