

Brain-Computer Interface (BCI) – UX Design For Visual And Non-Visual Interaction by Mental Commands In The Context Of Technical Possibilities

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Abstract

How do we interact with the digital world in the future by only using our thoughts to interact?

To interact with the digital world, we use gestures (most common: swipe gestures), our voice, facial expressions, and mental commands. The latter has become more important by recent press releases about scientific achievements for example from Neuralink[1] using invasive technology to control a computer game by thoughts only.[2] Another study says an application can display text on a screen by just thinking about a word. [3]

Currently, BCIs are mainly developed for neurotechnology and healthcare. But it's a question of time when these services will be available for commercial products for everyday life. (Until then manufacturers have to minimize health risks and face privacy and safety regulations.)

The thesis is that in the future, you will be able to interact with your digital devices just by using your thoughts and you'll do much faster. This makes sense in a wide range of situations where you do not have a free hand (manufacturing, sports) or cannot speak (underwater). But for such services, you cannot rely on conventional visual design guidelines or interaction patterns, frameworks, or libraries.

Interacting with a digital service by mental command has a lot of advantages the human brain comes naturally with some specific features that force us to find a radically new way to interact with digital interfaces.

The following study introduces you first to conditions of working with mental commands, comparing invasive and non-invasive technologies, and later on comparing several possibilities of interaction patterns for a BCI of everyday usage.

Introduction

The present work deals with the idea of a future digital interface that can be controlled by thoughts only. Just imagine you have your hands free for other activities while you interact with a digital and a

physical reality that is merged within your field of view. The future will bring information from your phone to your face. [4]

My hypothesis and main motivation as a scientist is my belief in a hardware-free future. Currently, the digital world appears to us mainly on a square screen of a mobile or stationary device. But what if the visual design of a digital layer merges with our physical field of view? Google, Apple, Facebook, and many more currently working on the next generation of smart glasses for daily use of a mainstream target group. And what if technology is evolved to this that a light beam project directly into your eye so your brain makes one image out of a natural and an artificially light source. And what, if I can interact with the digital and the physical world only by thinking about it?

This of course also raises a lot of side questions concerning privacy issues, ethical, political, and legal concerns. This paper focuses mainly on current technological possibilities and sketches interaction for different samples.

This paper bundles the most important findings from two years of research.

1. Definition and basic terms of a Brain-Computer Interface (BCI)

This chapter deals with the question about the definition of a brain-computer interface and starts with a short excursion into the difference between interaction and interface design before the explanation of the basic functionalities, hardware, and software. Finally, the chapter summarizes the opportunities but also challenges in creating interactive applications for a BCI.

1.1. Definition of interaction and visual design in common

“Interaction Design (IxD) is the design of interactive products and services in which a designer’s focus goes beyond the item in development to include the way users will interact with it. Thus, scrutiny of users’ needs, limitations, and contexts, etc. empowers designers to customize the output to suit precise demands.”[5]

The conventional interaction by gesture is completely different from the interaction by thought and due to the not yet fully developed technology for measuring brain activity, this places completely different demands on interaction design, which in turn also have a direct impact on the visual design of a BCI.

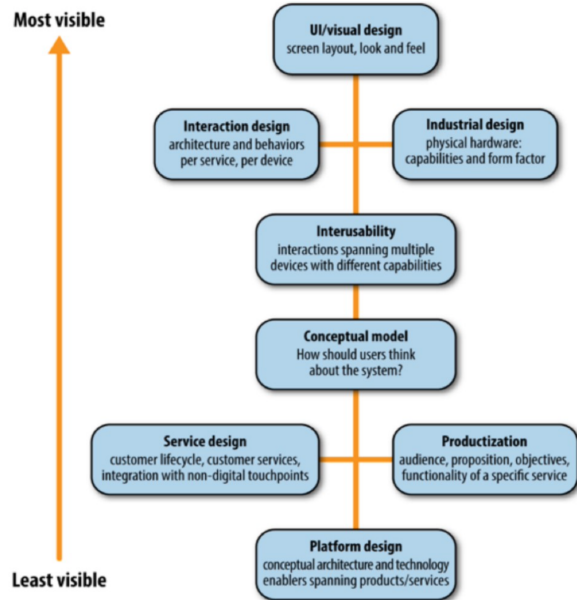


Figure 1: Designing Connected Products: UX for the Consumer Internet of Things [5]

1.2. Definition of a BCI

In short, BCI is the interface between the brain and the computer. These interfaces are usually established via specialized headsets, caps, or even in special cases with implanted chips in the head. The devices measure brain waves (electrical or magnetic) and this data is then evaluated and interpreted by a computer.

1.3. Invasive and non-invasive technology

There are two technologies to consider: Invasive and non-invasive technology. One of the best-known company in the field of invasive brain-computer technology is the US-Company *Neuralink*, founded amongst others by Elon Musk. This technology works by implanting a chip between your skull and your skin with surgery. *Neuralink's* main research field is on healing neurological disorders. Research by monkeys shows that the implanted chip is capable of much more: it can be used to control digital devices much faster than we currently do by interaction by gesture or voice.

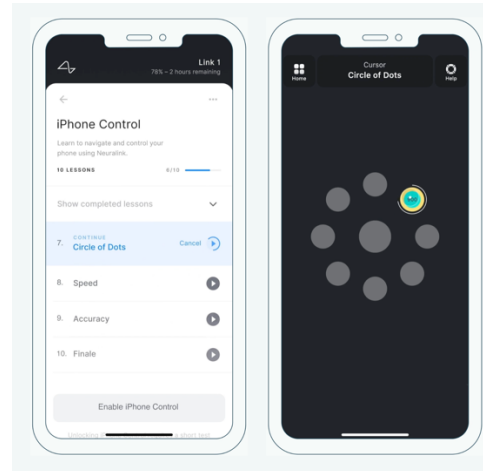


Figure 2: Visual Design of the BCI-App by neuralink.com to control invasive technology. Image from neuralink.com

For research, at the Technical University of Brandenburg, we use the non-invasive Technology of the US-company *Emotiv*. [6]

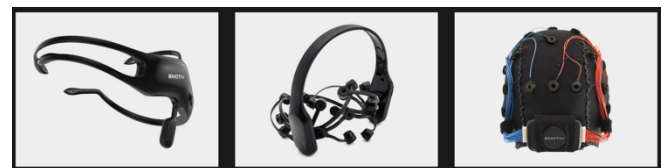


Figure 3: Three kinds of EEG-headsets: Insight, Epoch X, and Epoch Flex (from left to right) from emotiv.com

Because of the low consumer market penetration of BCI hardware to date and the focus on medical research, user interfaces for end-user software have been little studied.

For the measurement of brain waves, various techniques have been developed. The most commonly used is based on the measurement of electrical signals on the scalp. There are also techniques based on metabolic processes or magnetic fields. These are based on the measurement of blood oxygen levels but are much more complicated to measure and have a poorer response time.

For electrical signals, a distinction is made between electroencephalography (EEG) and electrocorticogram (ECoG). The EEG measures the corresponding brain current potentials using electrodes attached to the scalp. For this purpose, the voltage differences of the two electrodes are calculated with each other.

In the medical field, at least 12 different channels - i. e. 24 electrodes - are required for an EEG. For the non-medical field such as the BCI applications presented in this report, often fewer electrodes are used. These must be placed in specific locations on the scalp at a specific distance to function.

A classical EEG reaches a resolution of several centimeters, which means that the sensors also have to be placed at a centimeter distance from each other to avoid overlapping signals.

In contrast to the EEG, the ECoG works with a much higher resolution (less than one centimeter). This means that signals can be recorded much more precisely.

The higher precision is made possible by an invasive procedure. The sensors for the ECoG lie directly on the cerebral cortex and partially penetrate it. The poorer signal quality of the non-invasive technology is accepted as a trade-off for broader usability for most patients/consumers.

1.4. Foundations of the BCI

To understand a BCI, one must consider the various components of the system:

1. first in the processing chain is data collection, in this case, the measurement of electrical or magnetic fields of the head (in rare cases also chemical processes).
2. the measured values must be amplified and filtered to obtain useful data. These steps happen directly in the measuring device on the head. The cleaned data is then transferred to a computer via *Bluetooth* or cable in the 3rd step.
3. on the computer, the signals are interpreted and converted into commands. In addition, the recognized commands are also displayed to the user so that he has control over the application. Overall, the system is divided into many individual components, some of which are very complex, which must work together precisely and quickly to achieve a good result.



Figure 4: Workflow of a BCI (graphic: Kodalle)

1.5. Processing and implementation of brain data

The processing of the signals takes place in several steps:

- *Amplification of the signals.* The measured potentials are in the range of 5 to 100 μ V and must be amplified for further processing. This is done directly at the headset.
- *Filtering of the signals.* After amplification, filters are applied to the signal to remove possible interfering signals.

- *Quantification of the signals.* For processing on the computer, the digitization of the analog measurement signals is the next step. Here the values are measured with 2000 measurements / second and then converted into bit values. This procedure of the so-called quantification is also used for the digitization of audio signals.
- *Transferring of bit values to the computer.* The data transfer causes a certain delay, which can be improved by clever synchronization. For BCI applications, the bit values are examined for recurring patterns. When a previously learned pattern is detected, a corresponding signal is an output and this is passed on to the downstream software.

1.6. Interim summary

There are limits to the hardware we found out concerning:

- **Implantation technology** as from Neuralink (which has not been tested on human beings yet. First trials are planned for 2022 [7]. *BrainGate* researchers have already conducted tests with humans for medical purposes and in single cases only [8]. The conclusion is that in laboratories interaction by BCI is already much faster and more precise than conventional interaction by the gesture.
- **Non-implantation technology** (as used by us) can be summarized as:
 1. **Speed:** For the detection of brain wave patterns, the activity of many neurons within a certain time window must be recorded and digitized. Up to 2048 samples per second can be recorded. However, only 256 samples per second are then available to the user. By processing the command recognition, the speed drops even further, so that the *Emotiv* headset, for example, realistically recognizes 8 commands per second.

Conclusion: The execution of mental commands takes place with a time delay, whereby the user's ability to concentrate also plays a role. That is a problem with short reaction interactions.

2. **Signal Quality:** The second factor is signal quality. Depending on the design, the signal quality can vary. Invasive measurement methods have a significantly better signal quality than non-invasive headsets and caps. The number, placement, and conductivity of the electrodes can have a strong influence on signal quality. If the electrodes do not conduct the current well or are positioned incorrectly the signal quality will suffer.

Conclusion: brain signals might not be strong enough or not produce a clear signal.

3. **The interference signal:** Various electrical and magnetic signals can disturb the recognition. In particular, the frequency of 50/60 Hz can influence the measurements. The source of these disturbances can be reduced by the usage of various electrotechnical filters.

Wired BCIs have less interference - but are not particularly flexible in everyday use.

- The BCI Application:** Each BCI requires dedicated software to read, process, and display the data. The reading and processing of these are strongly connected to the hardware and therefore cannot be changed by the user in most systems. However, there are also open-source protocols and hardware that allow free access. There is usually no compatibility between BCI systems. This means that applications have to be adapted or rewritten for each system to be used.
- Data Processing:** Another limit is the processing of the data. Due to a lot of data and the fastest possible calculation. Currently, there are two different approaches for this: On a local level, the BCI can be connected to a computer that has the necessary computing power. However, this means additional costs as well as an increased maintenance effort. Another solution is to outsource the calculations to the cloud. All raw data is sent to a data center, processed there, and then sent back again. The advantage of this method is the low cost for the user. In addition, all types of end devices can be used to display the data, including smartphones, for example. However, this method can only be used with an existing and stable Internet connection.
- Practical use of the headset:** The next important experience is that to control a digital or physical product by mental power needs a lot of training and patience. First of all, you have to prepare the headset and fix 14 felt sensors that are soaked with a salty solution to the headset and then put it on your head. If you have a person helping you to adjust the sensors on the back head it helps a lot. The headset connects to your computer immediately and shows you on the screen which felt sensors have been successfully adjusted and which still need attention. Long or curly hair makes it much more difficult to receive signals and you do not have to worry about your hairstyling. After application of the headset it's ruined for sure and you should wash your hair.

Interim conclusion: Trying this with more than 56 students within 2 years we can state that 2/3 needed 15 minutes to adjust the headset at the first try until they got a solid connection. With the other third, it did not work at all, they were not able to create a stable connection.

2. BCI training software

After the headset is successfully adjusted you can start with the training. You have to register at [emotive.com](https://www.emotive.com) for free first. The moment you start your first training a colorful cube is being displayed on your screen. You can choose which command to train first. You can train neutral, push, pull, lift and drop by default. Training with 50 students lets us find out that the chance of successfully interacting with your digital service you should not try to train too many commands. The result will be non-specific. We recommend neutral, push,

left, right and pull. With these commands, you can interact with any service.

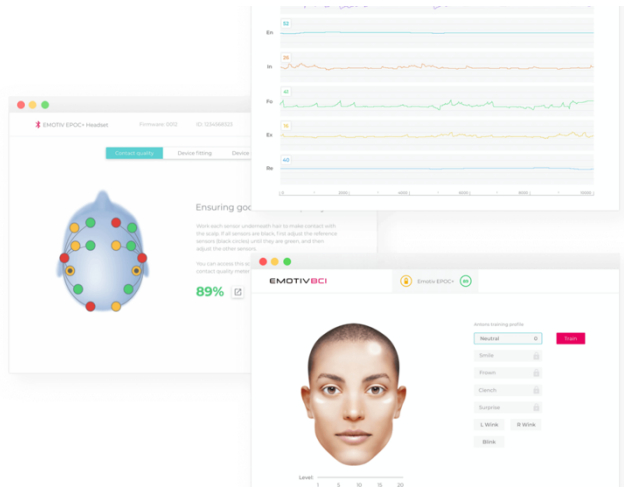


Figure 5: Visual Design of the EmotivBCI Software for BCI. Screenshots from [emotive.com](https://www.emotive.com)

The first time you start training, your training results might not be very helpful. After each try, the BCI gives you a result telling you how intense the signal was you created, and it advises you to try again. The software summarizes your successful training commands by using a Machine Learning algorithm. As soon as you have enough training sessions, the software will tell you and you can apply your new skills to your real project.

We conclude that it takes a minimum of 3 but not more than 5 sessions for a successful training unit of one command. One training session lasts for about 10-15 minutes, after that you feel completely exhausted, and many students claim to have a headache. Our brain is not used to focusing and concentrating in this way over a longer period. One of my Bachelor-Students worked on a combination of processing with computational design and a BCI and did daily meditation classes to be able to work with the BCI for up to 40 minutes without a break.

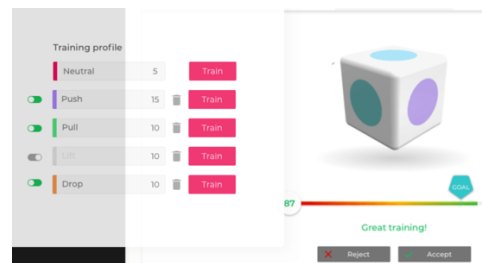


Figure 6: Visual Design of the EmotivBCI Software for BCI. Screenshots from [emotive.com](https://www.emotive.com)

Also, the first attempts might not show any good results. The cube on the screen does not move. But after several attempts suddenly you manage to move the cube on the screen, you lift it or turn it, or push it in one direction. Once your first time manages to interact with the cube on your

screen just by using mental commands feels like magic and every one of us was overwhelmed by this experience.

3. Software & API for a BCI

There are several interfaces to connect your application to the headset:

Nodered.js For the Node-RED-Environment (Node-based programming without the need of writing code) there are custom-made javascript-based libraries, f. e. the Emotiv BCI Node-RED Toolbox.

For more possibilities and complex work emotive recommends the Cortex API **which** is built on JSON and Web Sockets, making it easy to access from a variety of programming languages and platforms such as C#, Python, and JS Frameworks.

Emotive BCI Open Sound Control enables you to connect your headset and convert multiple data streams to a universal OSC format, giving a real-time multimedia control.

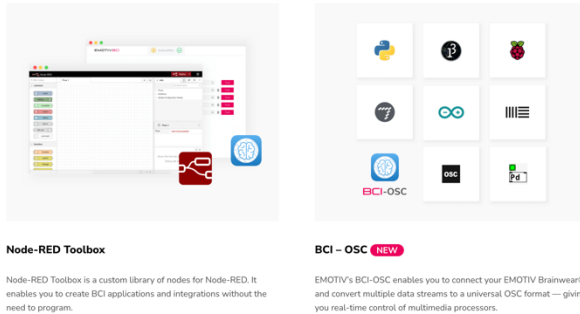


Figure 7: Visual Design of nodered.js Interface. Screenshots from emotive.com

4. Interaction Design for a BCI

The term *Interaction Design* is widely known as a way to navigate through a digital application. Still, many people talk about *clicking a link*, although more and more swipec through services, use voice in smart homes, navigation systems, and use gestures in spacious design applications as in Mixed / Extended Realities.

There are common rules about User Interface Design, f. e. Visual Design has to match the expectations of the target group. It has to be consistent regarding the color system, Fonts, Icons, and other visual elements:

- It should be understood intuitively.
- It should give feedback and status reports
- And many more (it would fill another lecture to complete this list)

But does it make a difference to create an Interaction Design for a BCI? All previously mentioned guidelines also apply to this. But there are three main factors you have to consider:

- It is helpful for the user to see a mental command has been sent (process bar)

- There are only 4 pre-trained commands to move the “cursor”. The whole information architecture should be based on this principle to make it accessible
- Because navigation by mental command is not fine-tuned, you need large buttons and interaction fields, otherwise, your thoughts might miss them.

5. Practical examples

The following three student examples show a successful interaction and user interface design for a BCI:

5.1. Controlling a Smart Home + with a BCI - Hub for smart home components realized through a Brain-Computer-Interface

Eric Dietzsch, Peer-Lucas Jeske, Derk-Janko Blauert
Project work in 5th term course of studies Applied Computer Science B. A. Seminar: “Cross-Device-Interaction”

Project description: to combine the now widespread solutions from the field of smart homes with a BCI to make the advantages of home automation and digitization available to people with disabilities. They will then be able to control basic devices in their environment without assistance and thus come to a step closer to the goal of self-determination. Our application is to be implemented on a vendor-neutral basis using an open solution that allows many different providers to be connected by *home-assistant* [8]. The following use cases are conceivable for implementation:

- Control of heating
- Control of light - In addition to the pure control of lamps, I could also include a control of notification lamps for the nursing staff (red = "I need help", green = "Everything is fine.")
- Control of doors

The following figures give a short impression of the visual design and technical implementation of a BCI application for a smart home environment.



Figure 8: Detail of a flowchart for a Smart Home Application by BCI. Image: Dietzsch, Jeske, Blauert

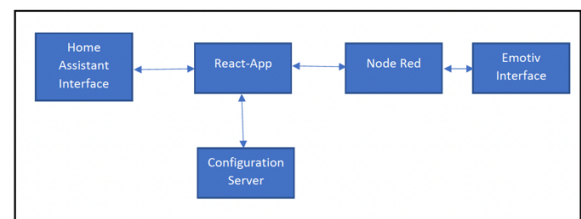


Figure 9: Workflow and technology of a BCI implementation to a smart home. Image: Dietzsch, Jeske, Blauert

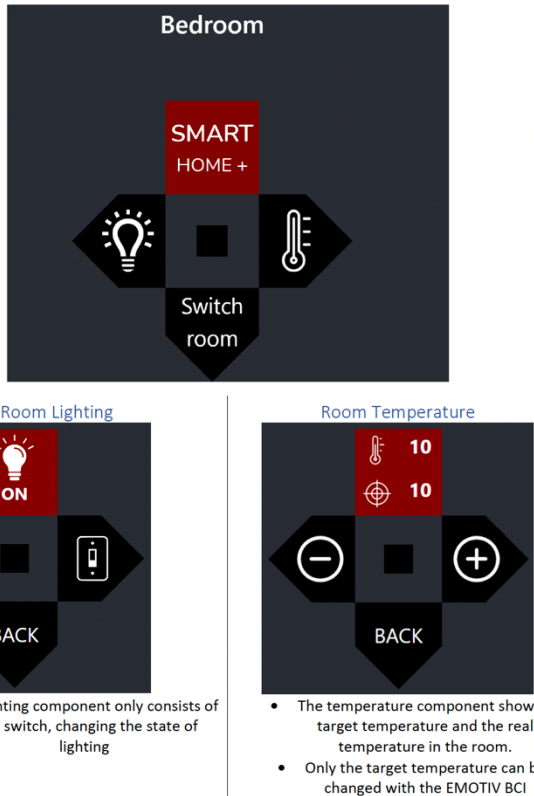


Figure 10: UID elements for a BCI implementation to a smart home. Image: Dietzsch, Jeske, Blauert

Outcome: Controlling a smart home with a BCI can be a solution for people who cannot stand up or are unable to provide input by voice or gesture. For use by a broader target group, the current application is not yet competitive with conventional smart home applications or input via Siri / Alexa or other voice assistants due to the effort required to set up the headset and the time delay.

4.2. Brain Music - Playing bass guitar with a BCI using an Arduino Board and Lego

Project work within an internship by Luis Rothenhäusler, student of B.A. Applied Computer Science.

Project description: this project focuses on using a BCI with mental commands to not only control a digital interface but a physical object. In this case, an artificial finger, building with Lego bricks, should hit a bass guitar string and create a sound. To enable this the nodered.js toolbox sends commands to an Arduino board.

First, the EEG data is collected. The raw data are analyzed live and translated into digital signals. These signals are translated into mechanical impulses. The mechanical impulses cause the hardware on the electric bass to vibrate the strings and thus produce tones. The collection of the EEG data happens using the EMOTIV Insights. The evaluation of the digital signals is done by the Cortex API, as well as a Node-RED instance. The conversion of the digital signals into mechanical impulses is the UNO R3. This drives four servos

and one motor, which are responsible for the sound generation on the electric bass with hammers.

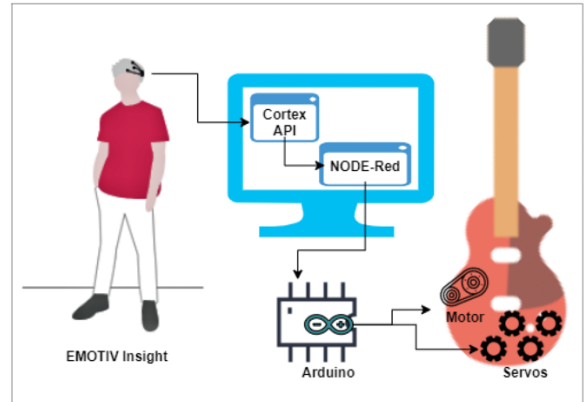


Figure 11: Concept of implementation for the implementation of playing bass guitar by mental commands via an Arduino board. Image: Luis Rothenhäusler

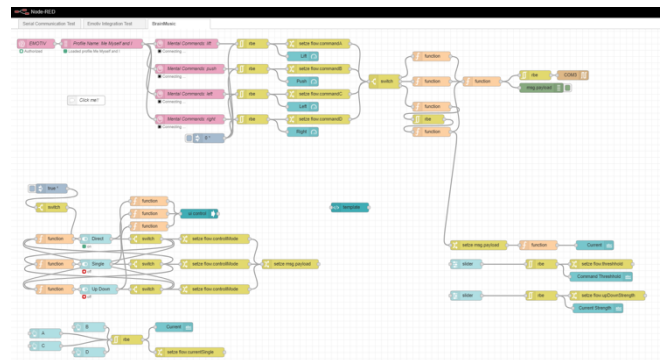


Figure 12: nodered.js toolbox for the implementation of playing bass guitar by mental commands via an Arduino board. Image: Luis Rothenhäusler



Figure 13: View of the finished application. Foto: Julia Schnitzer

Outcome: Special feature of this project is that a physical object can be controlled via mental commands. The connection via nodered.js to the Arduino board was relatively easy to accomplish. The construction of the artificial finger, which strikes the string of the bass guitar, caused problems. Here it is important to define the correct tension and hardness of the impact. Due to the time delay in the transmission of the mental

commands, no musical feats are possible with this technique and the human finger is not easy to replace. However, the work vividly demonstrates that it is theoretically as well as practically possible to play instruments by mind control.

Github repository: <https://github.com/StyxOo/BrainMusic>

4.3. Brain-Controlled Media Player: Controlling your Spotify Playlist by mental commands

Project work by Robert Beilich, Timo Boersch, Rick Lüdicke, students of Applied Computer Science M.A., course “Interaction Design”.

Project description: The aim of this project is to lay the foundation to integrate BCIs with already existing services that also have a benefit for non-disabled people to give the field more traction. The implementation of the media player consists of two main components: Integrating the BCI *Emotiv Epoc* into the system, generalizing the various input signals into well-defined outputs, readable by all manner of applications; and a graphical and audio user interface to interact with a media streaming service via the before-mentioned integration. For this project, *Spotify* serves as a representation and is integrated into a *React* web frontend by utilizing its *Spotify web playback SDK*. [10]

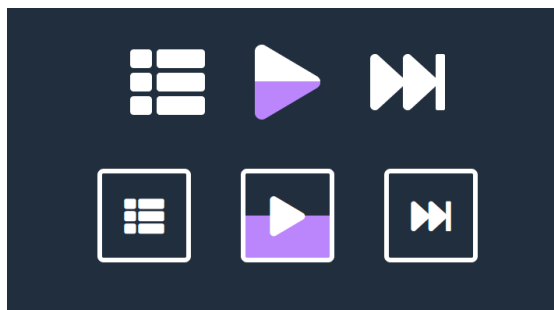


Figure 14: Designing buttons for the Spotify BCI application that includes a process bar (violet) that contains the strength of the mental command. Image: Beilich / Boersch / Lüdicke

Outcome: A fully functional web-based media player was developed and integrated with a BCI, offering a real social and technological value. Efforts were made to provide an accessible and well-designed UX, allowing easily understandable and adjustable brain-controlled interactions with the media player for all potential target groups, with a corresponding style guide for further development of the application. The application’s accessibility aspects have been set in correlation to the WCAG, illuminating its emphasis on assuring accessibility for a wide variety of individuals. Additionally, the partial rewrite of Emotiv’s SDK — especially the TypeScript typing and the handling of the BCI API’s calls and responses regarding mental commands, headsets, profile, session, etc. — is independently extractable and publishable, offering more functionalities, conveniences, and bug fixes than the previous implementation, while also removing its dependency on node-red. In further development, the remaining problems have to be remedied, and to prepare the application for general availability, adjustments according to Spotify’s style guide, have to be made. Besides that, the client ids and secrets for Spotify and Emotiv need to be hidden from the end-user and therefore some kind of server-side rendering has to get deployed. This can be

achieved with for example Next.js, which has a detailed guide to convert a React app, that was bootstrapped with CRA, into an application working with Next.js.

Regarding the Emotiv SDK, error handling needs to be implemented and refined, and the remaining not covered parts of the SDK, e.g. the BCI-lib.js, still need to be rewritten.

Github repository: <https://github.com/RobertBeilich/emotiv-sdk>

6. Press releases and related links

About this topic our two years of research also had some attention from the press:

1. Press-release of *Märkische Allgemeine Zeitung*, <https://www.maz-online.de/Lokales/Brandenburg-Havel/Keine-Zauberei-Brandenburger-Studentenschalten-Licht-mit-dem-Hirn-ein>
2. Podcast: *Große Fragen in 10 Minuten – Wie wird die Zukunft?* ARD audiothek. 23. April 2021 <https://www.ardaudiothek.de/grosse-fragen-in-zehn-minuten/wie-wird-die-zukunft/88564948>
3. Wiley Analytical Science Magazine, “Die Kraft der Gedanken – Interview mit Prof. Julia Schnitzer“ 27. Mai 2021. <https://analyticalscience.wiley.com/do/10.1002/was.000600119/full/>
4. Video: *TedX-talk “Über das Verschwinden der Hardware”* <https://www.youtube.com/watch?v=3jD4C8II4S8&t=369s>

7. Final Conclusion

There are still several serious issues about interaction with a BCI that make daily use currently difficult:

- Commands are still lagging with a non-invasive solution
- Complicated application
- Expensive
- No light wear Smart-Glasses open source available currently
- many necessary training sessions
- Ethical issues have to be solved
- Privacy and data security has to be ensured
- We are still far away from a mainstream solution for a BCI

But despite the many shortcomings of the system and unanswered ethical and legal questions, the importance of interaction via mental commands is already significant. It has been proven that, if successfully implanted, interaction with digital services can be many times faster, more precise, and more efficient. It is therefore only a matter of time before this technology can also be used for humans. For the time being, its use will primarily be in the medical field of neuroscience. Only in the

following years will an expansion of the technology in the mainstream be possible. Privacy, data protection, and ethical issues must be adequately addressed in advance. Also, many people will always be skeptical of invasive intervention. Whether an equally efficient application can be developed non-invasively in the future is completely open at this point. For acceptance by the general public, it is essential that such a technique can be switched off at any time at the user's discretion. My conclusion is therefore that BCI will bring a lot of relief in the medical field, but in the private field, it remains fiction at the current state of research.

8. Outlook

My vision is that of an increasingly hardware-free future. Our digital field of vision will expand and become detached from rectangular screens or smartphones. Smart glasses or accessories that allow us to project a digital image onto our retinas via artificial light beams will replace conventional devices. Our digital field of vision will merge with the physical one. The term virtual reality will no longer be accurate, as a reality merged with physical reality is no longer purely virtual, but real throughout. Our definition of reality will change; I like to talk about augmented reality and augmented intelligence here. Also shortly, we will interact with Extended Realities using gesture or voice, facial expression, or eye movement. To have our hands free in the future, interaction via mental commands would be the perfect complement, but as this work proves, it is still pure fiction at this point, as long as one does not want an invasive intervention. You will just think of yourself through digital layers.

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Born in Vienna, Austria. Julia Schnitzer is a Professor for Digital Media (research area: Interaction Design) at the Faculty of Informatics and Media at Technische Hochschule Brandenburg, Germany. She's the program coordinator of Master-course Digital Media M.A. Courses: Designing Interfaces for Internet-, Mixed Reality-, BCI -, Machine Learning- & AI-applications. Frontend Development and Processing, Human-Centered Design. Research in Brain-Computer Interface and Mixed Reality.

Member of the "Flying Faculty Program", visiting professor at German Jordanian University, Amman, Jordan.

Since June 2021, she is elected chief equal opportunities officer of her university. Member of the student council of the faculty of informatics and media.

Jury member of the Annual Multimedia Award Germany. <https://www.annual-multimedia.de>

Diploma-degree in Communication Design at HBK – University of Applied Arts, Brunswick and Erasmus scholarship for Graphic Design at Camberwell College of Arts, London.

Professional career: berlindesign.net, seller's platform of Berlin-based product design, was awarded as "Place of Ideas" by German President Johannes Rau in 2009. Former member of the Creative Industries Steering Committee of the Berlin Senate Administration. The external reviewer at DAAD and a jury member in the Annual Multimedia Award.

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