

Enabling General Applicability for Brain-Computer Interface Software Through Cloud Computing

Definition and implementation
of a neural/cloud interface



Daniel Burger

Department of Web Development
Middlesex University London

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Abstract

This is a rough draft of the abstract (not intended for reader as of now): There are various types of neural interfaces. There are various types of software for neural interfaces. There are various types of users for neural interfaces. The advantages and disadvantages of using local software versus software running in the cloud. A neural/cloud-based interface is defined as a production-ready and mainstream-ready BCI application in this thesis. Connecting web-based BCIs to the future of software, moving towards 3D and spatial computing, and how the web can play an essential role alongside BCI unobtrusive BCI technologies. Paradigm-shift for BCI software and 3D software running in browsers.

The goal is to provide a comprehensive overview of a neural/cloud interface and the components that comprise it. To lay the groundwork for future developers based on empirical technical experience in developing a real-world neural/cloud interface for IDUN Technologies' in-ear EEG sensor product. As part of this project, a public example code is provided.

We also discuss 3D on the web and the implications for human-computer interaction with a BCI based on a neural/cloud interface. Demonstrating the potential for additional use cases and the future of BCI software, web applications, and 3D software.

*This work is dedicated to the **IDUN Technologies team**, who have been extremely helpful in my journey into the neurotechnology industry. They taught me a lot about working in a scientific setting and allowed me to investigate various aspects of non-invasive brain-computer interfaces in combination with cloud computing.*

*Additionally, I would like to express my sincere gratitude to **Dr. Cao Tri Do**, who advised me and patiently taught me a great deal about the theoretical aspects of neuroscience, which was essential for completing this thesis.*

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Chapter 1

Introduction

This chapter introduces the reader to this thesis's primary focus, key topics, and broad explanations. It also displays the research question, goals, and objectives of the thesis's primary content and structure.

1.1 Background

There has been a long-standing interest in developing neural interfaces, systems that sense and interact with the nervous system's electrical activity. Successful research into the development of technologies that enable neural interfacing has been going on for decades, with the first experiments being conducted by Jacques J. Vidal in the late 1970s (Vidal, 1977). In particular, a related discipline focusing on the direct interaction between brains and computers via a brain-computer interface (BCI) has accumulated much momentum since the popularity of companies like Neuralink.

One aspect of BCIs is the development of imaging technologies that enable the measurement of brain activity. A distinction is made between different methods of measuring brain activity signals at different locations, such as invasive and non-invasive sensors. Whether it is an invasive sensor, such as in electrocorticography (ECoG), a method which uses electrodes placed on the surface of the brain, or a non-invasively placed sensor on the body, such as in electroencephalography (EEG), both methods measure the electrical field elicited by the firing of neuronal populations; however, with decreasing spatial precision, the farther the electrode is placed from the brain, the more tissues (e.g., bones) are between firing neurons and the measuring sensor.

The other aspect is the development of software that reads and interprets data from, e.g. sensors. Both aspects present their own set of challenges and complexities. Nonetheless, complete and applicable BCIs work in practice and have been used for many years in patients with neurological disorders (BrainGate, n.d.). There are also consumer and non-clinical BCIs available, such as the OpenBCI and Neurosity products, which aim to democratise the use of EEG sensors by offering low-cost hardware and open-source software.

1.2 Relevance

The possibilities for directly connecting the human brain to the outside world via or with computers are seemingly endless, given the (purely physical) assertion that all of our feelings, memories, dreams, and thoughts are most likely the sum of electrical activities in our brain. There are several use cases for utilising insights from our brain to interface with computers, such as controlling prosthetic limbs for amputees as shown on Figure 1.1, enabling communication for people with locked-in syndrome¹ (Chaudhary et al., 2022), or diagnosing neurological problems and improving the mental capacities of elderly patients (Belkacem et al., 2020) are promising examples, to name a few.



Fig. 1.1: Les Baugh, an amputee, is using his mind to control two robotic arms to perform several tasks that require fine motor control of his fingers and arms (Campbell, 2014).

¹Lock-in syndrome describes the paralysis of all voluntary muscles in its entirety, therefore making it impossible for people to communicate with the outside world.

It may appear evident that BCIs can significantly impact the field of therapeutics and accessibility for a small subset of the human population. However, one can envision not only alleviating deplorable living conditions but also improving the lives of healthy people through more natural or efficient ways of interacting with things or by directly altering human brains for certain benefits such as the possibility to enhance or delete bad memories (Spiers & Bendor, 2014) or record and guide dreams (Haar Horowitz et al., 2020).

Many use-cases still seem a long way from being applicable today, yet many capable people and even entire companies are developing BCI hardware and software aimed at the general population, such as, e.g. Neuralink (Urban, 2017). The general applicability of a BCI system to the mass market will depend on several factors, of which the form factor and invasiveness of the hardware are likely to be essential aspects. Nevertheless, the totality of the ecosystem in which the software resides is a valuable aspect that should not be overlooked.

1.3 Research question

Whether it is a bidirectional and invasive BCI or a unidirectional and non-invasive BCI, the data collected from the brain would always need to be processed, contextualised, and classified to produce an intelligible output to interface with things as shown on Figure 1.2.

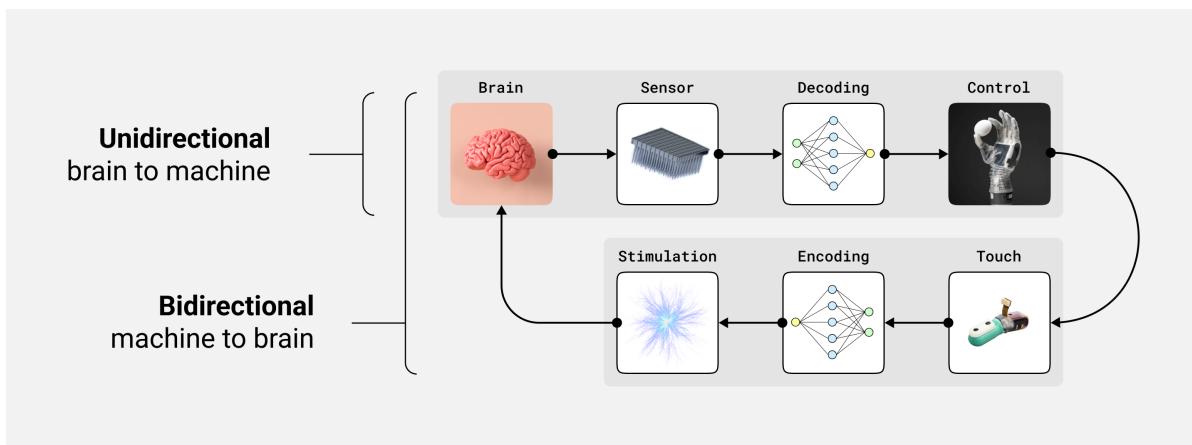


Fig. 1.2: Conceptual difference between a unidirectional and a bidirectional BCI and a simplified overview.

Most current BCI software systems being developed, e.g. for a BCI implanted in a living patient, are typically deployed in a local environment, i.e. the software system and its components are located on a physically nearby computer.

The author sees the opportunity to move BCI software from local environments to the cloud to enable a variety of benefits for the general population and mass-market. The research question of the present thesis is on determining what components such a cloud-based and mass-market-ready software system would require. The emphasis is on a holistic view of such a system, which means that the entire technology stack and context are taken into account in answering the research question.

1.4 Hypothesis

There is already promising research on implications of brain/cloud interfaces (B/CI) by Martins et al. (2019) or by Angelica et al. (2021), which analyse bringing hypothetical large-scale BCI software systems into the cloud. Nonetheless, their research focuses on speculations based on hypothetical scenarios in the future, usually based on the premise of other developed technologies such as neural nanorobotics, vital advances in 5G, or the presence of supercomputers in the cloud, e.g. for the augmentation of the human brain, and are thus somewhat distant from today's pertinence. To distinguish the research presented in this thesis, the author coins the term neural/cloud interface (N/CI), which refers to a holistic software system that connects a neural interface device such as a BCI to the cloud and then to other neural interfaces, software systems, or physical devices.

The primary hypothesis is that a N/CI is feasible with contemporary software technologies, requiring only theoretical groundwork based on empirical software engineering. To shed more light on this, this thesis looks at the process and lessons learned from the author's perspective in developing a real-life N/CI in the industry.

1.5 Goal and objectives

The overall goal of this thesis is to give the reader an overview of the definition of a N/CI and the software components that make it up. In order to achieve the goal, the author must achieve the following objectives:

1. Describe the motivation and context behind creating a N/CI.
2. Establish a clear definition, distinction and advantages of a N/CI.
3. Identify and define the most relevant aspects required to realise a N/CI.
4. Illustrate an example architecture of a N/CI to implement its components in practise.

Chapter 2

Research context

This chapter describes the research question's context and the current literature findings. The reader is educated on neuroscientific limitations, the state of current non-invasive BCIs, the motivation for developing cloud-based BCI software for the general population and the broad definition of a N/CI.

2.1 Limitations of BCIs

The possibilities of BCIs are not without limitations. In addition to the hardware limitations, the author addresses a broader issue related to neuropsychology that directly correlates with the software aspects, in addition to the challenges of computability.

2.1.1 Decoding neural data

It is important to emphasise that the task of decoding neural data is different from decoding thoughts, which is a critical factor for software. Moreover, decoding neural data and extracting the thoughts behind it so that the software can understand them are disciplines on their own. For example, getting computers to recognise letters written on a photograph is a very different problem from reading the written words in the sentences (i.e. computer vision and natural language processing). Another part is understanding the sentences and their meaning, as in natural language understanding (NLU).

NLU is considered an artificial intelligence (AI) hard problem, which means that the difficulty of these computational problems is assumed to be equivalent to solving the central problem of artificial general intelligence¹ (Demasi et al., 2010). Understanding less structured data, such as neural data, is more complicated than understanding structured and human-invented syntax such as written language because it contains more hidden features and semantics than a paragraph of text. As a result, the author strongly assumes that completely understanding neural data can also be considered an AI-hard problem. This constraint illustrates very well how far current research is from being able to interpret a person's thoughts based on measured neural data.

¹Based on the assumption that general human-level intelligence could be computable.

2.1.2 Abstract thoughts

To further emphasise the complexity of interpreting neural data, a practical example will be presented: Imagine a red house in the middle of a forest. Depending on the individual thought process, one might imagine the house with temporary visual imagery in mind, as in visual thinking, or one might imagine it more verbally, such as conceptually comprehending each word sequentially of what a red house is and that it is located in a forest (Amit et al., 2017) as shown on Figure 2.1.

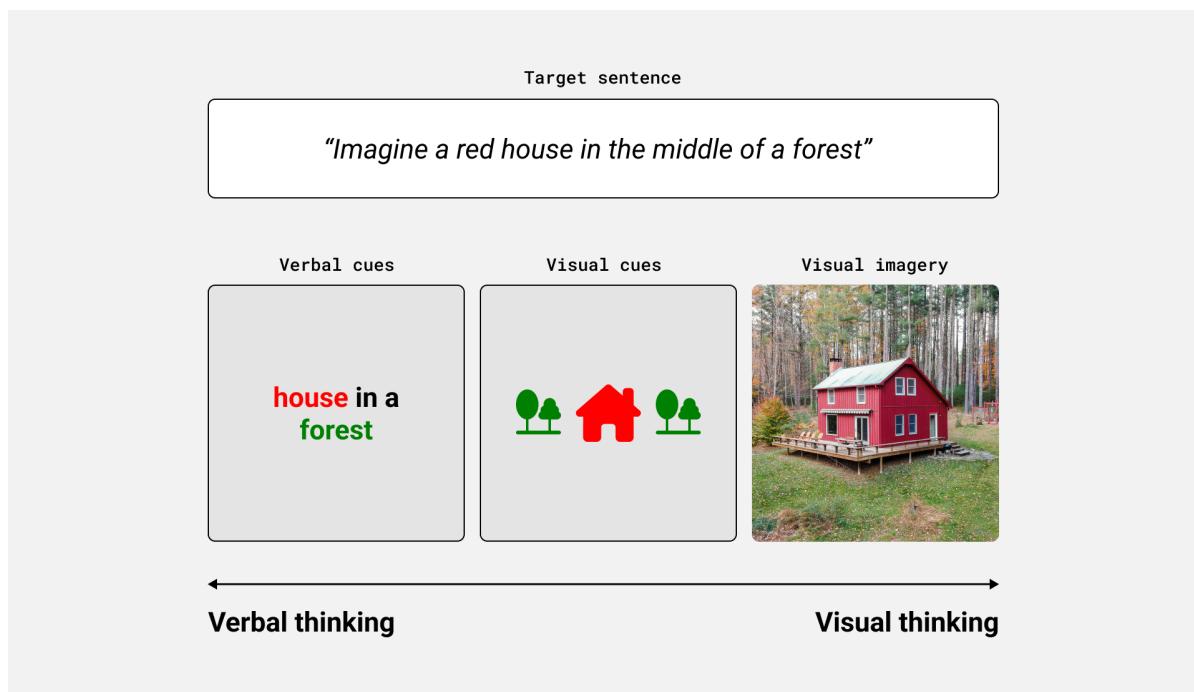


Fig. 2.1: Difference between verbal and visual thinking using the target sentence of a red house in the middle of a forest.

Additionally, it should also be addressed that different types of thoughts exist at different levels of abstraction and complexity. One can assume that the visual image of a red house in the forest is more abstract and far-fetched than, say, the movement of one's own thumbs, which has a clear physical counterpart. It gets even more complicated when one imagines abstract concepts that are inconceivable to visualise, such as the idea of a company. A company is an abstract, collectively agreed upon concept without a clear physical counterpart² and is, therefore, even less straightforward and more complex to decode the meaning of measured brain activity than the other mentioned example of the red house.

²Some people might think of a company building when imaging a company, others might imagine their website, their logo or physical products.

2.1.3 Technological limitations

Even though mind reading or decoding abstract thoughts seems very difficult to impossible, some functional tasks of the brain are still localised, which means that these signals are generated by local brain areas that can be identified, such as the motor cortex, which has been shown to be responsible for muscle movement, as shown in Figure 2.2.

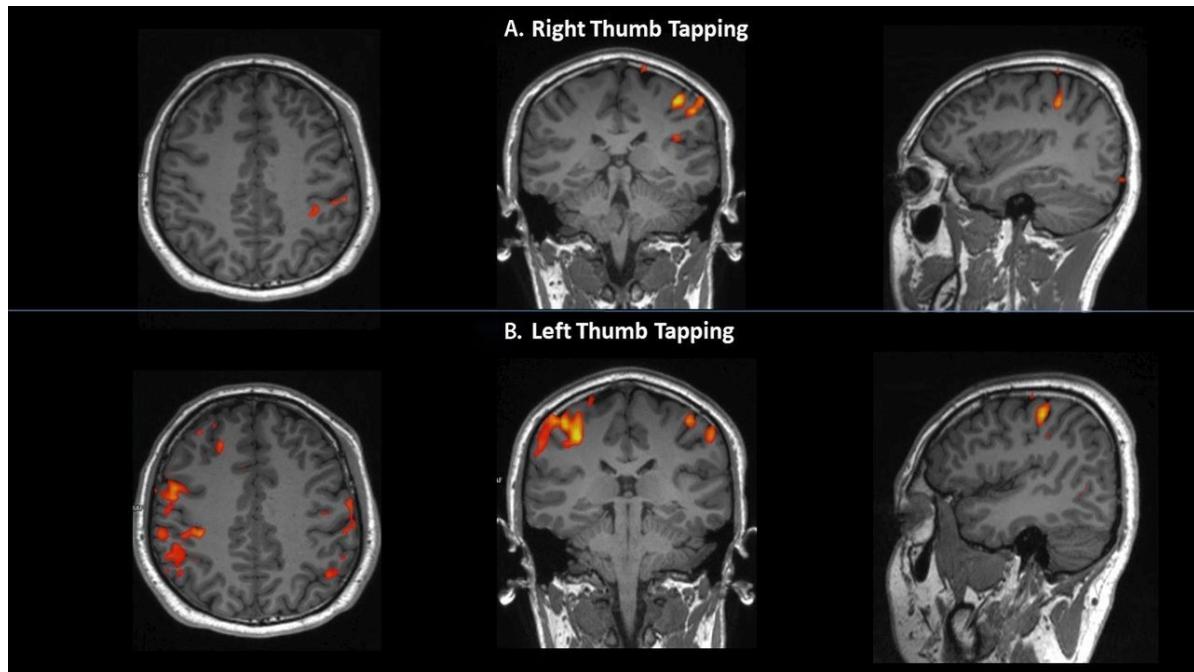


Fig. 2.2: Localised neurons during right and left thumb movement using functional magnetic resonance imaging (fMRI) (Rashid et al., 2018).

Examining the areas of the brain responsible for activating individual muscle strands can yield a comparable response of muscle stimulation in the brain and thus be measured as input for BCI software to, e.g. move a prosthesis. However, the more specific, more behavioural and abstract the thoughts are, the less the brain areas are spatially visible. With the intention of identifying, e.g. the thought of a red house in a forest, the author has identified three technological limitations:

- To understand single thoughts, it is essential to have sufficiently clear data with a certain level of detail (e.g., at the level of detail of eliciting action potentials of individual neurons³) and temporal precision (an action potential has a short duration of about one millisecond (Byrne, 2021)) to perform studies to extract possible localisation of

³Action potentials are the fundamental neurobiological and neurochemical processes through which neurons transfer information to each other.

individual thoughts. Current neuroimaging technologies cannot capture every process in sufficient detail of the entire brain at once to extract the activity of individual neurons while also having high temporal precision.

- Even if we could measure every single neuron in the brain with high temporal precision, we would have an extreme amount of data generated concisely. Let us say we would collect a float⁴ per neuron that represents the rate of change in voltage with respect to time with a frequency of 1 ms and then record each neuron in the brain a million times a second, taking into account that the average human brain has around 86 billion neurons; we would generate 305.53337637684 petabytes of data per second! This is currently not feasible for commercially available storage and processing resources.
- Even if we have the technology, it is a challenge because reproducibility of experiments is very difficult for neuroscientific studies (usually referenced as the replication crisis (Maxwell et al., 2015)). It is probably impossible to generate clean-slate brain data that is comparable to previously recorded data since our neurophysiological brain tissue changes over time due to neuroplasticity (Puderbaugh & Emmady, 2022), and since we are in different states of mind every millisecond of our existence, which can have different influences, such as insufficient sleep, something disturbing someone, mental distraction due to an important event that may have occurred since the last measurement, or a salient thought that randomly occurs while recording neural data.

2.1.4 Lack of data

As pointed out in the previous section, the last two points depend on advances in storage systems or the possibility that we do not actually need such precise brain data to understand single thoughts. However, to address the first point, some promising solutions already exist for measuring large parts of the brain with high temporal and spatial precision, such as time-domain functional near-infrared spectroscopy (TD-fNIRS), which the company Kernel employs in its Flow device (Ban et al., 2021). The TD-fNIRS system detects changes in concentrations of oxygenated and deoxygenated brain cell activity by using near-infrared light in response to neuronal activity. According to Kernel, the precision of TD-fNIRS is sufficient for better understanding the brain and using it for BCI applications. They, however, claim that collecting and organising longitudinal brain data from a variety of subjects is the key to solving the most difficult challenges in neuroscience (Kernel, n.d.).

⁴The size of a float on a Windows 64-bit application is 4 bytes which was used for the calculation.

Based on Kernel's claim, a recent publication from 2022 also claims that even data sets with several hundred people are too tiny to offer insights about the brain consistently; as a result, most published neuroscience studies with dozens or even hundreds of people could all be incorrect (Marek et al., 2022). In neuroscientific studies, brain tissue and activity variations have been linked to variances in cognitive capacity, mental health, and other behavioural features which set an important foundation of our current understanding of the brain. Neuromarkers⁵ of behavioural features are frequently sought in such studies to further understand the brain. The recent publication from Marek et al. claims that most of these so-called neuromarkers would not work when the collected data set is more extensive, which would pose a general problem for the field of neuroscience. UK Biobank's collection of brain scans is one of the first efforts to solve this problem ("Imaging study", n.d.), but it is still far from what we might need since, e.g. Marek himself claims that we might even need millions of data sets to start understanding the brain (Callaway, 2022). This is both fascinating and a possible significant constraint for BCIs, because understanding the brain is essential to making sense of the measured data to interface with it.

However, there is the other side of this argument from people like Andrew Ng, artificial intelligence pioneer and founder of the Google Brain research lab. He believes that machine learning, which underpins all BCI software, should be developed in a data-centric manner, which means that the quality of the data on which models are trained should be as high as possible to answer specific research questions rather than focusing on collecting a huge amount of data (Brown, 2022). However, this brings us back to the replication crisis, which is the difficulty in generating clean brain data comparable to previously collected data due to the nature of our ever-changing brain and mind.

Ultimately, there will almost certainly always be a mix of both approaches. As a result, for general applicable and mass-market-ready BCIs, a relatively large amount of qualitative brain data collected in specific and reproducible experiments or environments is required. This is where high-end, customer-focused BCIs could come into play because the adoption rate of a device suitable for everyday use is higher than the number of subjects in research labs, resulting in larger and more longitudinal datasets. This, combined with more targeted experiments, improved neuroimaging technologies, and advances in machine learning, could unlock enormous potential in brain research.

⁵A neuromarker is a biomarker that is based on neuroscientific data to detect biological properties such as, e.g. a disease or illness. For more information the interested reader can refer to Jollans and Whelan, 2018.

2.2 BCI landscape

This section will discuss the current landscape of non-clinical and non-invasive BCIs, their applications and the distinctions within their software offerings.

2.2.1 Real-world BCI applications

As mentioned in section 1.1, consumer-oriented BCI products are already commercially available. OpenBCI, a non-medical BCI company, does not provide a specific use case but hardware, as depicted on Figure 2.3, as well as software which is universally applicable. It can be used in research where EEG is used or in developing BCI applications. Several neurofeedback or research apps have been created using OpenBCI's products (OpenBCI, n.d.-b). Taking this information into consideration, we can see that the OpenBCI customer is responsible for developing their own BCI application or incorporating it into their research, rather than having a sophisticated end-user application directly from OpenBCI.



Fig. 2.3: OpenBCI's EEG device (Be Superhvman, 2017).



Fig. 2.4: NextMind's BCI device (Louise, 2019).



Fig. 2.5: Muse's meditation headband (Muse, n.d.).

Another example is NextMind's product, as shown on Figure 2.4. They do not focus on having an end-user application for their BCI, but they focus on offering a software development kit (SDK) for the Unity real-time engine to use their technology for brain-controlled actions in video games. One significant difference between NextMind and OpenBCI is that NextMind includes a built-in classification of neural data captured by hardware, in this case, classification of active visual focus on virtual objects based on steady-state visual evoked potentials (SSVEP). Because their business model is presumably based on the unique selling point of their active visual focus classifier, NextMind does not provide access to the raw EEG data collected by the sensors. Nonetheless, NextMind's product is less focused on a specific use case, as its applicability is limited to games inside the Unity engine.

A relatively closed and specific BCI is e.g. the EEG headband by Muse as shown on Figure 2.5. Its purpose is to measure meditation and sleep. They also offer an end-user app to help people better understand their meditation and sleep and how to improve them. The Muse headband is, compared to the previously mentioned products, not unidirectional BCI per se, as there is also biofeedback based on neural data. However, the vital difference between Muse and, e.g. OpenBCI is that they abstract away the neurotechnology. Users do not need to know anything about neuroscience, neurotechnology or the interpretation and classification of neural data to get useful functionality for their use case. They also do not need to understand the software system's underlying architecture. They only need to know how to pair the device with their smartphone via Bluetooth.

Aside from full-stack BCI solutions, where a company provides a complete BCI solution, including hardware and software, some companies focus solely on the software aspect. Neuromore, a company that provides a neural signal processing software platform, is one example. The company is hardware agnostic, which means one can plug nearly any BCI hardware or sensor into their computer and connect it to the Neuromore Studio software.



Fig. 2.6: Screenshot of the Neuromore Studio software (Neuromore, n.d.).

Neuromore Studio, as shown on Figure 2.6, is free and open-source software that runs locally on various platforms. It provides a variety of drag-and-drop interfaces for creating and managing signal processing pipelines. For example, one can transform EEG data to extract band power, create triggers based on band power selection, and generate conditional outputs to, e.g. move a character in a video game.

The author attempts to differentiate the offerings of the consumer-oriented BCIs mentioned: They either provide the hardware (with software that at least connects to the device) but are then more generally applicable to use cases not defined by the company behind the BCI, such as OpenBCI, or they are application-specific in terms of both the software and the hardware, such as the Muse headband.

Although this thesis focuses on consumer-oriented BCIs, the applications of various BCI offerings can still be distinguished based on whether they are more consumer-oriented or research-oriented, such as the distinction between, e.g. NeuroSky, creating EEG-based BCIs for hobbyists and Emotiv's professional and expensive EEG systems, which are more research-oriented. However, NeuroSky and Emotiv provide a research version and a consumer or enterprise version of their software and hardware, aiming for general-purpose applicability across customer segments and use cases.

Other considerations include whether the applications are rather steady-state evoked, such as based on a frequency of noise laid on top of virtual objects to detect which object the person is looking at (e.g. as NextMind is doing), or whether they track the totality of mental states without evoking neural signals with external stimuli, such as in tracking sleep or concentration levels, both of which arise primarily evoked from inside the mind. This distinction can be made as passive, active or reactive BCI, as Alimardani and Hiraki coined in their work on passive BCIs (Alimardani & Hiraki, 2020). However, the author does not want to include this dimension because it would introduce additional complexities related to the BCI software application layer.

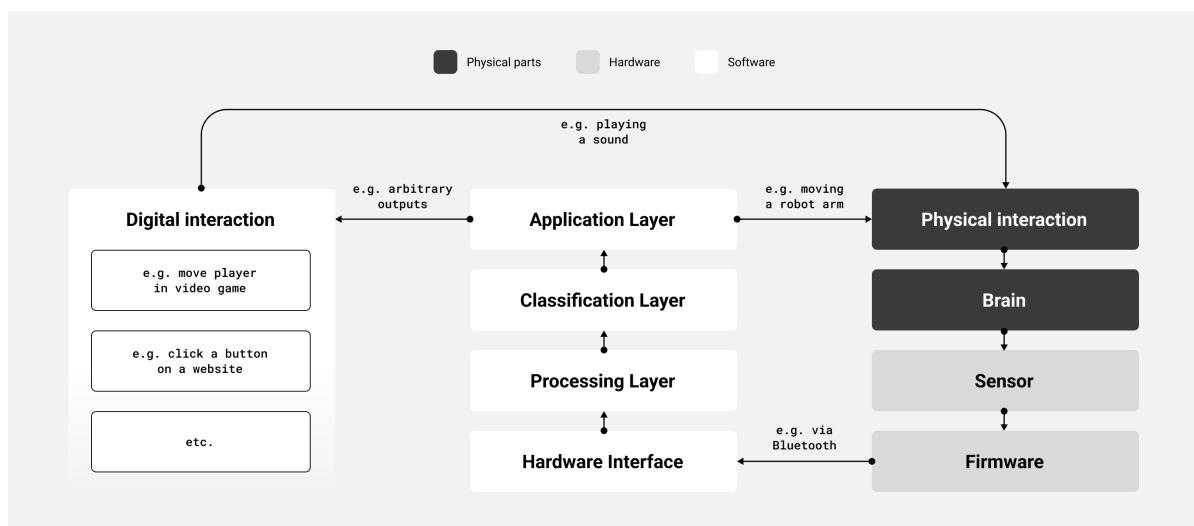


Fig. 2.7: Architectural overview of BCI components including a bidirectionality due to neurofeedback in form of e.g. playing a sound in a certain frequency to enable SSVEP.

The application layer, as shown on Figure 2.7 is the part of a BCI that gets the interpreted data from, e.g. a classification model and turns it into applicable functionality to interface with a physical or digital counterpart to, e.g. move a player in a game or start playing sound on the computer via its speakers. There is also the physical part, e.g. the brain and a physical interaction counterpart in the form of, e.g. a robot arm. The totality of the software stack is responsible for processing the data, e.g. extracting the relevant information from the raw data and turning it into any desired and meaningful output for the application layer.

2.2.2 Unobtrusive hardware and software

The unobtrusiveness of hardware and software is another aspect to consider when discussing BCIs. Unobtrusiveness in hardware means that it is either not visible at all⁶, such when sensors are implanted beneath the skull, or that it is in a form factor that is already socially established.



Fig. 2.8: IDUN Guardian hardware,
rather unobtrusive BCI.



Fig. 2.9: Neurosity Notion hardware,
rather obtrusive BCI.

The prototype of, e.g. IDUN Technologies, a Swiss neurotechnology startup, as shown in Figure 2.8 measures brain activity in the ear canal that aims to resemble the form factor of established in-earbuds. Figure 2.9 shows the Notion device from Neurosity, which measures EEG on the head and is not comparable to a socially established form factor such as earbuds.

⁶There are other things related to the overall user experience (UX) that are sometimes included in the notion of unobtrusiveness, such as comfort, reusability and convenience, where the author only implies physical characteristics such as shape and size.

What is considered socially established and accepted truly depends on the society and context, as one could argue that wearing a Neurosity device under a hat while talking to a friend is more acceptable than wearing in-earbuds. Still, the implications of different form factors must also be considered, such as the possibility of moving the device and thus creating motion artefacts in the signals or the position of the sensors. The ear canal is e.g. ideally closely located to the brain's auditory cortex but not so much for the visual cortex, which is located at the back of the head. However, further hardware implications for BCIs are not a topic covered in this thesis.

Nonetheless, it is perhaps not as simple to discuss the unobtrusiveness of software as it is with hardware. Unobtrusive⁷ software, as defined by the author, is the abstraction of the underlying software or system that executes the logic to fulfil a task without the user knowing what the technical requirements are. As an example: To use an HP ENVY Photo 6200 printer with one's Android phone, one must first download the HP Smart app and the HP Print Service Plugin app that acts as a driver for the printer in order to get it set up and running (HP, n.d.). In the case of the HP printer, the user must understand some of the underlying technical requirements in order for it to work, rather than simply concentrating on the task of printing something. For example, unobtrusive software is when one gets a new computer mouse that they simply plug in and it works⁸.

Unobtrusive software in BCI refers to the ability to connect one's hardware to the computer or smartphone and use it without the need for additional software such as drivers or command-line interface (CLI) software. As an example: To use an OpenBCI device, one needs to open the graphical user interface (GUI) app, connect the hardware, presumably test its quality, begin a data stream session, and output the stream via a network protocol such as a Lab Streaming Layer (LSL), connect to the signal from, e.g. Neuromore Studio (OpenBCI, n.d.-a), run the data through a classification pipeline, and then connect the output from Neuromore to a video game via the engine itself to have controls for the video game. It should go without saying that this is not unobtrusive software. There are examples of software that is included as an executable file and thus is relatively unobtrusive, but the software is closely linked with the hardware and the brand behind the hardware, or it is in the proof of concept (PoC) stage rather than a production-ready application. Buying a new pair of headphones and plugging them into one's computer to enjoy neuro-enhanced⁹ experiences interacting with the brain's outputs or measuring brain data across all apps and the operating system would be an example of proper unobtrusive BCI software.

⁷Other words for unobtrusive could be discreet, fully-integrated, invisible or simply "in the background".

⁸Unobtrusiveness usually correlates with usability, but it is not always the case, e.g. more advanced users would not consider locked-in abstraction as more usable.

⁹Neuro-enhanced software can be described adding additional features to input methods via the brain.

2.2.3 Production-grade software

There is no clear definition of what production-grade software is, but in most cases, software developers agree on the following points:

- Software that works at any time when access is required. It is therefore capable of frequent and intensive use in, e.g. commercial or industrial environments.
- Software whose behaviour is deterministic and predictable and is, therefore, well-tested, well-documented and optimised in terms of speed, efficiency and security for the given context (e.g. the size of the user base). Usually, developers agree on a Definition of Done (DoD) inside their team to what is considered production-ready, e.g., test coverage of 80+%, peer-reviewed and commented code, and a common code style guide, to name a few.
- Software that runs in a production environment, i.e. on a cloud computing cluster for actual users rather than in a test environment for test users or, for example, on hardware delivered to real customers, and that can adapt itself to the context, e.g. to a higher access rate or insecure user-generated input. In most cases, especially in cloud computing, production-grade also means larger data sets, such as in databases, the possibility of a more significant number of edge cases due to a larger user base, and, most importantly, more available computing power on production instances.

As stated in previous sections, most BCIs, such as the OpenBCI, are not intended for production. They are intended for PoCs used in examples, such as controlling objects in games or conducting research. End-to-end and full-stack BCIs for production are rare, as most are very specific and not intended for general purposes, such as the Muse headband, or the software aspect is intended for PoCs or research, such as with, e.g. Emotiv. Pure software products, such as the one from Neuromore, lack the hardware component and miss e.g. an SDK that can be integrated into existing software for different platforms. Neurosity, e.g. aims to provide a universally usable and unobtrusive software stack that is even open-source. However, because the hardware is not unobtrusive enough, it does not qualify the author's definition as production-grade and mass-market-ready (apart from the fact that it is not known whether their software stack is aimed to be used in production (Neurosity, 2022) due to, e.g. third-party developers providing disclaimers of being a work in progress (Turney, 2022)). Companies such as e.g. Neuralink are presumably working on a general-purpose, unobtrusive and production-grade software system which enables developers to build production apps and even platforms on top of it for a variety of use cases without

being limited (Musk, 2019), in their case, since it is a bidirectional BCI, developers are even able to write data back to the brain. Since their aimed hardware is also as unobtrusive in its form factor (since it is implanted), they have a high potential to become one of the first general applicable and mass-market-ready BCIs if we ignore the fact that we need surgery to get the device itself (Neuralink, n.d.) and other considerations as a harder opt-out of the device compared to, e.g. plugging out earphones.

2.3 Neural/cloud interface definition

This section discusses the definition, need and differentiation of a N/CI and the paradigm shifts associated with it when discussing BCI software.

2.3.1 BCI software on the cloud

Looking at Figure 2.10, we can see that the three software layers of a BCI-component illustration, as pictured on Figure 2.7 are highlighted. This is due to the fact that these components are not bound to a physical interface such as a cable or Bluetooth.

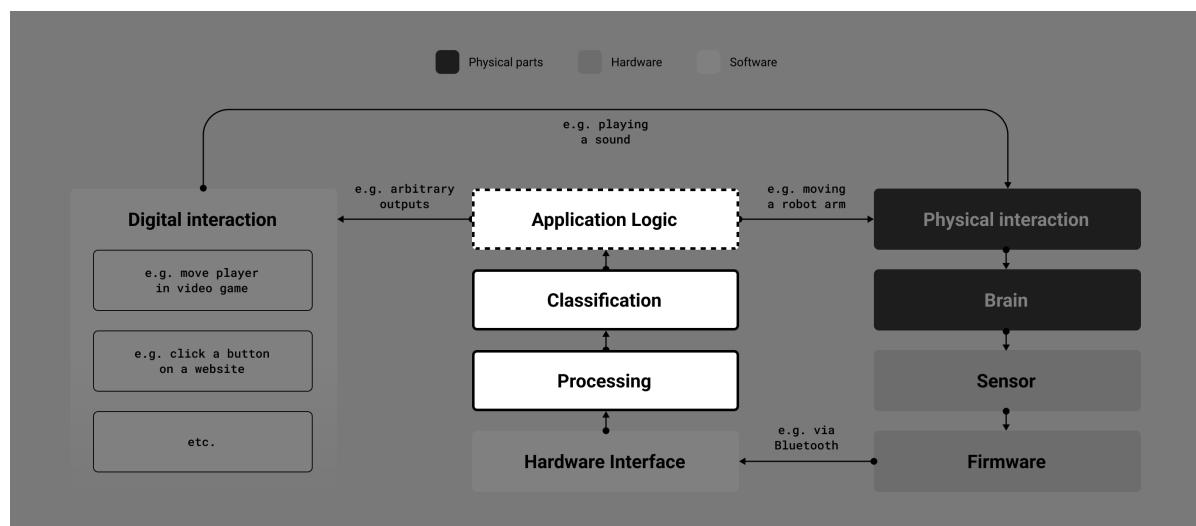


Fig. 2.10: Highlight of the software components as shown on Figure 2.7 of a BCI that could be moved to the cloud.

Running software on the cloud means that developers or companies can access provisioned information technology (IT) infrastructure through the internet, usually with a pay-as-you-go pricing model (Amazon Web Services, n.d.-d). The development speed of software applications can drastically improve since software developers can only focus on software rather than incorporating the hardware and network aspect of setting up their

server farms, therefore abstracting the hardware part away. What started with simple computers that can be rented in a server farm such as it was with, e.g. Amazon Web Services (AWS) Elastic Compute Cloud (EC2) (Barr, 2006) ended up being a diverse offering from cloud providers with various abstraction levels as shown on Table 2.1.

| Type | Description |
|---|--|
| Infrastructure as a Service (IaaS) | IaaS gives access to data storage space, virtual or dedicated computers, and network services. The greatest degree of flexibility and administrative control over your IT resources are provided by utilising IaaS. |
| Platform as a Service (PaaS) | PaaS lets developers concentrate on developing and managing their code rather than worrying about the underlying infrastructure (often hardware and operating systems). An example is Kubernetes. |
| Software as a Service (SaaS) | SaaS provides a whole product that is run and controlled by the service provider. The phrase SaaS often refers to end-user apps (e.g. web-based email). Developers don't have to be concerned about how the service is handled or whether the underlying infrastructure is maintained. |

Table 2.1: The three abstraction levels and types of cloud computing
(Amazon Web Services, n.d.-d).

The majority of businesses are anticipated to embrace a cloud-first strategy by 2025, according to Milind Govekar, vice president of IT research and consultancy company Gartner, and will not be able to fully implement their digital plans without the usage of cloud-native architectures and technologies (Gartner, n.d.-b). The impact and importance of cloud computing cannot be underestimated, and its success is also reflected in the annual spending on cloud computing resources, estimated at €474 billion in 2022 (Gartner, n.d.-b). Cloud computing is such an extensive and complex topic that it could quickly fill entire books. The author categorises three essential points from a bird's eye view that certainly plays a vital role in BCI software: 1. Dedicated and deterministic environments, which explains that an environment of a software programme always stays the same independent of the end-users hardware, 2. elastic and high-performance availability, which explains cloud computers that have an on-demand and adjustable high-performance and 3. provided services for speed, which explains the concept of pre-made and dedicated software written primarily for the cloud and specific use cases. The following list goes more into detail about the mentioned topics in the context of BCI software:

1. **Dedicated and deterministic environments:** Running code for BCIs on different end-user platforms, such as Windows or Android, can have drawbacks because each device has its processor, graphics card, operating system version and drivers, which can make developing software that requires stable and good performance, such as a neural data processing pipelines, time-consuming and difficult to maintain, as developers must keep track of every factor of the end-user devices. This is fine for BCIs that are not intended for the general public, such as specially designed BCIs for people with, say, locked-in syndrome, but for the general public, a vast amount of different end-user devices could come into play. When code is run on a dedicated machine, such as a cloud computer with clearly defined hardware and operating system specifications, it becomes less error-prone and more deterministic.
2. **Elastic and high-performance availability:** Because the cloud model usually runs as an as-needed model, the initial purchase cost of computer hardware is split and shared across usage. Developers have access to tremendous computing power that would not be easily afforded if purchased independently. As a result, when developing a computationally intensive algorithm, developers can use high-performance central processing units (CPUs) and graphics processing units (GPUs) to complete tasks much faster than consumer hardware on end-user devices. Performance can also be increased as needed, e.g. to handle computationally heavier tasks that are not used as frequently or to handle more requests when, e.g. the demand for the software increases due to an increase in the number of users, which is a process known as elasticity (Gartner, n.d.-a). Furthermore, the cloud provides far more storage capacity than end-user devices.
3. **Provided services for speed:** The vast majority of cloud providers are providing more specialised services as we move closer to PaaS. Provisioned database servers, for example, exist solely to serve as a database, so the underlying hardware is optimised for the database software running on it, such as, e.g. PostgreSQL. Hundreds of cloud computing services are available, including 200 from AWS alone (Amazon Web Services, n.d.-d), all of which address specific use cases. This is extremely useful when it comes to cloud-based BCI software. One example is the aspect of live streaming of brain data, which we will go over in greater detail in the implementation chapter of this thesis. The services accelerate development speed by eliminating the need for teams to reinvent the wheel repeatedly, next to also providing out-of-the-box scalability due to built-in elasticity and the concept of fully abstracted hardware via the serverless model (RedHat, 2022).

A N/CI utilises cloud computing by running certain software components of a BCI system in the cloud with the benefits as mentioned before. Multiple BCIs can communicate with each other or with other software or hardware over the internet, enabling remote human-computer interaction. Figure 2.11 depicts how two or more BCIs can interface with one another using cloud software. The red arrows represent the typical local BCI. The blue arrow depicts how BCI B can execute business logic via the cloud over the internet, enabling digital and physical interactions with, e.g. high performance. The green arrow depicts how BCI A can communicate via a N/CI with BCI B even if they are not in the same geographical location.

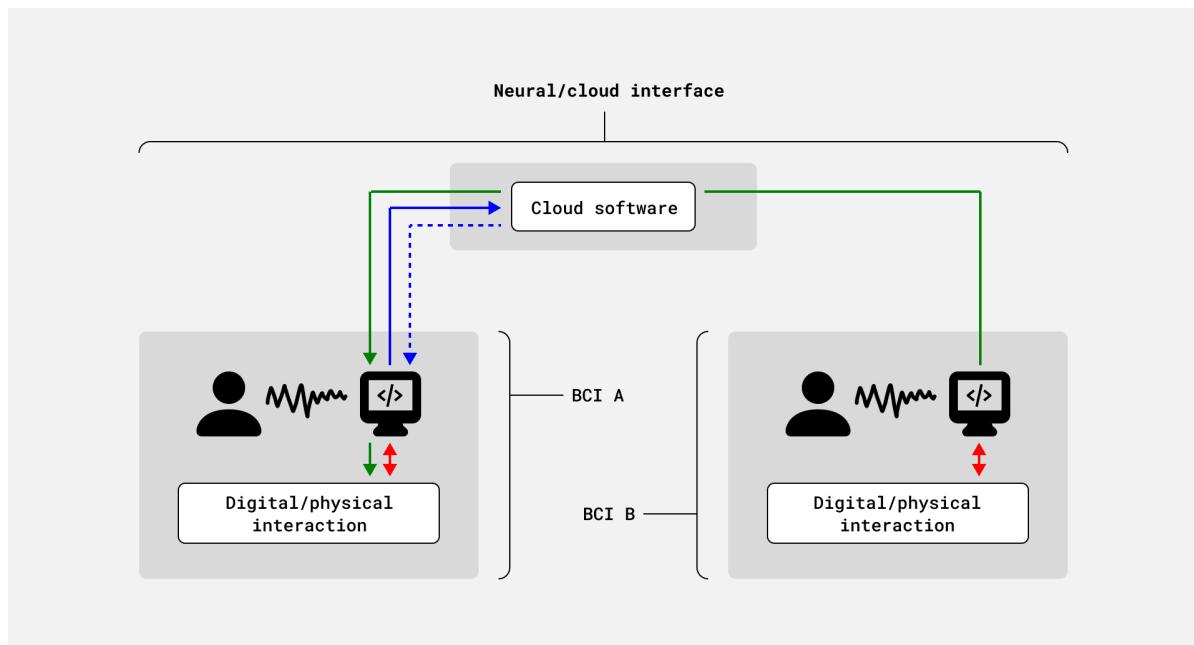


Fig. 2.11: A N/CI is the connection between multiple BCIs.

2.3.2 Distinction between existing research

The concept of running BCI software components remotely and on the cloud is not novel, as research into the concept known as asynchronous BCI (An et al., 2016) or internet-based BCI (Lampe et al., 2014) has been ongoing for some time. However, when we look at the research from, e.g. Zhang et al. from 2018 on their cloud-based deep learning framework to enable, as they describe Human-Thing Cognitive Interactivity, we see a strong emphasis on algorithms and machine learning but less on aspects such as the cloud architecture and mass-market-readiness (Zhang et al., 2018). They address the latency and the size of EEG samples sent in near-real-time to a server, as well as the corresponding calculation,

but there are no more details in regards to the proposed and very simplified architecture chart's protocols and effective cloud architecture, all of which factor into the author's aim to develop a N/CI. Another related paper by Ahamad looks at the system architecture of a BCI for the Internet of Things (IoT), but this time from the perspective of algorithms optimised for time series data such as EEG, but still with no mention of the effective cloud architecture of such a system (Ahamad, 2022).

The author of this thesis introduces the concept of three-dimensionality for the definition of a N/CI based on the previously mentioned topics and research that touch on the issues of this thesis, which are essential to achieve general applicability and mass adoption for BCIs from the perspective of the software system for the actual implementation of such a system.

2.3.3 Requirements of a N/CI

The term N/CI positions itself as a software system in the intersection that can undoubtedly be defined as production-grade rather than being in the PoC stage, unobtrusive implementation rather than obtrusive software and general-purpose applicability rather than being made just for a specific use case. Figure 2.12 illustrates the position of a N/CI within the mentioned properties. Subsequently, Table 2.2 summarises the definitions as described in this thesis.

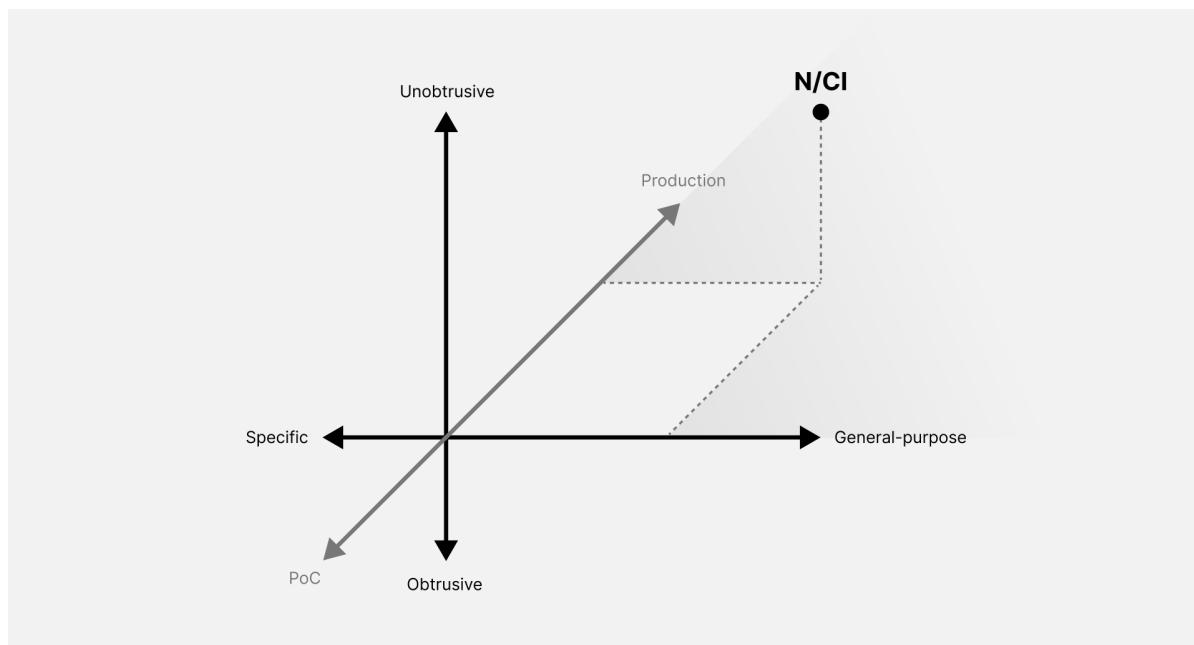


Fig. 2.12: Visualisation of the three-dimensionality of the term neural/cloud interface with its three axes and differentiation of six terms.

| Axis labelling | Description |
|------------------------|--|
| Production | As previously stated, this is the range in which a software system is deemed ready for production. Because the definition is vague, it is difficult to identify specific requirements that must be met for a system to be considered production-ready. However, for a N/CI, this means running in a production environment, e.g. in a cloud, on a real-world end-user server rather than, for example, in a proof-of-concept environment such as in a lab. |
| Unobtrusive | As previously stated, an unobtrusive software system is one in which the end-user does not need to understand the underlying architecture and requirements in order to use the software or even know certain parts of the software system. In the reverse case, users need to install special packages or download additional companion apps to make a N/CI work on their computer or smartphone is not the aim of the author's definition of a N/CI. |
| General-purpose | A general-purpose software system is one that can be used for a variety of functions. As an example, consider AWS. It is general-purpose, which means that developers can create cloud software on AWS that can be either a financial application or a backend for a mobile game; there are no specific use cases. This means that a N/CI, unlike the NextMind BCI or the Muse headband, should provide general-purpose functionality rather than specific use cases, i.e. it is not limited to a specific set of functions. |
| PoC | A BCI software system that serves as a proof of concept cannot be considered N/CI because it is not intended for production and thus all the effort required to create a production system, such as quality assurance with unit or end-to-end testing, is unnecessary. A PoC system does not usually run in a production environment, as the goal is, for example, to test a specific functionality of a use case rather than to deliver the software to end-users. |
| Obtrusive | An obtrusive BCI system, for example, may still be production-ready if it targets specific use cases while remaining unobtrusive because neuroscientists or developers, for example, expect to have access to the underlying software architecture or technical requirements and thus do not want to abstract from it. If it is obtrusive software, such as OpenBCI, this usually means building the production-ready part on top of it is necessary, which does not fit the author's proposed definition of a N/CI. |
| Specific | If a BCI system is only used for one use case, such as Muse for sleep and meditation, companies or developers who want to offer a different use case, such as a mind-controlled keyboard with a P300 system will have to reverse engineer Muse's EEG output or use a different BCI hardware that is less specific and closed, and then build their own production-ready and unobtrusive software on top of it. |

Table 2.2: Axes label descriptions of the three-dimensionality for the definition of a N/CI as shown on Figure 2.12.

With an unobtrusive form factor like e.g. the one developed by IDUN Technologies, a significant hardware barrier to becoming a mass-market BCI has already been tackled. Next to the hardware, IDUN intends to provide a business-to-business (B2B) software platform, allowing 3rd-party developers to create software on top of IDUN's offerings through a universal brain application programming interface (API). Because they allow others to consume this API in end-user-facing apps, it must be production-ready and unobtrusively able to be integrated. IDUN's hardware and software aim to be general-purpose rather than specific, allowing others to build any BCI-enhanced app (IDUN, n.d.).

All of IDUN's requirements systematise one of the first BCIs aimed at the general public, which satisfies the broad definition of a N/CI. The fundamental motivation of the author is to standardise collaboration and research on this novel and interdisciplinary field of BCI software and cloud computing.

Chapter 3

Methodologies

This chapter describes the project-related academic methodologies in the given context of the author and the planned approach to achieve the thesis's goals and objectives. The reader is introduced to the rationale for the intended workflows, hardware, and software tools.

3.1 Derivation of the case study

In October 2021, the author began working as a cloud software engineer at IDUN Technologies, an ETH spin-off startup in Zürich, to further develop their existing software products. IDUN had already created a PoC software system that included a web-based single-page application (SPA) hosted on AWS Amplify, a backend-as-a-service product aiming to simplify the deployment of backends for mobile and web apps. IDUN's in-ear sensor sent EEG data to a physical network bridge via Bluetooth and then to the cloud via the internet. The raw EEG data was saved and available for download in various file formats.

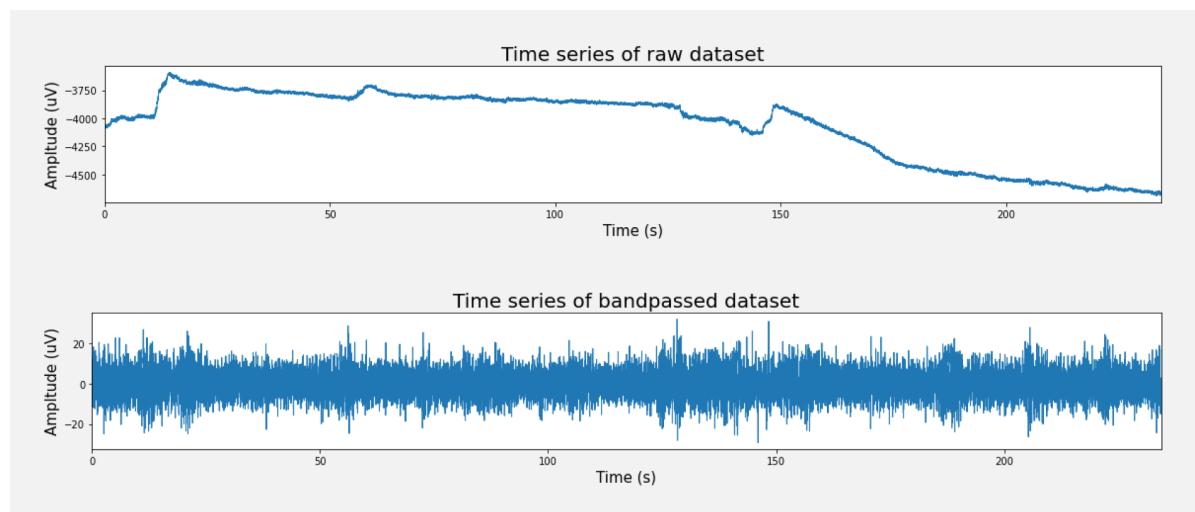


Fig. 3.1: Difference between raw and filtered EEG data from IDUN's in-ear device.

In addition to raw data, the IDUN SPA provided transformed data, such as, e.g. filtered data, which included low-pass and high-pass filtering of EEG data as shown on Figure 3.1. This transformed EEG data was then saved alongside the raw version on the cloud.

The EEG data could also be visualised in near-real-time on the SPA as a time-series x- and y-axis plot. Additionally, users could control the device by sending start and stop commands to the hardware components. The architecture overview is displayed on Figure 3.2 in which IDUN GDK refers to the IDUN Guardian Development Kit.

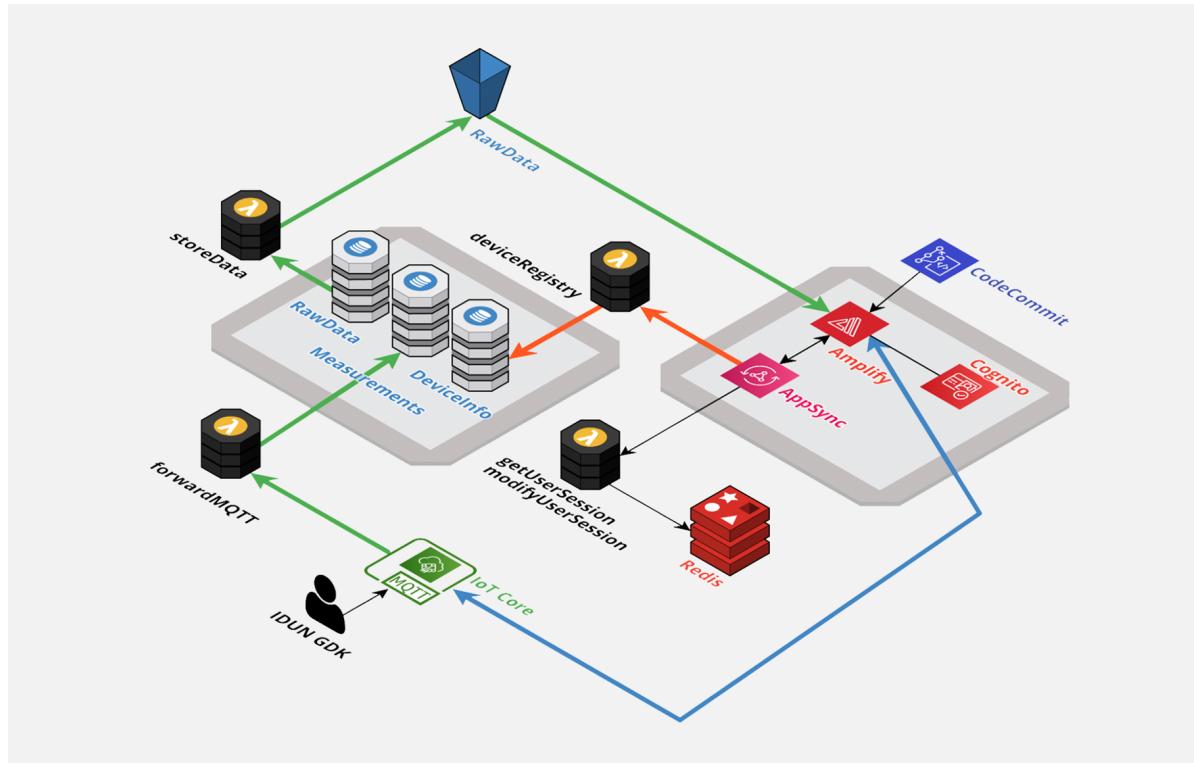


Fig. 3.2: IDUN's software architecture at the end of 2021.

The system was in a relatively unstable state and had strange error sources that made it impossible to reliably record EEG data for more than a few minutes, making the product unusable for existing customers or a mass-market launch. While working on the system, the author encountered various technological bugs and flaws as described in the following list:

- AWS Amplify is great for frontend developers who want to build simple backends with CRUD¹ operations, but it is not intended for anything custom-made, such as, e.g. the streaming-focused aspect of EEG data. Therefore, AWS Amplify must be abandoned as soon as possible, or the project will be built with the wrong tools and foundations.
- The network bridge was a Raspberry Pi 4 Model B running Python code, which after some analysis, turned out to be the primary source of most of the bugs due to limits in computational power. The question was raised whether the network bridge was

¹CRUD is an acronym describing general operations of a backend system: Create, Read, Update and Delete.

needed since IDUN intends to build a completely mobile system, not tied to a network and directly connected to, e.g. a mobile phone.

- The cloud's heartbeat functionality was missing, which meant that the cloud knew nothing about the hardware devices, and simply assumed that data would flow in as soon as the start command was sent to the device, creating a pure happy path scenario.
- The cloud infrastructure was automatically provisioned by AWS Amplify, which uses AWS CloudFormation in its core, which is an infrastructure as code (IaC) tool, that ran inside of AWS CodePipeline, AWS' continuous integration service, which made everything coupled to specific AWS services where the technical decision to use them was not made based on reasoning but based on Amplify's creators to utilise them.
- All software in the cloud was built using the AWS Console (the AWS GUI). Therefore, no current state in the form of IaC reflected the current infrastructure, which made it impossible to reproduce the cloud in different environments, e.g. prevent a blast radius if something went wrong.
- The data was streamed via IBM messaging and queuing middleware telemetry transport (MQTT), a publish-and-subscribe transport protocol commonly used for IoT devices that, e.g. regularly send telemetry data. The purpose of MQTT was not to send high-frequency EEG data in real-time but rather to minimise network bandwidth (MQTT, n.d.). Therefore, there was also a need to rethink this technological decision based on the nature of IDUN's EEG sensor, which produces 250 EEG samples per second.
- The SPA was a thick client, meaning that it ran a lot of business logic, such as filtering raw data for real-time visualisation. This was another technological misstep, as the client-side JavaScript ecosystem is far inferior compared to, e.g. the Python ecosystem that could run in the backend to handle such tasks. If possible, shipping business logic that could hold intellectual property to clients should be avoided if possible, especially with a commercial product.
- The SPA was not connected to a single endpoint on the backend and used the MQTT stream and the non-real-time aspects of the app (e.g. login or list of recorded EEG data) via different sources. For example, the MQTT stream was subscribed directly from the device itself and did not run through AWS Amplify's API, which made coupling the systems into a coherent and robust API cumbersome.

- The state of the whole system was difficult to handle due to the decoupled logic from the MQTT stream and Amplify's API. Combined with the lack of a hardware heartbeat, it was very tedious to figure out what the user was doing and what was being sent. As an interim solution, AWS ElastiCache, a provisioned service for in-memory databases like Redis, was set up. Unfortunately the state was now both handled in the SPA and on ElastiCache simultaneously which enacted even new problems such as sending EEG data to the void if the user closed the browser during a data stream.

Due to growing problems with the existing software system and an ever-increasing technical debt as a result of the software not being test-driven or developed without clean code quality standards, resulting in bugs and quirks that are difficult to track down, the author proposed to halt the implementation of new features and restructure the system from the ground up using a more software engineering-oriented approach. The company's management approved the request for this redevelopment in early December 2021. At the time, the author was already working on his original Bachelor project, which focused on a mind-controlled multiplayer game, assuming that IDUN's software system would be stable by the time the Bachelor project began. The original Bachelor project's focus was officially changed at the end of 2021 to create a thesis on the redevelopment of IDUN's cloud software.

3.2 Case study

As mentioned in previous chapters, IDUN manufactures an EEG sensor in the form of in-ear headphones. Their vision is to sell their hardware and license a software product coupled with the hardware called Neuro-Intelligence Platform (NIP), as shown on Figure 3.3.

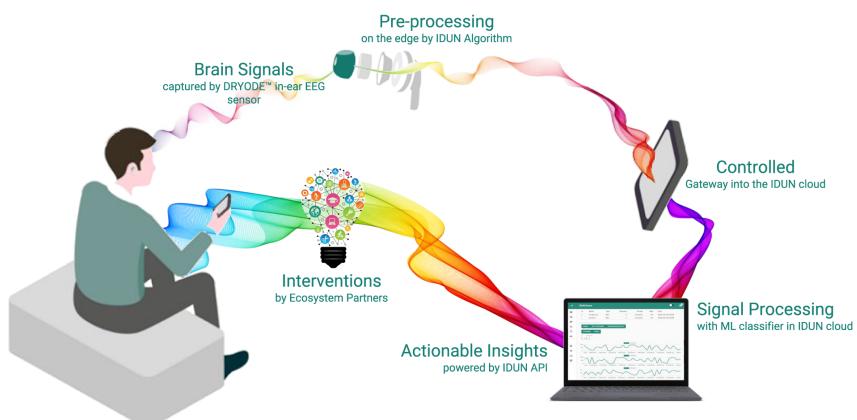


Fig. 3.3: IDUN's vision of a closed neurofeedback loop (IDUN, n.d.).

The mission is essential that an unobtrusive BCI device, such as an in-ear headset, can be worn for the majority of the day while measuring neural data that is sent in real-time to the cloud to process and classify actionable insights that other developers can use to build their interventions (e.g., apps, websites, and games) on top of it to promote mental health and well-being. Furthermore, the aspect of longitudinal data is essential, implying that it could be advantageous to store neural data over a long period and run classifiers on it from time to time to understand one's brain better.

It is essential to select an appropriate research method to develop a system that would fulfil the company's mission and vision. The author chose a case study because it is an effective method for dealing with unusual and atypical cases while providing new and unexpected perspectives in certain situations such as in a deep-tech startup like IDUN.

3.3 Procedure

This section describes the planned procedure for conducting a case study-based research methodology to develop the proposed N/CI at IDUN Technologies as part of their NIP.

3.3.1 Project stages

The goal was to conduct qualitative research and examine the use case from various perspectives. In addition, two other methodologies were used in the case study: 1. Expert interviews, which entails locating experts on topics such as cloud or BCI and asking them questions that will assist in answering implementation questions, and 2. group discussions, which aim at learning about people's attitudes and opinions about related topics.

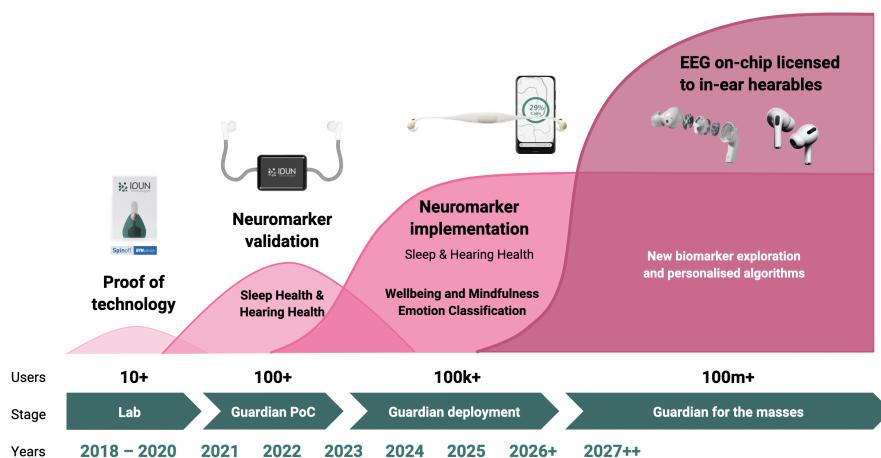


Fig. 3.4: IDUN's plan to achieve their goals (IDUN, n.d.).

Before defining the project stages, it is essential to look at the timing of IDUN's roadmap as shown on Figure 3.4. There are three essential pieces of information: The stage in which the technology resides, the estimated user base size, and the time frames of these stages that want to be achieved. The author was working towards a version starting to be released in 2023, ergo working on the N/CI placed in the Guardian deployment phase. As the company is still implementing the first neuromarkers into the product and is focusing on four use cases due to the size of the team and the mass production of hardware and sensors, the sales team is targeting the sale of devices to about 100'000 people.

Another constraint is the deadline of the bachelor's thesis of the author, which is set on the 5th of August 2022. User size, company stages and the deadline for the thesis are important context information for defining the project stages for this use case. Following on Table 3.1 are the proposed project stages to execute the case study:

| Project stage | Description |
|--|---|
| 1.1 Define key technical requirements and constraints | Based on the internal hardware, the neuroscience and data science departments and the IDUN mission and roadmap, the author needs to define the purely technical requirements and constraints. Some constraints are e.g. hiring of advisors, time limits and risks due to investment rounds. Some purely technical requirements come from e.g. the firmware team or the material scientists, such as maximum latency or the data structure of the digitalised and amplified EEG. |
| 1.2 Extensive literature research | Already since the beginning of the original bachelor thesis, the author started to do literature research in the field of BCI, which is very helpful for the new focus too. Further literature review now includes books on data intensive applications and cloud, articles and research papers. |
| 2.1 External user interviews | Defining users personas with IDUN's product manager, application engineer and sales team, finding real people to represent these personas, preparing an external interview framework and questions, gathering as many insights as possible. |
| 2.2 Creative workshop and prototyping | Based on the insights from the user interviews, conduct a creative workshop with IDUN's product manager and application engineer. The results are design artefacts such as wireframes, user flows, interactive prototypes and architecture diagrams which are essential for internal group discussions. |
| 3.1 Internal group discussions | The design artefacts are used for an internal validation with the department heads. Several group discussions are held with each department, ranging from materials science to business development. Based on the group discussions, the artefacts are adapted and improved. |
| 3.2 Expert interviews | Define experts in different areas of BCI, cloud and EEG, and neuroethics. Create a framework for expert interviews and questions that are still unclear or open based on the design artefacts. Conduct expert interviews and gather as many insights as possible to adapt and improve the design artefacts. |
| 4. Start bootstrapping | While the design process is still ongoing, you can already start implementing the most important technical requirements, with anything that is a flexible bootstrapping of internal development processes to ensure quality assurance, for example, not being tied to the other phases. |
| 5. Iterative and agile implementation via Scrum | IDUN works with Scrum, for this the author has introduced Scrum in the research and development department. Scrum at IDUN has three-week sprints and there are ten sprints from January 2022 to the end of July 2022 that can be used to go through the design process and implement the designs. In the process, there are several iterative processes to validate and test the increments of the system based on insights from the implementation, ongoing literature research, insights from other departments or the design process (i.e. user interviews) that is still ongoing. |

Table 3.1: Project stages to answer the research question of this thesis.

Number 1.1 is crucial before starting anything else. Number 1.2 is continuously in progress. Numbers 2.1 to 3.2 take place simultaneously while number 4 is ongoing². As soon as numbers 3.2 and 4 are completed, number 5 can be started.

²Number 4 refers to bootstrapping, which usually refers to the practice of setting up development environments that include, e.g. initial Git repositories, folder structures and creating accounts on cloud providers.

3.3.2 Group discussions

According to the author, it is critical to conduct user interviews with external people who do not have too much insider information about IDUN to avoid developing a very technical product that only someone with much company-specific knowledge can use. Based on the user interviews, the goal is to create design artefacts in Figma for everything GUI-related and in Miro for everything architecture-related. These design artefacts are then used to communicate the creative design process to IDUN's internal staff based on the findings from the external user interviews. The ideas and findings should be presented and validated concerning IDUN staff's understanding and product perceptions. Because the development of a complete neurotechnology product involves many disciplines ranging from physics to machine learning, the company must have a shared understanding of what the software component of the NIP, ergo the N/CI, will look like and what functionalities it will have.

3.3.3 Expert interviews

It is critical to consult experts after the external and internal validation and design process and its iteration through group discussions. In the author's experience, it is difficult to, e.g. engage consultants at an early stage of the process without knowing what one wants to build because advisors, e.g. from a consultancy firm, tend to push for commercially oriented ideas to generate their revenue rather than thinking about the project's long-term success. Experts are chosen based on the author's experience and the experience of other IDUN Technologies employees, such as data scientists and neuroscientists. According to a previous blog post by the author, the importance of ethics in the field of BCI is critical (Burger, 2022). As a result, it is crucial to include neuroethics experts in the plans and ideas for IDUN's N/CI as well.

3.4 Software and tools

There is a great amount of software and tools that can be used to construct a comprehensive software system, such as IDUN's N/CI. The author had some leeway in deciding which software and tools (i.e. libraries and frameworks) to use. Nonetheless, some software and tool limitations should be considered before beginning the implementation:

- IDUN has received a large number of credits from Amazon for its AWS account, which should therefore be used to avoid creating redundant costs when using another cloud provider.

- The Python ecosystem has strong roots among engineers and researchers at IDUN, which should be taken into account too. An example of this is Python's Jupyter Notebooks, a state-of-the-art software tool used at IDUN and in the data science industry.
- The author himself needs to be comfortable with the existing knowledge of software and tools for building IDUN's N/CI; otherwise, he would have to relearn everything before the actual implementation, which would make things even more complicated. The AWS cloud, for example, would be one such case where the author initially had more knowledge and experience with the Google Cloud Platform, so the need to learn an entire cloud provider is in front of him.
- Any new tool that is not open source and free to use should be carefully considered in terms of future maintainability, security and learning effort.
- Wherever possible, redundancy in the workload should be avoided, as a venture capital-funded startup like IDUN has a particular runway time that describes the company's remaining time before it runs out of cash. Spending, e.g. an entire sprint working on something that is then thrown away, can be business-critical, so every software and tool decision is carefully weighed.

3.5 Checkpoints for progress

Progress is reviewed at the end of each three-week sprint. IDUN's entire research and development team and stakeholders, such as C-level management, attend the review events. Each department asks questions about the author's progress and findings. The planning for the upcoming sprint will take place based on the topics discussed in the reviews. Asana, a project management tool, mirrors the overall product backlog and the personal backlog of the author's bachelor project and tracks progress in terms of story points and remaining epics in its dashboard. In addition to Asana, documentation of all project stages will be documented in Notion. Screenshots of the mentioned artefacts will be attached in the appendices.

The author wants to emphasise an important point: the quality of the work is an essential component of the chosen methodology, made even more crucial when one considers the extensive list of flaws in the current IDUN software system. This can only be avoided by implementing extensive quality assurance measures (i.e. unit tests and continuous integration pipelines) during the bootstrapping project stage. To quote Robert C. Martin from his Clean Architecture book: "The only way to go fast, is to go well" (Martin, 2018).

Chapter 4

Implementation

This chapter goes into the implementation details of building the software parts for the NIP of IDUN and discusses the key events that occurred during this empirical software engineering process, such as the realisation of the novelty and the need for a definition for a N/CI.

4.1 Timeline

Procedures, such as enlisted in the project stages presented in subsection 3.3.1, are a good guide for project implementation, but in the end, such plans run in unexpected ways. As a result, researching and implementing a non-trivial system such as a N/CI requires a high level of agility.

The effective timeline at the time of writing is shown in Figure 4.1. It includes the previously mentioned project stages but is differently structured as initially described. Table 4.1 explains why some project stages were completed differently than initially planned.

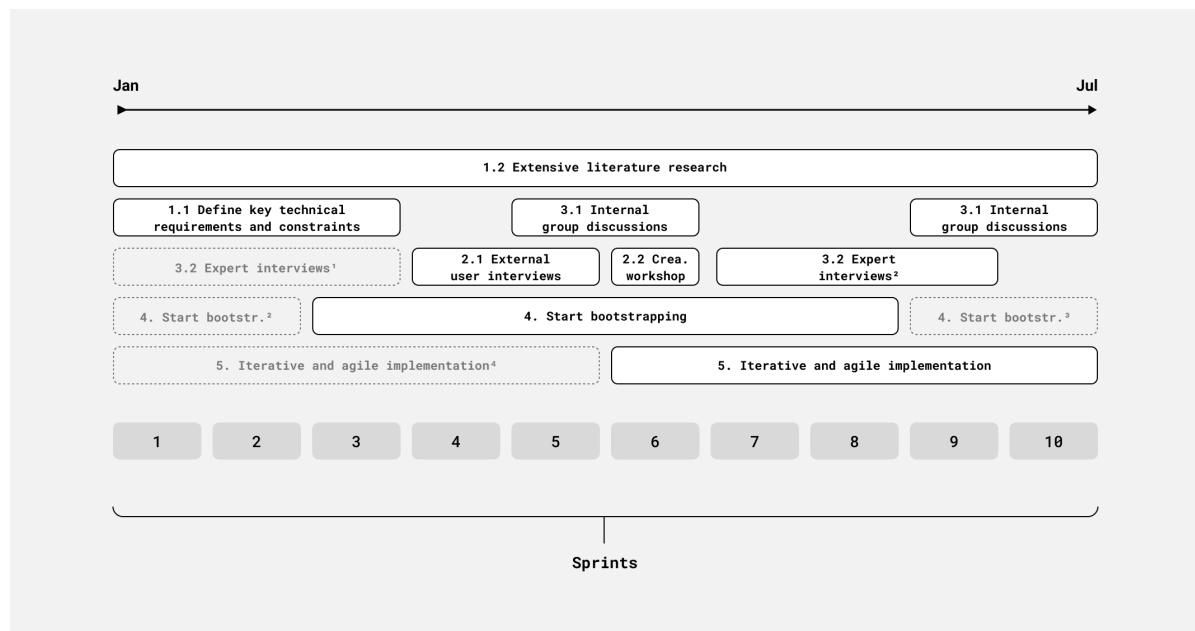


Fig. 4.1: Effective timeline of the last ten sprints with project stages in white and specifically planned stages outlined in grey.

| Special stage | Description |
|---|---|
| [1] 3.2 Expert interviews | The author was able to use the first expert discussions in advance thanks to the help of one of the sales staff's networks. The experts were Nuvibit's experienced enterprise cloud and solution architects. The first topics were strictly technical in nature, focusing on medium-term technological decisions in the context of the company and the timetable. |
| [2] 4. Start bootstrapping | This special stage describes the phase in which the author established more organisational structures, such as a professional Scrum or GitHub setup. Furthermore, the time was used to create a more professional AWS organisational setup with various organisational units, as described in the AWS Best Practice Guide (Blackham & Elmalak, 2020). |
| [3] 4. Start bootstrapping | Since the creation of two different Python SDKs (as discussed later in this chapter), more bootstrapping tasks were due at the very end of the given time frame, mostly including the setup of a private PyPi installable Python package and SDK-specific quality assurance pipelines and automations. |
| [4] 5. Iterative and agile implementation | Iterative and agile implementation began as soon as needed, without waiting for the design process to be completed (i.e. avoiding a waterfall process). Prior to gaining insights from the design process, time was spent on everything else, such as evaluating technologies, further bootstrapping, first example codebases, or maintaining the old codebase a bit. |

Table 4.1: Special project stages in the effective schedule as shown in Figure 4.1 and their explanation of why they took place there.

Several key events occurred during the implementation that shaped the future course of the project and research. This was primarily due to initially unplanned early expert discussions or uncertainties in the requirements as the user-centred design process was still being prepared. These key events are overlaid with the effective project plan as shown in Figure 4.2. These three green key events are the most influential key events.

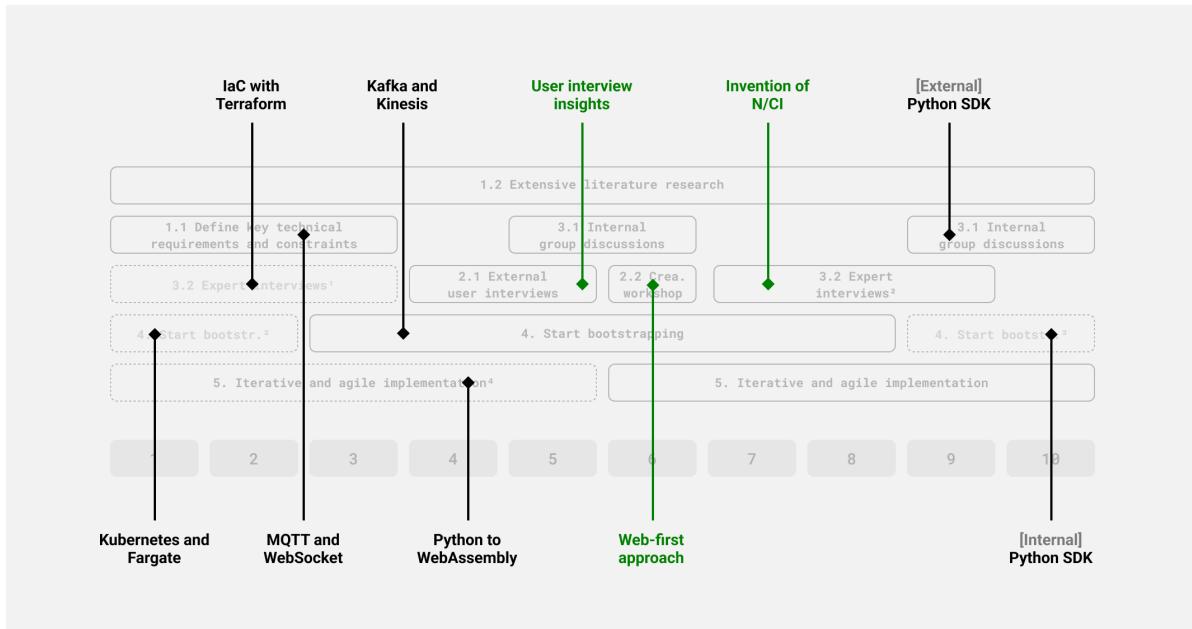


Fig. 4.2: The key events overlaid on the effective project schedule as illustrated in Figure 4.1, with the most influential events coloured green.

4.2 Key events while building a N/CI

This section goes over each key event as shown in Figure 4.2 and discusses why it happened and was critical to the project's success. The following outline of the key events is not chronologically described but starts with the most significant ones.

4.2.1 User interview insights

The conduct of user interviews was one of the most significant key events. This process began with developing customer personas based on the sales team's previous experiences with real customers and the planned customer segments targeted by C-level management. The author does not want to go into too much detail about how the personas were created and how the process went because the focus is on the results based on the user interviews, not on the persona creation process itself. The personas are illustrated in Figure 4.3, and a more detailed version is included in Appendix D.

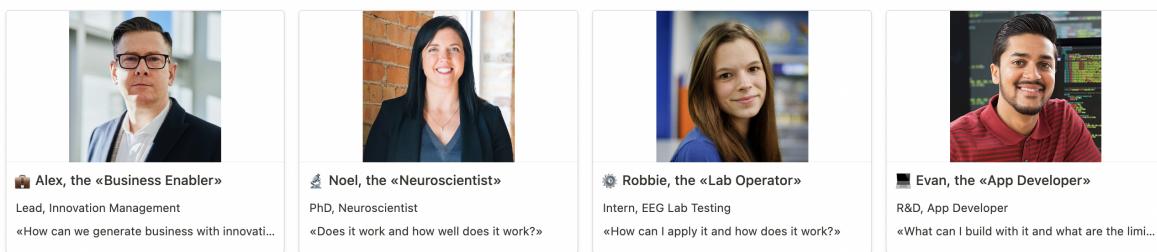


Fig. 4.3: IDUN's customer personas.

Real people were then chosen to represent the personas as accurately as possible. The IDUN staff scoured their network to accomplish this. Finally, the author compiled a list of twenty individuals. Seven people were chosen from this list and invited for separate interviews. The interview outline was planned in collaboration with IDUN's product manager and an industry UX expert, Laura Bendixen, who works as a UX designer at Blick.ch. The author completed the outline based on Laura's expertise with previously conducted user interview sessions, which can be found in Appendix A. All user interviews were conducted remotely and lasted no more than 1.5 hours. During the interviews, insights were transcribed on post-its. People working with BCIs or EEG were interviewed, as were PhD students working in research labs, developers who, e.g. had never worked with BCIs or had extensive experience building even own BCI software, and business enablers from companies responsible, e.g. for BCI-based accessibility. More details about the chosen individual interviewees can be found in Appendix A.

The questions were non-leading and open-ended, with the primary goal of allowing interviewees to express themselves, capture their perceptions of the BCI industry, and introduce IDUN's vision and mission upfront. The goal was to determine what software offerings a mass-market BCI-software device would need to provide, such as convincing developers who have never worked with BCI to include neuro-enhanced features or convincing researchers to use IDUN's NIP in their research. The questions and answers were all about different things. More technically oriented people inquired about speed, performance, and privacy concerns (ergo, more production-readiness thinking), whereas researchers inquired about signal quality, the ability to synchronise with other data streams, and access to raw data (more general applicability thinking). After the last user interview, all post-its were compiled, similar insights were grouped, and the product manager, as well as the author, categorised the most important insights into a list:

- **There are two prominent use cases: using the NIP for research and developing an end-user-facing app.** These are two critical distinctions. Researchers would use the NIP to learn about the brain due to previously cumbersome data, such as through simple-setup remote experiments or real-life long-term experiments outside of laboratories. The NIP would, in such a use case, still be used in production, but not to potentially thousands or millions of users in an app intended for end users. The company or developer using the NIP would have physical access to the hardware in the research use case because they would most likely buy one or more devices and hold them in their reservoir. In contrast, companies targeting production use cases would ship the devices as, e.g. white-labelled hardware through their own or 3rd-party channels. Perhaps we can even go so far as to say that because IDUN distributes the device so well, companies and developers do not need to sell the device themselves but can assume that users own such headphones and then access the brain API such as e.g. today's developers can assume that every end-user has GPS access in their smartphone.
- **Visual demos that are easily accessible for someone owning the hardware are essential for all personas, most notably an Alex.** A visual and simple demo should demonstrate what one can do with the NIP from IDUN and inspire others to conduct research, build apps or enable business and opportunities. These demos need to explain to the different personas the different benefits; next to that, the end-user should be able to try out the demos to see the benefits of BCI-enhanced technologies. People like Evan should be able to adapt demos with their codes to create their own versions of them.

- **The user of the NIP needs to have as low-level control over the data flow and classification as possible** but also with an option for less technical users to use it and build things, similar to, e.g. AWS: AWS itself is only an API to use cloud IT resources, but they also have the AWS Console app to build everything via a GUI instead only via the API. What is very important here is that people such as, e.g. Noels need to know precisely what algorithms were used or the methodologies for specific classifiers to justify them and integrate them into their research. They do not, in most instances, actually need raw data access, as plotting functionality would also be enough; therefore, IDUN's NIP should have somewhere functionalities to plot and visualise data.
- **In order to ease the use of the GUI and the API of the NIP, IDUN needs to provide, next to satisfying documentation, libraries for specific environments** that make the unobtrusive implementation of the NIP easier. Such as e.g. providing a client-side JavaScript package that is lean and easy to use that can be integrated into existing apps. Examples for such code integration would also need to be provided by IDUN so that people like Evan can easily adjust them and more quickly start integrating them into their apps or research codebases. The personas would need to abstract the brand IDUN as much as possible, e.g. Intel is doing with their Intel-inside ingredient strategy (Intel, n.d.).
- **End-users need control over their data so that other companies accessing the NIP API cannot collect their data** on their servers and do everything they want. Imagine if, e.g. the operating system layer of one's smartphone would not offer an opt-in mechanism for the cameras, then 3rd-party developers could install spyware and record without the user permits it. When, e.g. users start to use multiple apps with a NIP integration, there needs to be some way to control the opt-in and data access without the app developers having any saying on the decisions. There needs to be a technical limitation from the side of the hardware or the cloud to ensure user privacy and data security for end-users.
- **Researchers are very interested in the raw EEG data and the synchronisation possibilities with specific protocols** such as LSL to combine, e.g. a heart rate sensor with the EEG collected from IDUN's hardware. The NIP software offering needs to give enough freedom to combine the data without letting all other collected data flow into the NIP from IDUN. This means that the NIP should be able to collect, transform and, most importantly, label data in correlation with other data streams with a local option to satisfy researchers like Noel.

These insights were critical in determining that there must be sufficient freedom for raw data research without releasing raw data into mass market production environments to protect end-user privacy. As a result, an opt-in mechanism outside of third-party ecosystems is required. A library that can be implemented in end-user apps and connects directly to the hardware without the need to download a companion app from IDUN itself is also required. This library should allow researchers to access it locally and, e.g. use their preferred protocols to synchronise tags and labels with other data streams. Nonetheless, IDUN's NIP should once again provide some control over how much raw data can be collected and restrict access if, e.g. the proposed research project or experiment time frame is exceeded. Furthermore, additional NIP functions should be added to visualise easy-to-use demos for all personas, as well as a way to use and control the NIP without having to write code, but with enough flexibility and transparency that there is trust in the system and even advanced users can work with a visual tool instead of code.

4.2.2 Invention of N/CI

The insights from the user interviews, combined with the ongoing research on B/CI and remote BCI mentioned in the introduction chapter, were key to realising the novelty of this new interdisciplinary approach to developing a real-world and mass-market BCI software system running in the cloud and targeting the general population via general applicability. In this thesis, the definition of three-dimensionality was already mentioned in the context chapter, but it is essential to mention that the realisation that such a system is novel and has not yet been defined only emerged in the seventh sprint. The findings from the user interviews were primarily in the direction of the N/CI definition, while the literature review was primarily in the direction of distinguishing between existing research and definitions.

Once a first draft of the definition was written down, the research and separation of work packages could be more easily tackled and explored due to a better understanding of what was new and unexplored. At the time of the end of the seventh sprint, the author's goal was to develop further and define the definition and motivation in the form of the last part of the context chapter of this thesis, which had to be introduced first before moving on to the methodology and implementation chapters, because without a broad understanding, the reasons for the motivation and the general definition would have been difficult to understand.

4.2.3 Web-native approach

Before Sprint 6, there were some ideas about future architecture roadmaps designed by the author of this thesis, as shown on Figure 4.4.

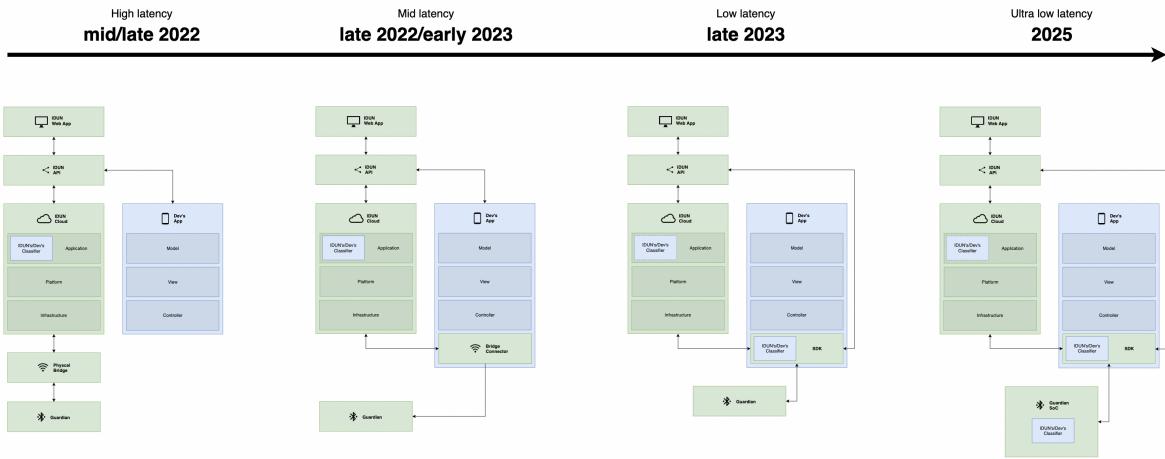


Fig. 4.4: Original architecture roadmap of IDUN's NIP.

The initial architecture roadmap was part of the project's initial phase to define the key technical requirements and constraints and show how the NIP software stack would move from a high latency system to a low latency system. More details on the latency aspects are discussed later in this thesis. Nonetheless, one aspect of this old architecture roadmap was that IDUN would continue to maintain and develop the physical hardware network bridge and eventually port it to end-user devices as a companion app. However, just before Sprint 6, the author stumbled upon the work of Flynn and Brewster of the BCI platform called Brains at Play and its use of Web Bluetooth, which is a new and experimental API for browsers that allows websites to connect directly to a Bluetooth Low Energy (BLE) device. The Brains at Play platform is a hardware-independent BCI software platform with similar goals to Neuromore Studio. The main difference is that they offer their app as a web app; therefore, everything runs in the browser without downloading additional software. The author contacted Garrett Flynn, one of the founding partners, and discussed the implications and findings of using Web Bluetooth, e.g. EEG data such as that from IDUN's sensor (later, Garrett Flynn was also invited to the user interviews as one of the persona representatives for Evan). Garrett Flynn's findings were entirely positive, and he strongly recommended working with the API as it makes deploying a BCI platform much more effortless than deploying applications for any operating system, especially any BLE interface. However, one of the main disadvantages of Web Bluetooth was browser compatibility, as shown in Figure 4.5.

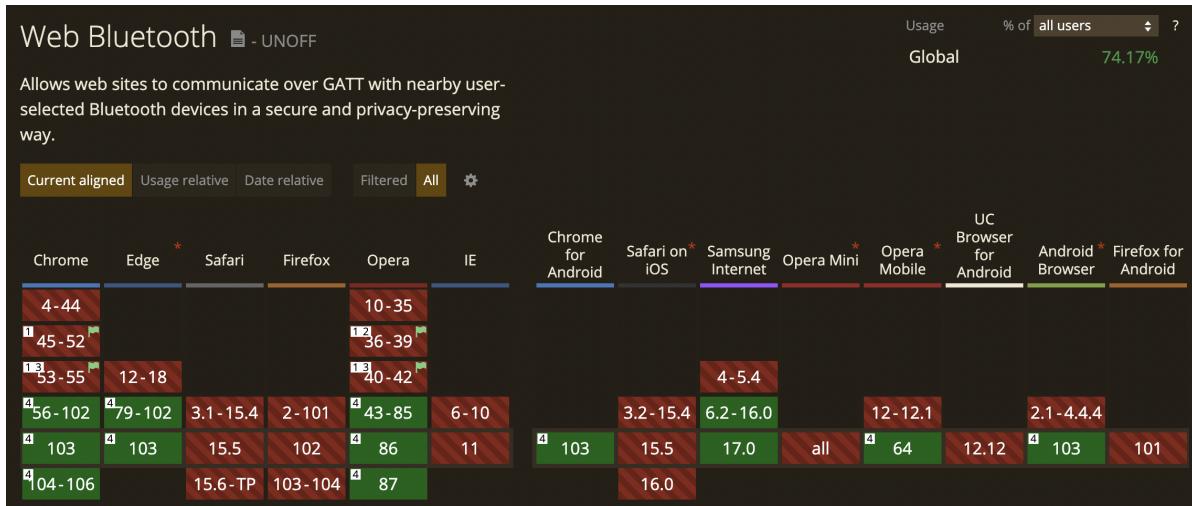


Fig. 4.5: Browser compatibility overview of Web Bluetooth (Caniuse, n.d.).

Nevertheless, IDUN is building a product that aims for an extensive user base in 2-3 years, as can be seen on their roadmap in Figure 3.4, which means that browser compatibility could come and ease out over the coming years once browser manufacturers start implementing the API. One problem, however, is that the web Bluetooth API cannot be run in a service worker, making it impossible to run in the background when e.g. the device has its screen locked or another app is currently opened on a smartphone (WebBluetoothCG, 2018), which is an intermediate problem, even for the upcoming smaller and specific user groups with the current personas. While researching Web Components, the author came across another technology: Capacitor, a JavaScript library that can compile and run web apps as native apps, with the ability to access native APIs (Ionic, n.d.-a), such as the camera or, especially important for IDUN, the BLE API (Capacitor-Community, 2022). Developers can use Capacitor to write BLE code with the same interface as Web Bluetooth, compile the code and run the applications on native devices with background functionality.

After further research, as shown in Appendix D, almost the entire Sprint 6 was spent evaluating the possibility of using Web Bluetooth for IDUN's NIP. At the end of the sprint, a working PoC SPA was created with an iOS and Android build that fulfilled all needs in terms of developer experience, the latency of the EEG signal from the device to a visualisation plot and the power consumption of lower-end smartphones. Following this, the author proposed to change the original architecture roadmap as depicted on Figure 4.4 and skip the first two steps and go directly to step 3 in order to accelerate the development pace and enable greater market maturity for IDUN's NIP as soon as the end of 2022.

The use of a web app, combined with the use of modern APIs and the compilation of the app for mobile applications when compatibility is not guaranteed, is called a web-native

approach (Ionic, n.d.-b). Besides the time saved by not having to develop platform-specific apps but using a single code base, this approach also has the advantage that a library that abstracts the logic of connecting a BLE device such as the IDUN device can already be created into a single installable unit, e.g. in the form of an NPM package. This library can be implemented in end-user apps and connects directly to the hardware without the need to download a companion app from IDUN itself, and is one of the solutions to the findings from the user interviews. The time saved with a web-native approach allowed IDNU to already focus on creating such a library and using it in their web app, which would be the console or GUI as in the AWS example, allowing dogfooding for IDUN's own software offerings and eliminating preliminary issues before releasing the library to the public (Techopedia, 2016).

4.2.4 Python to WebAssembly

Another key event during the ten sprints took place about two sprints before evaluating the web-native approach. The idea was that, as mentioned in section 3.4, when it comes to how important and necessary the Python ecosystem is for IDUN and external people as presented in the personas, it might be possible to create Python code for specific neural signal data processing, compile it to WebAssembly, a low-byte compilation target for high-level languages that run mainly in the browser, and then use it in web applications such as, e.g. the GUI application of IDUN's NIP. Sprint 5 evaluated compiling Python into WebAssembly, which seemed promising at first but turned out to be too far away from today's possibilities. There is an interesting open source project called RustPython, a Python interpreter written in Rust that allows the interpreted code to be compiled in WebAssembly. However, the project's maturity is currently unsuitable for production, as the maintainers even mention it (“RustPython”, 2022).

Another option would be to use Pyodide; the CPython interpreter ported to WebAssembly (“Pyodide”, 2022). Apart from the fact that the creation of a web application would be drastically more significant if a complete Python interpreter were sent to the browser, this interpreter also does currently not have the functionality to add additional Python packages apart from the standard library, e.g. PyPi, which makes it easy to build vanilla Python on top of WebAssembly codebases, but not with custom packages installed, such as machine learning packages needed for EEG classifiers. The only options left were to develop an own Python to WebAssembly compiler, contribute to the two open source projects, or give up the task of embedding Python code in a web application such as IDUN's GUI application to interact with NIP's API. The latter was chosen because it was still too early, immature and time-consuming, as the results of Sprint 5 showed.

4.2.5 Kubernetes and Fargate

One of the first technical decisions the author of this thesis made was which technology to use for creating backends for an n-tier¹ system like IDUN's NIP. The use of a microservice approach was already given by the fact that a polyglot backend was needed, such as Python for data-heavy tasks and TypeScript for real-time and API-specific tasks due to the maturity in the previously mentioned examples of each language. If one decides to take a microservice approach, one can still debate whether to proceed with serverless functions instead of hosting container images. Given the requirement to use AWS mentioned in section 3.4, the only way to host serverless functions was to use AWS Lambda. AWS Lambda was already used in the previous PoC version of the software system at IDUN and did not work as well as in cases where, for example, batch processing of previously collected data would exceed the maximum computation time or CPU limit of AWS Lambda. This, coupled with the cumbersome aspect of handling dozens if not hundreds of serverless functions and managing the entire "cluster" of multiple functions and their versions and endpoints, led to the decision not to use Lambda for the most essential and critical parts of the backend in the author's experience so far.

Building microservices not with serverless functions on AWS, has multiple solutions: the most prominent ones are utilising Kubernetes via AWS Elastic Kubernetes Service (EKS) or AWS Fargate, which is a serverless and easier-to-use version of Kubernetes (Amazon Web Services, n.d.-c). The author consulted cloud experts in the very first sprints from the company Nuvibit to guide the decision. The author himself is not experienced in Kubernetes and would need to learn many ways to implement a Kubernetes cluster, which was one of the items mentioned to avoid mentioned in section 3.4. Nuvibit recommended going with AWS Fargate since it is similar to Kubernetes but abstracts most things away to concentrate on adding business logic rather than handling overheads coming with introducing a Kubernetes cluster. Fargate is per se also serverless, making it cheaper for a product with hard-to-estimate usage such as IDUN's NIP in the beginning but still gives enough flexibility in specifying the underlying hardware for computationally heavier tasks that, e.g. would exceed AWS Lambda. As soon as IDUN goes toward utilising large-scale deep learning models that utilise specific GPU units, Fargate will come to its limits since specifying GPU tasks is impossible (AWS, 2019). One way or another, this decision will have to be reconsidered in the future to avoid a long-term commitment to one provider such as AWS and to the increasing investments of Kubernetes from several cloud providers.

¹The term n-tier refers to an architecture design pattern where the logic of presentation, application processing, and data management are decoupled from each other, as in the case of, e.g. multiple microservices.

4.2.6 Kafka and Kinesis

Another early technical decision, made with the help of expert interviews, was which streaming technology to use. As with many things in software, there are hundreds, if not thousands, of ways to solve a problem, such as streaming text-based data like the EEG data from IDUN's device over the internet to the cloud. Initially developed by LinkedIn, Apache Kafka is a very prominent technology for such a use case. It is battle-tested, used in production by large technology companies (Apache, n.d.) and well maintained by an active community ("Apache Kafka", 2022). However, similar to Kubernetes, it comes with much overhead, and the author himself has no experience with Kafka, so he would have to learn everything from scratch. Another option is to use AWS Kinesis, a service AWS provides to process data streams over the cloud, as Kafka does, but without the overhead of managing the Kafka instances themselves. AWS Kinesis allows streams to be replayed, restored and sent to an AWS Fargate cluster, e.g. real-time processing of the data, or data to be stored securely in storage systems such as AWS Simple Storage Service (S3) as shown on Figure 4.6. An important aspect is that the data source can also come from a WebSocket stream, which will be addressed in the next section. However, the decision for Kinesis was relatively easy, as the reasoning was similar to that between Kubernetes and AWS Fargate. The decision was also supported by the experience and opinion of the cloud experts at Nuvibit.

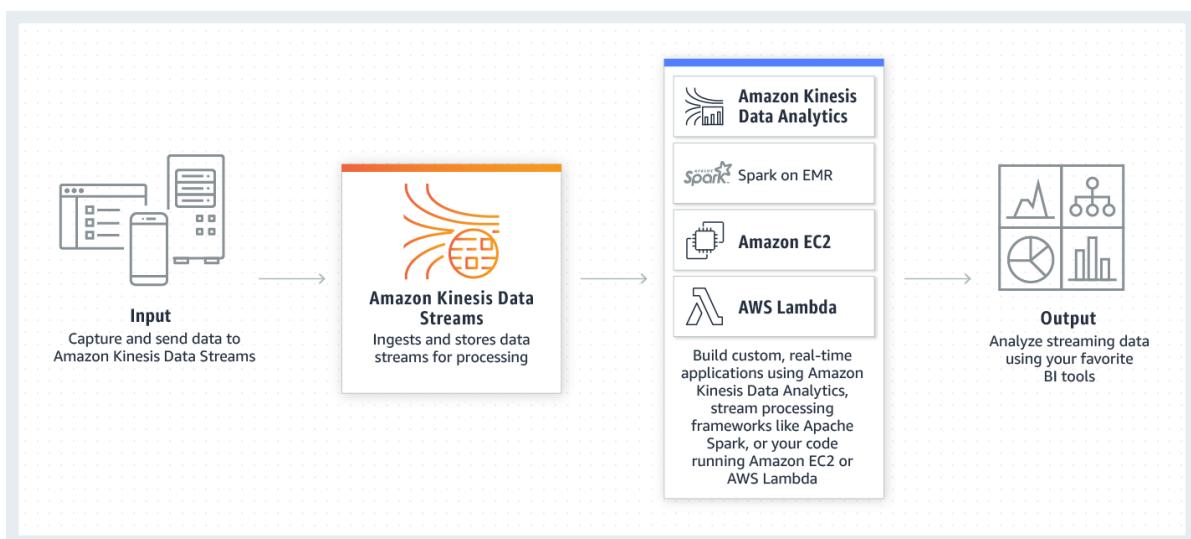


Fig. 4.6: Example use-case architecture of AWS Kinesis
(Amazon Web Services, n.d.-a).

4.2.7 MQTT and WebSocket

As previously stated, a decision had to be made regarding the technology to transfer data from a physical device, such as IDUN's EEG sensor hardware, to the cloud. Previous engineers at IDUN used MQTT to stream data from the hardware directly to the web app, as mentioned in the list of bugs and flaws in section 3.1. MQTT is not well suited to sending high-frequency data in real-time, such as EEG, and it is geared toward lower-power IoT devices rather than, say, a computer or smartphone to which the IDUN device would be connected. As a result, the decision to use something else had to be considered. Another option is to use WebSocket, which is designed for high-frequency updates that can be updated in real-time in both directions. IDUN would want to use a high-frequency protocol because, e.g. HTTP can only handle about ten requests per second, whereas e.g. WebSocket can handle nearly 4000 requests in the same amount of time. The main reason for this significant difference is that, e.g. the browser limits the number of concurrent HTTP connections, whereas a WebSocket connection has no limit on the number of messages it can send or receive (Luecke, 2018). Sending EEG data at a frequency rate of 250 samples per second from the IDUN hardware and receiving multiple classification responses from the cloud based on the chosen classification necessitates more than ten requests per second.



Fig. 4.7: Photo of an internal group discussion with the firmware engineers from IDUN.

WebSocket also integrates easily with the earlier technology decision for AWS Kinesis, as Kinesis can subscribe to an API gateway service from AWS that can be used to build Representational State Transfer (REST) APIs (more on this in section 5.2). An internal group discussion with firmware engineers for IDUN’s hardware was organised to validate this decision, as shown on Figure 4.7, as it was too BCI specific to ask, e.g. Nuvibit’s cloud engineers. The alignment with the firmware roadmap and its interface, which would be necessary for, e.g. the BLE library that would consume it as mentioned in subsection 4.2.3 was key to the success of building an example N/CI at IDUN.

4.2.8 IaC with Terraform

As mentioned in the list of bugs and flaws in section 3.1, AWS Amplify took over handling IaC via AWS CloudFormation. When creating the new version of the system without Amplify, the author was now free to choose which IaC technology to use. The author could have again used AWS CloudFormation, but without AWS Amplify, or he could have used the more modern AWS Cloud Development Kit (CDK), which provides specific syntax in specific languages for building IaC (Amazon Web Services, n.d.-b). However, there is a very well-known technology in the industry called Terraform, an open source and YAML-based tool from the company HashiCorp, which is similar to, e.g. AWS CloudFormation’s JSON syntax in declaratively describing IT resources in the cloud, with the big difference that it is cloud agnostic, meaning that Terraform can be used to build and deploy IT resources not only on AWS but on any cloud provider currently supported by HashiCorp (HashiCorp, n.d.). Nevertheless, Terraform is currently still in beta, which is usually not a very good sign for production readiness; nonetheless, Terraform is used in production by various large tech companies (StackShare, n.d.). Again, Nuvibit’s cloud experts were consulted to decide which IaC tool to use, as the author had no experience with, e.g. AWS’ CDK or AWS CloudFormation. As a result of the expert interview with Nuvibit, it was clear that Terraform was the right way forward for IDUN, as future multi-cloud setups or other IT resources can also be handled via Terraform e.g. Auth0 authentication tenant setups, GitHub organisation setups via IaC and more. In addition, the author already had experience with Terraform, which was another argument for using Terraform.

The decision to use Terraform was also made relatively early in the process and laid the foundation for every infrastructure built after that to be based on Terraform code. Tools like Infracost and tfsec were set up as part of the bootstrapping project stages in order to assure quality in the form of linting over IaC code via tfsec in continuous integration and continuous delivery (CI/CD) pipelines or calculating price estimations based on IaC code as soon as writing it in the editor via the Infracost add-on.

4.2.9 Python SDK

The key event called Python SDK on Figure 4.2 happened quite late in the process but was one of the important events. It describes the realisation of creating a public and a private Python library mainly for the Noel persona. The realisation followed internal group discussions with the neuroscience team at IDUN. Before these internal group discussions, the author assumed that a GUI application such as the console application of IDUN's NIP in combination with an API and a client-side library would suffice for applications created by, e.g. Evans. However, as mentioned in the last point of the user interviews listed in subsection 4.2.1, there would need to be a way to control the EEG data collected by IDUN's device and synchronise it locally with other data sources, such as heart rate data, without having to send the data to the cloud². Noels would use a GUI application like the idea for the console application of IDUN's NIP. However, they would nonetheless still like to have low-level control of the data, e.g. to include it in PsychoPy experiment scripts or to connect the data via an LSL stream, e.g. to a reference EEG device to compare EEG signals (which is, e.g. particularly important for IDUN's internal researchers). For this, they would need a library that allows them to connect to the device without an app, if possible only for research purposes. After the internal group discussions with the neuroscience department, the author proposed building an SDK that precisely does this.

Parts of this SDK can also be made public as part of the software offerings from IDUN, such as connecting to a device for limited research purposes or to, e.g. visualise plots specifically made for IDUN's EEG data as also mentioned as one of the user interview insights in subsection 4.2.1. An internal SDK version of this can e.g. be used to, e.g. include raw data pre-processing pipelines and feature extraction as preparation for machine learning classifiers which are all part of IDUN's provided intellectual property and should not be made public. Nonetheless, this internal SDK can be used in the neuroscience team and production, e.g. Python microservices that process data in real-time. The reason why one would want to have that is that if, e.g. a data scientist creates a new script for processing EEG data that can be used, e.g. demos, used in research and even in production for an API endpoint that IDUN sells, then they all would need to have the exact source of the code. An internal PyPi Python package for the SDK is the solution to that. This realisation came pretty late and is, as of writing, still ongoing.

²The reason for this is that one cannot synchronise data sufficiently over an internet network due to latency problems or time drifts.

Chapter 5

Results and summary

5.1 Key aspects of a N/CI

5.1.1 Stream-based events

5.1.2 Critical and non-critical

5.1.3 Hardware-accelerated encryption

5.1.4 Per-device auth and opt-in

5.1.5 Graph database

5.2 Example architecture of a N/CI

5.3 Achieved goals

5.4 Summary and reflection

5.5 Discussion

5.6 Conclusion

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Appendix A

User interviews

User interview outline

User interview with Paul Doyle

User interview with Ghena Hammour

User interview with Nicole Zahnd

User interview with Melanie Baumgartner

User interview with Mayank Jain

User interview with Martin Hutchings

User interview with Jacopo de Araujo

Appendix B

Design artefacts

First console web app wireframes

Second console web app wireframes

Auth page wireframes

User journey architecture

Appendix C

Repositories

idn-guardian-cloud

idn-guardian-console

idn-guardian-sdk

idn-internal-sdk

spatial-place

Appendix D

Other documents

Architecture explorations

Customer personas documentation

Asana project plan from IDUN

Asana project plan from the author

Web-first approach proposal

Other documentation