MODULAR HEADGEAR DESIGN
FOR NEUROTECHNOLOGICAL APPLICATIONS

MASTER THESIS
by
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Over the last ten years, different products have been introduced to the market with which consumers can analyze or even modify the activity of their brains. When it comes to the design of these neurotechnological headgears, there are contradictory requirements between the functionality, fit and experience. As a result, current devices are generally either oversimplified in their capabilities, or limited in their comfort, accuracy or quality of the interaction. This report describes the development of a novel headgear design that addresses this compromise and aims to offer a better balance between these three properties through the introduction of modularity.

At first a better understanding of the technological possibilities is created through literature research. Three technologies are selected for implementation in the headgear: EEG, fNIRS and tES. Relevant anthropometric data are thereafter collected and requirements are formulated regarding ea. the target range of head shapes and the accuracy (‘technical fit’) of the product placement. Key application scenarios are then selected for which the modular product can be most valuable. These scenarios are used to formulate requirements from different users and contexts. The selection focuses on the at home neurorehabilitation after brain trauma, on ‘neurofeedback’ training and on general cognitive enhancements.

This preparatory phase sets the stage for an iterative creative process in which the main contradictions in the assignment are tackled. The final design comes about in a three-step manner. First there is a focus on the basic modular structuring of the components. Next the concept is further elaborated upon in terms of form and interaction, and later in detailed solutions, materials and production.

The result of this project is a design that goes by the name Nerva headgear. It is an adaptable frame that can be used to place the various technical tools on the different target locations on the scalp. The frame is built up of elements that can be re-configured. The necessary electronics can be connected to the structure. In this way the product can be adapted for different applications, users and usage contexts. It can be set up to target only the areas of interest and using only necessary technological tools on the scalp.

By extending or rotating some of the key components of the headgear, the product can be adapted for users with different head shapes and sizes. Furthermore, it is possible to regulate the pressure that is exerted on the scalp. This allows to optimize the comfort and the signal stability during use.

A prototype is developed and put to test to assess the performance of the design on the aspects functionality, fit and experience. The evaluation shows many points for further improvement, but the concept remains intact. The important features of the product have proven to be feasible and the practical potential is affirmed. The adaptability for different head shapes was found successful (though various adjustments are suggested) and it is believed that the design can potentially outperform alternatives in its technical fit. The overall user experience has remained generally positive, especially on its hedonic qualities. A study with a more representative user group should be performed in the future to assess the true pragmatic qualities of the design.

The project outcome shows that it is possible to introduce high levels of modularity and adaptability in the design of consumer products, whilst still providing a satisfactory user experience. As such one can develop product propositions that perform better than competition on the relevant properties.
Preface

The human brain has always been a fascination of mine. There is nothing more crucial to our existence, yet it is still such a mystery. When a friend asked me what I was looking for in my graduation project, I jokingly said ‘If you know anything in the area of brain hacking, I’m in.’ Soon after that I realized that my graduation project was actually the perfect opportunity for me to dive into this slumbering fascination. An idea was born and I set out on a mission to become a designer in neurotech. If only for a moment I could operate at this frontier of our scientific understanding and our knowledge of ourselves. Wouldn’t it be the best metaphor to end my education by developing something that can hack that which is educated in the first place?

This report documents the process and results of my graduation project. The domain of neurotechnology has proven to be a very exciting playground for designers. Not ever before did I take on a challenge that required so many different aspects to be considered, balanced out and assured. Also never before have I worked out an idea individually to such extends on a holistic and a detailed level as what I have done in this project. I can only look back with a feeling of accomplishment and look forward with confidence to a next chapter in life after this education.

Although the combination of neurotechnology and graduation seems like the perfect mix for an existential crisis, I have felt enchantment throughout. This project marks the end of my studies, but I wish that my curiosity and desire for learning may never stop. To the reader of this report I wish you too can find that which triggers all your senses and take charge.

Enjoy,

Potte van Duuren

ACKNOWLEDGEMENTS

A special thanks goes out to my supervisors Zoltán Rusák and Anton Jellema for their enthusiasm when I pitched this project and their valuable feedback during the process. I’d like to thank Titus for giving me all the room I needed to work on this project, quite literally and figuratively. Thank you Lisa for liking my brain like I like yours and patiently guiding me through these past months without complaints. And thank you dear parents for your support in everything that my curiosity has taken me to, leading up to this point in my life.
1. Introduction
1.1. About the project

1.1.1. CONTEXT OF THE PROJECT

GRADUATION PROJECT IN INDUSTRIAL DESIGN ENGINEERING (IDE)

This report presents the outcomes of a Graduation Project in the program of Integrated Product Design (IPD) at the TU Delft, faculty of IDE. The theme of this project was believed to be an excellent opportunity for academic learning and demonstration of skill, since it touches upon key topics for many design projects: the integration of technological and user aspects. The supervisory team represents expertise on these two topics. The time that is assigned to the project is 23 weeks of full time work.

THE DOMAIN OF NEUROTECHNOLOGY

This project is set in the domain of neurotechnology. This field deals with the development of tools to interact with the brain and the central nervous system. These tools can be divided into two categories (University of Freiburg, 2016):

I) technical tools to measure and analyse the activity of the nervous system,
II) technical tools to modify the activity of the nervous system.

A variety of techniques is available to achieve this measurement and modification. This stretches from surgical implants to non-invasive devices for consumers. As technological developments progressed, the quality and affordability of the technical tools has increased significantly.

As a result, the company NeuroSky released the first neurotechnology headset for consumers in 2007 (Figure 1), shortly thereafter followed by the company Emotiv (Economist, 2007). These headsets can be used to measure the activity of one’s own brain at home. Since then, many start-ups have entered this market with a variety of applications that include human-computer interaction, brain training and user monitoring.

The last years have seen an increasing interest in neurotechnological developments, illustrated by the $100 million American BRAIN initiative (NIH, 2014), the European BNCI Horizon2020 project (Brunner et al., 2015) and by the steep increase in granted patents for neurotech applications (Fernandez et al., 2015).

With the growing attention of media and consumers it can be said that the age of neurotechnology has arrived.

This sets the stage for designers to get involved and bring successful product propositions to the consumer. This project is aimed at developing such a new product proposition within the domain of non-invasive neurotechnological headgear.

Figure 1: The NeuroSky headset uses one sensor on the forehead to give insights on the brain’s activity (NeuroSky, 2007)
1.1.2. **PROBLEM DEFINITION AND ASSIGNMENT**

The assignment originated from observing the current market of neurotech headgear. There appears to be an inherent field of tension in this domain when it comes to the **functionality**, **fit** and **experience** of these products. This can be illustrated with an example:

Covering the complete head with electronics is not desirable from the end-users point of view regarding comfort, convenience and appearance. However, the more parts of the head are covered, the more functionality can be offered with the technology (in theory). Hence, increasing the functionality puts stress on the product experience.

Furthermore the variation in users' head shapes and sizes makes the dimensioning of any of these products a tough challenge for the designer. The exact reproducibility of target locations can be hard and this challenge becomes greater as the number of locations increases. As a result there is a risk of either longer set-up times (limited user experience), or inaccurate placement (limited product fit). This in turn can lead to variation in signal quality.

In other words, commercial players in the neurotechnology domain have to make a compromise between functionality, experience and fit. The result is that products are generally either oversimplified in its capabilities or limited in their other qualities.

These three key elements that are in odds with each other are defined within this project as follows:

- **Functionality**: The range of capabilities of the product and its suitability for a variety of applications;
- **Experience**: The overall perceived quality of the interaction of the user with the product in a context;
- **Fit**: The conformity of the dimensions of the product to anthropometric and technical requirements.

**Solution direction**

A new solution is envisioned for the problem that is discussed: A modular type of headgear can be developed that is adaptable to suit the requirements of various contexts. Through modularity it should be possible to find a better balance between the attributes **functionality**, **experience** and **fit**, not having to limit any of them drastically. The goal of this project is to propose a design solution that does that.

*Design a novel headgear for neurotechnological applications that addresses the current compromise between functionality, fit and experience and through modularity finds a better balance between them.*
1.1.3. THE APPROACH

This project uses four distinct phases while working towards a new product proposal: Analysis, Concept Development, Detailed Design and Evaluation.

The goal of the Analysis phase is firstly to understand the basic principles of the domain of neurotechnology headgear. The three element key product attributes in the assignment (functionality, fit and experience) will be used as themes to explore this. The research is executed through extensive literature studies, expert meetings and observations. This leads to the identification of requirements for the final concept and the main design challenges that need to be solved during conceptualization. At the start of every Analysis chapter, the methods that were used will be explained further.

After this section there will be a phase of repeated converging and diverging creative steps. The output of the previous phase forms the starting point for this. This development is done in a three-step manner, in line with the Fish Trap model (Muller, 2001). First the main overarching product or product platform structure will be created. Next we will zoom in on the components of the concept and define forms, connections and interactions. In this phase there is a strong focus on visuo-spatial techniques such as design sketching and rapid prototyping.

In the third step of the development the details of the concept proposal will be filled in and all dimensioning, materialization and assembly aspects of the product will be developed. This is done with digital modelling and simulations and based on the collected anthropometric data. At the end of this phase the product is almost ready for production, excluding some of the final engineering.

The detailed product proposal is put to test in a final Evaluation study. In this study the proposal is tested on the three key performance elements functionality, experience and fit. A prototype is produced to test the usability and find its main points of improvement.

The project is then concluded with a reflection on the design and process.
1.2. About the brain

1.2.1. INTRODUCTION
Before any further presentation of the Analysis, this chapter will explain the basic working principles and anatomy of the brain in relation to neurotechnology. This information is a foundation for further understanding of the report.

1.2.2. MEASURING THE ACTIVITY OF THE BRAIN
Neurons are the specialized cells in our brains. They use small electric impulses to transmit signals to each other. If they fire signals together, the signals become strong enough to measure. Rhythmic patterns occur in the current fluctuations. These are called brain waves. Brain wave frequencies are associated with different cognitive states (see Figure 3). Many of the technical tools in neurotechnology are meant to measure or modify these so-called electromagnetic signals.

The more active the neurons are, the more blood they require. Hemodynamic techniques measure this as an indicator for activity, rather than the electromagnetic signal. Since it is an indirect measurement of neural activity, it has a lower temporal resolution (it is slower) compared to electromagnetic techniques. Measuring the blood flow can provide insight into the activity of regions of the brain, but does not contain the information that brainwaves do (Tan & Nijholt, 2010).

Neural pathways connect neurons from one site in the brain to the other. In this way the different parts of the brain can communicate with each other. Advanced neurotechnological tools can create an image of the neural pathways in your brain. Our body is capable of creating new neural pathways throughout our lives. This ability to reorganize and adapt is called neuroplasticity. It is an important focus point for treatment of brain damage, learning difficulties, exercise and meditation.

Main insights
In the different sections of the Analysis phase, the main insights will be listed at the bottom of the section like this for clarification.

- Fluctuations in electrical excitation and blood flow are the basis of the analysis of brain activity.
- Different cognitive states can be identified or monitored by analyzing the electrical brain signals.
- The ability of the brain to reorganize and adapt can be 'exploited' in neurotech applications

Figure 2: Representation of a neuron with a neural pathway.
Figure 3: Brainwave frequency characterization (Hammond, n.d.)
1.2.3. DIFFERENT REGIONS OF THE BRAIN

Groups of neurons together are associated with different functions, depending on their location in the brain. For neurotechnology applications it is important to have an understanding of these functional localizations to decide which areas to target or what conclusions to draw from the data.

The outer layer of the brain is known as the cerebral cortex. Non-invasive neurotechnology mainly measures or modifies the activity of this part. As a whole it is divided by deep grooves into four lobes. These can be further subdivided based on different criteria, such as the exact ‘ridge’ or the cellular composition. In Figure 4, a division is made based on overarchig functional correlations. We can see here for example that a lot of perception happens in the back of the brain, most movement is coordinated in the middle, and much of the reasoning happens in the front of the brain. At times different functions are only a few millimeters apart, especially in the central and temporal region. This makes that such areas can require high spatial resolution of neurotechnologies.

- Specific functions have specific associated locations in the brain and can in this way be targeted.
- Different regions of the brain can require different precision when targeted.

1.2.4. BETWEEN THE SCALP AND THE BRAIN

The brain is enclosed by cerebral spinal fluid (CSF), the skull and skin. Signals that are given or taken through the scalp (for measurement/modification) are affected by these layers in various ways. The thickness of the skull and skin, and the volume of the CSF vary among the population and are not constant over the scalp. In practice this means that the activity recorded at (or applied at) a site on the scalp can not solely be associated with the area that is directly underneath. The signals are diffused and only with advanced computational tools they can get restructured. Neurotechnology focusses hence not only on technical hardware tools, but also the development of computational tools.

- The interaction (analysis/modification) is often not precise because signals get diffused by hair; skin, skull and CSF.

Figure 4: The functional localization of the cerebral cortex (After The Times Online UK (2010)).
2. Analysis
2.1. Introduction

The project assignment is to “Design a novel headgear for neurotechnological applications that finds a better balance between functionality, fit and experience”. The goal of this Analysis phase is to come towards a realistic and well-considered program of requirements for the further interpretation of the assignment. Furthermore the most interesting design challenges that are to be addressed in the conceptualization will need to be brought forward.

The assignment identifies three key aspects of neurotechnological headgear that are in odds with each other: functionality, fit and experience. These three aspects are used as guiding framework during the Analysis to reveal relevant requirements and insights.

The first theme that is discussed is functionality (2.2). The goal is to get an understanding of how the future design can be made suitable for a wide variety of applications. First a selection is made of neurotechnologies that are suitable for implementation in wearable consumer products. This is based on a literature study and evaluation. The selected technologies are then further explored. The basic working principles and components of these technologies will be discussed, as well as the practicalities of implementing them in headgear. Requirements are formulated based on these discussions. At the end of this section there is a clearer image on how the future product proposition could exactly offer a wide range of capabilities from a technological view point.

The second theme that is discussed in the Analysis is that of the product fit on the head (2.3). Relevant anthropometric standards and measures of the head will be explored in relation to the domain of neurotechnology. The variation of the human scalp will be decomposed and the expected range of the target group is established. This is done by research into scientific literature and anthropometric databases. This too leads to a set of requirements and for the final design.

The last section discusses the user and context of the product, which relates back to the aspect experience (2.4). First a better understanding is developed of potential users and usage context of the future modular headgear design. A selection of focus applications is made and the characteristics of those and their users are then discussed. Real-time user- and context research is herecomplemented with its digital variants (video footage, forum posts). The different users and context for which the product is envisioned to be useful can have contradicting requirements. These will be brought forward. This is where the modularity, which is the approach of the assignment, can provide an outcome.

The Analysis phase is concluded with a Program of Requirements, a Design Vision and the identification of main design challenges for the next stage (2.5).
2.2. Technological functionality

2.2.1. INTRODUCTION
In this section of the report, the technological functionality of the future product will be discussed. This is the first aspect in the series of three that together compose the tension field in the domain of neurotech headgear. Part of this project’s goal is to propose a new headgear design that is suitable for a wide variety of applications. This section works towards a better understanding of what that actually means for the headgear design in a technological conception.

Firstly the different neurotechnologies that are interesting for wearable applications are selected (2.2.2) and their basic properties are explored (2.2.3-2.2.5). It is discussed what requirements they bring to the product design when applied on the head. A first step towards their implementation in headgear is made through a discussion on the different strategies to combine (2.2.6) and rearrange the configurations (2.2.7). The information is established by an extensive study in scientific literature and complemented with market observations.

2.2.2. SELECTION OF TECHNOLOGIES

MEASUREMENT OF BRAIN ACTIVITY
Mehta and Parasuraman (2013) reviewed how different technologies for measuring brain activity score on mobility and costs (see Table 1). Techniques with no mobility or high costs can be discarded in this project since they are not fit for consumer wearables. The study shows three techniques that are still suitable, these are Electro Encephalography (EEG), functional Near InfraRed Spectroscopy (fNIRS) and TransCranial Doppler Sonography (TCDS).

The suitability for wearable applications of these first two techniques is underpinned by other research (e.g. Gramann et al., 2011; Pinti et al., 2015; Safaie et al., 2013) and products on the market. TCDS however has not been implemented in wearable applications up to now (as far as the authors knowledge) and its application fields are limited. Based on this it is decided that EEG and fNIRS are the two techniques that are relevant for implementation in this project. The former measures electrical activity and the latter blood oxygenation. This contributes to the cause of striving for a broad functionality, as both electromagnetic and hemodynamic domains are represented.

Table 1: Characteristics of neurotechnologies for measuring brain activity. Adapted from Table 1 in Mehta & Parasuraman (2013). Fields that are marked green were selected for this project.

<table>
<thead>
<tr>
<th>Analysis Method</th>
<th>Mobility</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td>fMRI</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td>fNIRS</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>TCDS</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>EEG</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>MEG</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td>PET/SPECT</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td>DTI</td>
<td>None</td>
<td>High</td>
</tr>
</tbody>
</table>

MODULATION OF BRAIN ACTIVITY
The signals of the brain can be modulated by sending magnetic, electrical or ultrasound signals into the scalp. These techniques are called Transcranial Magnetic, Electrical and Ultrasound Stimulation (TMS, tES, TUS). The latter two are promising for wearable applications (NEURECALL INC., 2016). They are affordable and mobile and there is a promising outlook described in scientific publications (Hameroff et al., 2013, Legon et al., 2014). However, the immaturity of TUS and the limited understanding and control over its safety measures (Sanguinetti et al., 2014) makes that it is not interesting for this project. This means that tES is the only relevant neuromodulation technique to analyse for implementation in this project.

Table 2: Characteristics of neurotechnologies for modifying brain activity. Based on NeuRecall Inc. (2016). Fields that are marked green were selected for this project.

<table>
<thead>
<tr>
<th>Modulation Method</th>
<th>Mobility</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMS</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td>tES</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>TUS</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

EEG, fNIRS and tES are suitable for implementation in headgear applications.
2.2.3. ELECTRO ENCEPHALOGRAPHY

An Electro Encephalogram (EEG) is the measurement of the electric current generated by the brain. This creates an image of the brain’s activation that can then be analysed. The activity is recorded through electrodes on the scalp. There are two main types of electrodes. Wet electrodes use a conductive gel to lower the skin impedance and are superior in signal quality (Oliveira et al., 2016). Dry electrodes are placed directly on the skin and are hence more practical for consumer products.

A basic EEG setup requires an active, a reference and a ground ‘channel’ (Figure 5). The active channel measures the area of interest, in relation to the reference. This reference can be placed on another scalp site or neutral position, like the earlobe or mastoid (Tan & Nijholt, 2010). The reference and ground can be combined into one channel, leaving a minimal set up with two electrodes. A basic full-scalp EEG uses 19 channels. The gel from wet electrodes bridges the gap through hair at hairy regions. Dry electrodes need to be specially designed to make skin contact. ‘Comb style’ designs can thread through hair (Figure 6). Rubber polymer or foam based electrodes were introduced to increase user comfort (Chen et al., 2014).

EEG electronics are small and basic systems are very affordable (see Figure 7). The electrodes typically have a diameter of about 1 cm. They are connected to circuitry that contains amplifiers, filters, an A/D converter and a recording device. Together with digital processing this can separate the desired signal from e.a. background noise, powerline interference and muscle contraction artefacts (Teplan, 2002).

A moderate pressure is needed to keep the electrodes in place and minimize movement artefacts. A typical pressure of about 100 g/cm² is recommended (Ozawa et al., 1986) but a range from 50-500 g/cm² can be acceptable if comfort is not at risk (Grozea, Voinescu & Fazil, 2011). The pressure on electrodes is correlated with the impedance of the skin. Therefor it benefits the signal quality to have a constant pressure over the different target sites. This is important for the headgear design.

Specialized electrical engineering is outside the scope of this project. There are various suppliers that produce open source hardware that can be used in this project, or even as basis for a final product. An overview of such electronics is presented in Table 3. ‘OpenBCI’ and ‘Ganglion’ are the most capable systems. They have a high bitrate, samplerate and resolution, which are aspects of the product quality. They are most interesting for implementation in the project or even in a final product proposition. They are designs from the same manufacturer.

The headgear should be able to contain a minimum of 2 electrodes (active + ref/gnd) and should be expandable.

The earlobes/mastoids should be among target sites of the headgear:

An electrode size of ca. 1 cm² needs to be accounted for:

‘Comb style’ designs can thread through hair at hairy regions.

The pressure over all channels should be similar:

A pressure of about 100 gr/cm² should be present on the target sites.

‘Comb style’ designs can thread through hair at hairy regions.

Table 3: Specifications of available Open Source EEG hardware as provided by their respective suppliers.
2.2.4. FUNCTIONAL NEAR INFRARED SPECTROSCOPY

Near infrared light penetrates skin, bone and tissue, but is absorbed by the protein Hemoglobin (Hг) in our blood, which transports oxygen. When a NIR lightsource is pointed at the brain, the reflected light contains information about the level of oxygen, which is related to activity. This is the principle of fNIRS (Figure 8). There are different fNIRS techniques, of which Continuous Wave (CW) is most suitable for wearable applications. It is affordable, simple, small and light weight (FERRARI & QUARESIMA, 2012; VON LÜHMANN, 2014).

Most modern systems use multi-wavelength LEDs as light emitters. The reflecting light is measured with Silicon Photo Diodes (VON LÜHMANN, 2014). These can be coupled directly to the scalp to make optical contact. This benefits the mobility and system simplicity (DIVYA & RAJ KUMAR, 2012). For a good signal they should be placed perpendicular to the scalp and their spacing should be rigid. Disturbances in their spacing will lead to signal fluctuations. In order to prevent stray light from hitting the optodes they are shielded with black foam (COYLE ET AL., 2005) (see Figure 8).

Hair should be moved aside since it disturbs the optical signal (especially dark and thick hair). A number of systems have been designed that can help to move the hair aside (e.g. TAKASHI, 2008) but they are not found to be very successful (D. HAIRSTON ET AL., 2014). Brush style probes are also developed for fNIRS research (KIAN ET AL., 2012) but are not yet commercially available and would require high investments.

The distance between the emitter and detector varies. Generally it is about 25-35 mm, and no further than 5 cm (LEÓN-CARRIÓN & LEÓN-DOMÍNGUEZ, 2012). They are often set up in a grid with multiple emitters and detectors. This is the reason that fNIRS probes on the scalp are usually several centimeters in width an length (see Figure 9 & Figure 10).

Next to a light emitter and a detector, the hardware consists of amplifiers, filters, A/D converter and current regulators. Different types of noise are filtered out digitally, such as that from bloodflow in the extracerebral tissue and artefacts of motion, heartbeat and respiration (NASEER & HONG, 2015).

The only open source hardware for this project is the OpenNIRS system (VON LÜHMANN ET AL., 2015). The components costs ca. 250$. 

- The headgear should facilitate the placement of LEDs and SPDs directly on the scalp.
- The setup of the headgear should allow for multiple LEDs and/or SPDs in different arrays.
- The typical distance between detector and emitter is about 30 mm.
- Probe sizes of 40-80 mm in width and 10-40 mm height need to be accounted for.
- OpenNIRS circuitry and design can be taken as starting point for the new headgear design.
- Black foam that absorbs NIR light should be used around the LEDs and SPDs.
- The sensors should be placed perpendicular to the scalp in order to optimize signal quality.
- The spacing between LEDs and SPDs should be rigid in order to prevent signal fluctuations.
- A succesful way to move hair aside before application needs to be found.
2.2.5. TRANSCRANIAL ELECTRICAL STIMULATION (tES)

In transcranial Electrical Stimulation, a very low current is passed through the brain to stimulate or inhibit brain activity. This is done by electrodes on the scalp. It is considered to be safe and has little known side effects (as long as one follows protocols). The effects of the stimulation are typically quite subtle. Depending on the location and electrical signal, tES it is believed to help neurons trigger more easily (Plautz et al., 2003), stimulate nerve growth (Fritsch et al., 2010), induce specific brainwaves (Voss et al., 2014) or affect hormone regulation in the brain stem (Tyler et al., 2015). The most common version of the technology is known as tDCS (transcranial Direct Current Stimulation).

The set-up of a tES device basically consists of a battery, a resistor and two electrodes. Stimulation occurs underneath the one, whilst the other causes inhibition. They are placed on the scalp as shown in Figure 11. To prevent inhibition of brain activity, this electrode can be placed for example on the shoulder. Supporting hardware includes safety fuses, a small microchip with a number of protocols and current control. The total system costs are usually well below $50.

The spatial resolution of tES is low since the skull and skin cause much signal diffusion. The electrodes are therefore often quite big, commonly over 20 cm$^2$. Saline soaked sponges are the most popular electrode choice, but smaller gel cup and self-adhesive electrodes (similar to EEG) are also used. There is no dry electrode alternative since that would lead in this case to skin irritation. The contact stability is much less crucial than for the other two techniques, since the signal is not interpreted but sent.

‘Ring setups’ of a number of smaller electrodes can offer more spatial focality when stimulating brain areas (Datta et al., 2009) (see Figure 12). This is at times referred to as HD-tES. Yet larger area electrodes are often still preferred and believed to work better (Ho et al., 2016).

» The headgear should be able to work with larger saline soaked sponge pads as well as smaller electrodes
» A probe size of over 4x4 cm needs to be accounted for in the headgear design
» The shoulders or arms need to be part of the target sites of the headgear as ‘neutral’ electrode site.
» Two channel setups should be possible that target various regions on the scalp.
» Ring setups (4x1) can offer enhanced functionality and should be considered for implementation

Figure 11: A typical tES setup using two sponge electrodes on the scalp (NeuroConn, 2013).
Figure 12: A HD-tES setup with a ‘4x1 ring montage’ (Soterix Medical, n.d.).
2.2.6. COMBINING DIFFERENT TECHNOLOGIES

The next generation of neurotech devices should combine different technologies to optimize the functionality and interaction (Edelman et al., 2015). It opens up a new range of applications, such as closed-loop brain stimulation management. It can also enhance other applications such as the creation of more comprehensive analysis tools (Castellone, 2013). This makes it interesting within this project too.

The different combinations are investigated. Naturally there are challenges when it comes to the application of multiple neurotechnologies on one scalp. The main findings are:

- The electrical signals of tES can interfere with EEG readings (if operated concurrently on the scalp). Extra hardware and advanced software is needed to even this out (Schestatsky et al., 2013; Schlegelmilch et al., 2013).
- Excess fluid from tES sponges can disturb the signals from neighbouring EEG electrodes.
- In EEG and tES the electrodes are placed on top of the target region. In this way they block each others access to the same cortical area (Soterix Medical Inc., 2016).
- There are hybrid EEG/tES electrodes available so that they can target the same area, but the technologies cannot be operated at the same time (NeuroElectrics, 2016).
- Since fNIRS electronics are placed around rather than on the target region, it is more suitable to be combined with the other two. Also since it uses optical signals rather than electrical signals, there is no real risk of interference (Khan et al., 2013, McKendrick et al., 2015).

Different examples are found that show that these practical limitations can be overcome (e.g. Ha et al., 2016, Roh et al., 2014) (Figure 13). At this point it is believed to be especially relevant to allow the combination of stimulation and measurement because it opens a whole new domain of applications.

Ring setups (see Figure 12) can be an good opportunity to combine different technologies. In the same way that tES electrodes are placed around each other, the fNIRS probes could be placed around a central electrode (or EEG around tES). In concept development this potential can be explored.

- The headgear should allow to use EEG and tES alternatingly over the same or different areas, using small tES electrodes.
- The headgear should be able to perform tES and fNIRS simultaneously over the same cortical area.
- Combining EEG and fNIRS (or even all 3 technologies) can be included but is not a priority.
- Ring setups can be used as gateway to combine two technologies in the conceptualization phase.

**Figure 13: Different multimodal neurotech headgeard systems. Clockwise from top left they are:***

- Hybrid (fNIRS+tES cap from Soterix Medical with optodes (black) around the electrodes (Soterix Medical, 2015).
- Hybrid EEG+tES cap from NeuroElectrics (n.d.).
- Concept proposal from Ha et al. (2016) that combines (fNIRS, EEG and tES)
- Concept proposal from Roh et al. (2014) combining EEG and tES.
DISCUSSION AND CONCLUSIONS

The new product can offer a wide functionality by adaptively integrating three selected technologies: EEG, fNIRS and tES. Together they cover a large number of possible applications, as they represent the different domains of electromagnetic analysis, hemodynamic analysis and neuromodulation. A list of currently available neurotech headgear for consumers that uses EEG, fNIRS or tES is compiled and included in Appendix I. This can be referred to in further stages of the project.

Since the selected technologies all have a distinctly different approach of interacting with the brain, it is interesting to combine different technologies. It is considered most relevant to combining EEG+tES and fNIRS+tES. ‘Ring setups’ and the use of hybrid probes are interesting gateways to do so.

In the most basic setup all selected technologies have only 1 or 2 channels on the scalp, but basic full head setups can have about 20. This makes it sensible to implement a type of adaptable channel count in the headgear design. It is not in the aim of this project to facilitate full-head configurations, so 8 to 10 target sites is seen as sensible maximum. The potential variations in probe size (1 - 20+ cm²) should be taken into account during design. When larger fNIRS probes or large tES sponge pads are used, the available number of channels can be reduced.

If the channel count is adaptable, their positioning on the head should be so too. In anticipation of the conceptualization phase, we can propose six different ways to achieve this. It depends on the usage scenario which of these strategies is preferred. These six ways are to design a headgear with:

1. Mechanically movable channels (e.g. a sliding rail or extendable elements);
2. Flexibly movable channels (e.g. a deformable wire or non-rigid materials);
3. A build up that can be changed and its components rearranged to target other sites;
4. Different replaceable modules that target combinations of sites for specific applications;
5. A shape that can be reoriented on the head to target different sites (e.g. place it backwards);
6. All sites permanently covered, but one can rewire the connections to those that will be used.

It is crucial for the functionality of the product to correctly deal with hairy regions of the head. A successful way of moving hair aside could be a unique product feature. Moreover, hairy regions (can) require different electrode designs for successful interaction. Different sensor types can be offered to the end user to meet varying quality, location and experience requirements. Snap connector style electronics can be used to deliver this flexibility. Next to sites on the scalp, the shoulder and earlobes should be included as optional ‘neutral’ target locations.

Other than clean contact with the skin, the signal quality depends mostly on the secure placement of the sensor and the quality of supporting hardware and software. Pressure is needed for a secure placement. The pressure over different channels is ideally equal and about 100g/cm². This should be taken into account during conceptualization and evaluation. Further specialized electrical engineering for noise and artefact reduction is beyond the scope of this project, but open source hardware can be used during development.

List of formulated requirements

» The headgear should be able to adaptively integrate EEG, (CW-)fNIRS and/or tES technology.
» Combinations of EEG+tES and EEG+fNIRS should be possible. Other combinations have less priority.
» The headgear should be compatible with different types of electrodes/probes, including [1] wet gel cup style EEG and/or tES electrodes of about 1-3cm² [2] self adhesive EEG and/or tES electrodes of about 1-3cm²; [3] dry flat and brush style EEG electrodes of about 1cm² and height up to 2cm [4] sponge pad electrodes of sizes at least up to 20cm² and height up to 2cm [5] Custom, shielded, LED and SPD arrays with a spacing of 25-40mm; [6] hybrid probes (optional).
» The sensors should be placed perpendicular to the scalp in order to achieve the best signal quality.
» Different hair styles and types should not hinder the headgear functionality. Assistance to move hair aside could be integrated.
» The headgear should have an adaptable channel count between 1 and 8-10 channels. This can be less when using larger fNIRS probes or tES sponge pads.
» The headgear should incorporate adaptable channel positioning on different target sites on the scalp.
» The earlobes, mastoids and shoulders need to be included among the headgear target channels.
» A pressure of about 100 gr/cm² should in all cases be present on the target sites, and no more than what is perceived as uncomfortable, with a maximum of 500 gr/cm².
» Open source hardware (OpenBCI, OpenNIRS, OpentDCS) can be used during development and should be considered for implementation in the final product proposition.
2.3. Product fit on the head

2.3.1. INTRODUCTION
This chapter discusses the theme of fit of neurotechnological headgear. This has both an ergonomic and a functional aspect. The ergonomic fit deals with the conformity of the product to anthropometric measures of the user(s). The functional aspect can be referred to as technical fit and includes in this case: accuracy (proximity to target area), repeatability (test-retest reliability) and stability (resistance to movement). First the relevant standards and measurements are identified and explained (2.3.2). The main differences in head shapes are then explored and a design range is established (2.3.3). A benchmark is thereafter presented so as to formulate requirements for the technical fit of the future product proposition (2.3.4). These sections are based on one or two-dimensional datasets, additional literature research and observations. Lacko and associates (2016) assessed the suitability of using a parametric 3D digital head model for neurotech headgear design. They conclude that it is a feasible alternative to the traditional anthropometric approach, leading to similar (but not necessarily radically better) accuracy and repeatability. Therefore this chapter largely deals with traditional anthropometrics. Yet, it includes an exploration in the availability and suitability of 3D digital head models that can be used in later stages of the project (2.3.5). It is concluded with a set of requirements for the final design in section 2.3.6.

2.3.2. RELEVANT STANDARDS AND MEASUREMENTS

THE 10-20 PLACEMENT SYSTEM
The 10-20 system is a standard method that describes the positioning of electrodes on the scalp based on a few reference points. It results in a map with 21 sites that are identified by a letter (referring to the lobe) and a number (odds for left, evens for right) (Figure 14) (Jasper, 1958). For example, site F3 is on the left frontal lobe. Expanded versions (called the 10-10 system and 10-5 system) identify 74 or even more sites (Oostenveld & Praamstra, 2001). The standard allows researchers to reproduce each other's findings. Using a measurement tape one can find the location of F3 on every head. The exact procedure to localize 10-20 sites is ambiguous, starting with the interpretation of primary reference points. It also does not clarify if one should base inter-location distances on hemispheric or anterior/posterior division. This leads to differences in site locations. Jurcak, Tsuzuki & Dan (2007) conclude that as long as a detailed rule is followed, there is no particular method better or worse. The standard is originally developed for EEG but it is also used in the domain of tES and at times in fNIRS research. Commercial neurotech products often target these sites too. Using this standard in this project is hence inevitable.

ANTHROPOMETRIC MEASUREMENTS
The ISO7250 standard (Basic Human Body Measurements for Technological Design; ISO, 2015) describes common measurements used in static anthropometry. It includes the head measurements.
Circumference (ISO 7250:4.3.12) Sagittal arc (ISO 7250:4.3.13) and Bitragion arc (ISO 7250:4.3.14), which are relevant within the 10-20 system. The exact method of measurement however differs, especially for the sagittal arc measurement (Figure 15 and Table 4).

The scientific literature seems to lack accurate measurements of the actual 10-20 metrics for a large population (to the best of authors knowledge). Therefore the ISO metrics are used to explore the general size and shape of the human scalp and its variation. The following sections will hence discuss head dimensioning related to the ISO standards.

### THE SIZE OF THE HEAD

It is the endeavour to include a large audience in the new headgear design. The ISO7250 standard is used to identify the variance that occurs in the international adult population (ISO, 2015) for the relevant measures. Data for European, Asian and World ranges were analyzed separately so that racial differences are not neglected. An own design range is established by listing the smallest 5th percentile (P5) and largest 95th percentile (P95) of different ethnicities (see Table 5 and Figure 16). A substantial amount of the adult international population is in this way included.

### THE RATIO OF THE HEAD

The growth of the head does not happen linearly over the three listed metrics. This means that product for different head sizes also need different shapes (Lacko et al., 2016). There is little to no data available on the ratios between circumference, sagittal arc and bitragion arc. However, the breadth/depth ratio of the scalp (also known as Cephalic Index (CI)) is a common way to describe head shapes. For the lack of desired data, the CI classification can be used to describe the design range.

### VARIATION OF HUMAN HEAD SHAPES

#### INTRODUCTION

There are different levels of detail on which one can assess the anthropometric data. In this report the anthropometry of the head is decomposed into the following levels: 1. The size of relevant metrics; 2. The ratio of these head metrics; 3. The 3D shape of the scalp surface and 4. The correlation with the underlying regions of the brain.

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The CI classification identifies three main head types (see Figure 18). There is a significant difference in CI of different human ethnicities (Farkas, 1994, Ball et al., 2010). For rigid products such as bicycle helmets this can lead to problems. This is also the case for current neurotech headgear. For example, in conversations with expert users it has been indicated on several occasions that the Emotiv EPOC headset (see Appendix I) does not fit well on the heads of Asians. It has been modelled after a 40th percentile (probably western) male head (GMAC, 2010) and is simply too small for large brachycephalic head shapes. Within this project it is desirable to include Asian, Caucasian and African head shapes. Especially head-breadth seems to be a critical factor for product fit. In order to include wider Asian head shapes, the product needs to accommodate for heads up to 171mm in width (P95 Asian (ISO, 2015)) and allow for a CI ranging from 75 to 87 (Farkas, 1994).

- The headgears’ scaling should not happen linearly, but freely in the three directions.
- A cephalic index ranging from 75-87 needs to be accounted for in the headgear design.
- Head width is a critical factor and wider heads up to 171mm in width need to be accounted for in the headgear design.

THE SHAPE OF THE SURFACE OF THE SCALP
A study by Lacko et al. (2015) assesses the variability of the shape of the surface of the human scalp in the western population. It shows the largest variation is located around the brow ridge, frontal and occipital regions (see Figure 19). For an optimal technological functionality, the probes should always be placed perpendicular to the scalp. The variation in the shape of the scalp should be overcome, or the product might not have sufficient contact for different 3D head shapes. This should be taken into account during concept design. Some type of angular freedom or flexibility can be integrated on the elements that touch the scalp. This is then especially relevant on the forehead (sites Fp1/2, Fz and F3/4) and the regions at the back(O1/2, Pz and P3/4). The sponge based electrodes already adapt to these variations themselves.

- The headgear should successfully couple with the scalp (perpendicular full contact) despite shape variations.
- Ideally the probes in the headgear design have angular freedom in order to allow for scalp shape variation, especially in frontal and occipital positions.

THE CORRELATION BETWEEN THE SCALP (OUTSIDE) AND BRAIN (INSIDE)
The exact shape and cellular architecture of brains differs from person to person (Brett, Johnsrude & Owen, 2002). In practice this means that an electrode that is placed on a 10-20 site can be projected on different cortical structures (Koessler et al., 2009). The only way to know the exact build up is by advanced research methods such as (f)MRI.

The uncertainty of this relationship affects the interpretation of fit. When measuring brain activity at a specific site, you will always have to accept this anatomical inaccuracy. It is not possible to know exactly what area you are measuring (without advanced research). It is hence extra important that measurements on the same person have a high repeatability. It might be a bit inaccurate, but it is the same every time.

- You always have to settle with a certain level of inaccuracy as a result of the anatomical differences between individuals.
- The repeatability when targeting a site on the scalp is considered to be at least as important as the accuracy.
CONCLUSION
The relevant dimensions of the head do not grow linearly. The different ratios in head shapes vary significantly, especially between different ethnicities. A crucial point in current products is the suitability for large head breadths. A range is established that lists the minimum and maximum dimensions for which the product in this project will be made suitable. It covers a large part of the international adult world population.

The remaining subtle differences in head shape are important to take into consideration. On this smaller level of detail is it expected that differences are not so much affecting the accuracy of systems, but are mostly affecting the reliability of the scalp contact. The fact that the accuracy is not expected to be a main issue at this level of detail is due to the ever-present anatomical variance of the brain. A certain level of anatomical inaccuracy is inevitable. This makes it extra relevant to provide a high repeatability (consistency between consecutive applications of the product).

2.3.4. BENCHMARK OF THE TECHNICAL FIT
The technical fit can be described as the accuracy, repeatability and stability of the product in relation to the target sites.

David Hairston et al. (2014) assessed the average distance between EEG electrodes and the target location of three commercially oriented EEG systems. Depending on the site, the error lied anywhere between 0 and 80 mm. It averages at about 23 mm over all systems and sites, compared to about 17 mm for the laboratory grade caps. Considering that the medical caps come in 3 sizes and the commercial products are one size fits all, the difference is quite limited. It would fit in the philosophy of this project, as laid out in the problem definition and assignment, if the end result here is also a 1 size fits all solution. The goal is then to bridge the small accuracy gap between these systems.

A recent paper from Lacko et al. (2016) describes an expandable headgear design that is based on elaborate statistical head shape studies. The reported accuracy is only slightly better than other commercial systems: 22 mm. The repeatability of the system developed by Lacko et al. (2016) is slightly better than that of other systems: a discrepancy of 11 mm on average. It illustrates that accuracy is hard to achieve with products that are intended to be suitable for different users, but repeatability remains better intact.

Research of Koessler et al. (2009) and David Hairston et al. (2014) show that the Parietal and Occipital sites are the most difficult regions to target with high accuracy. An explanation can be sought in the fact that people can more easily (visually) identify frontal reference points than those on the back of the head, and align the products accordingly. This is a problem that can potentially be solved through design and where an increase in accuracy can be achieved.

Following these numbers it is decided that an average accuracy error of under 25 mm is acceptable and conform current practice. Furthermore the average repeatability error should be under half the accuracy (12.5 mm) and the maximum errors of individual sites shouldn’t be more than twice that (max 50 mm inaccuracy and max 25 mm irrepeatability).
2.3.5. THE USE OF DIGITAL HEAD MODELS

ACQUISITION

This section will discuss the availability of relevant 3D head models for the use in the later phase of this project. Many high quality anthropometric 3D head models that are commercially available (such as those used under EN960 (CADEX, 2006), the SizeChina project (BALL, 2011) and CADANS (VLEUGELS et al., 2016) require investments that are beyond this projects capabilities. An online search for available models has led to the acquisition of the five 3D head models developed by Zhuang et al. (2010) under the NIOSH (Figure 20). The models are initially developed to illustrate the variance in the anthropometric measurements of the human face based on statistical analysis of 3D scans. Its suitability for describing the head variance of the selected target group in this project hence needs to be evaluated.

EVALUATION

The 3D models are imported into SolidWorks (D’Assault, 2015) for further analysis. Here the main anthropometric measures are extracted and the 10-20 target sites are plotted on the surface (see Figure 21). This process is described in Appendix II. These models are well suitable for interpreting 10-20 site locations and can be used for digitally analysing the accuracy of the future headgear concept.

The question remains if these models are representative for the adult target audience. In order to assess this swiftly, the maximum breadth of the widest model is analysed. This analysis has shown that the head models do not correctly represent the full target audience range. Though the lower limits of the range are included, the maximum head width covered by the models is 160 mm (as opposed to 171 in the design range (see section “the Ratio of the head”). The largest CI value is only 81 instead of 87. The set can be used to represent only average head forms (though significantly different) and no extremities.

CONCLUSION

Five digital head models were obtained from the NIOSH. All 10-20 sites could successfully be plotted on these heads. The heads do not cover the complete target range of head sizes and shapes. These models can still be useful to develop and test different concept designs in this (early) stage. After the evaluation phase it can then be considered whether or not more comprehensive 3D models are needed for further optimization of the proposal.

Figure 20: Five statistical anatomical shape models of the human head and face (Zhuang et al., 2010).

Figure 21: The cranial arc lengths and 10-20 sites are projected on the large head model of the NIOSH set.

» The NIOSH 3D headforms can be used as tool during the headgear design, but should not be used exclusively as they do not represent the upper bounds of the design enveloppe.
2.3.6. DISCUSSION AND CONCLUSIONS

This chapter has explored the theme of product fit in relation to neurotech headgear. This contains both the ergonomic fit (on the head) and the technical fit (influencing the functionality). With regard to the ergonomic fit, the analysis resulted in the formulation of a design range that should be covered by the product. This range covers the expected differences in size and ratio of the heads of the adult international population. The metrics that are included in this range are based on the 10-20 standard that is common for neurotechnological research and applications.

The technical fit concerns the accuracy, repeatability and stability on these 10-20 sites. Regarding stability - and considering the previous chapter - it is important that the differences in head shapes do not result in radically different pressure distribution of the probes on the scalp. This is an interesting design challenge that needs to be incorporated in the conceptualization phase. Furthermore the subtle variations in head shape that occur need to be accounted for to ensure proper skin contact of the probes.

A benchmarking study has revealed target values for accuracy and repeatability regarding the 10-20 target sites. The goal is set to achieve an accuracy within 25mm and a repeatability within 12.5 mm. This would match current best practices of consumer products.

It has proven to be hard to find readily available 3D digital head models that cover the target range. A set of digital head models was obtained from the NIOSH. These were evaluated and found to be insufficient to describe the full expected variation. However, they were found suitable for successfully mapping 10-20 positions on the scalp and can be used as a starting point in the 3D development of the product design phase.

List of formulated requirements

- The headgear design should aim to include all different head shapes, without the need of a sizing system.
- The headgear should (adaptively) target the sites from the 10-20 standard.
- The accuracy of the product when targeting 10-20 sites needs to be below 25mm, averaged over all sites. Ideally it would equal medical systems with an accuracy of 17 mm.
- The maximum average accuracy discrepancy of a 10-20 target site needs to be below 50 mm.
- The headgear should assist the user to align it well with occipital and parietal regions.
- The average repeatability error of the product should be below 12.5 mm, averaged over all sites.
- The maximum average repeatability error of a 10-20 target site needs to be below 25 mm.
- The headgear should be able to accommodate for a head circumference ranging from 523 to 610 mm.
- The headgear should be able to accommodate for a sagittal arc length ranging from 313 to 414 mm.
- The headgear should be able to accommodate for a bitemporal arc length ranging from 322 to 402 mm.
- The headgears scaling should not happen linearly but freely in the three directions.
- A cephalic index ranging from 75-87 needs to be accounted for in the headgear design.
- Head breadth is a critical factor and wider heads up to 171mm need to be accounted for in the headgear design.
- The headgear should successfully couple with the scalp (perpendicular; full contact) despite shape variations.
- Ideally the probes in the headgear have some angular freedom in order to absorb minor scalp shape variations.
2.4. User and context of the headgear

2.4.1. INTRODUCTION
This section of the report discusses the user and the usage context. In (bio-)medical applications, user experience is often under-addressed (McCurdie et al., 2012). Now neurotechnologies get used in more daily life settings, the user experience needs to catch up. The viability of the technologies is otherwise at stake (Cafazzo, 2013). This section aims to clarify what elements constitute the user experience and what this means for the future headgear design.

The information is an aggregation of literature research and user/expert studies through online forums, audiovisual footage and real-life conversations. In part the theme is approached through the Value Proposition Design (VPD) framework, a systematic approach to ‘deliver products that fit well with users’ (Osterwalder, Pigneur, & Papadakos, 2014).

First different possible usage contexts are presented (2.4.2). A selection of key scenarios is made that are believed to benefit most from an adaptable headgear solution (2.4.3). These scenarios are explored and traits of the users and context are discussed (2.4.4). This leads to requirements regarding the technology and setups and the perceived experience which could contribute to a user friendly product proposition at the end of this project (2.4.5).

2.4.2. COMMON USAGE CONTEXTS
Most of the applications of neurotechnology are medical. This includes the diagnosis of brain trauma or the monitoring of patients with e.g. epilepsy or sleep disorders (Teplan, 2002). This is done with both EEG and fNIRS. Brain stimulation techniques are also mainly used in this domain, such as in post-stroke recovery. This field is known as neurorehabilitation. Other applications target disorders like depression or Alzheimers.

Neurotech is also used to monitor/improve traits such as focus, relaxation and learning. Products targeting wellness and entertainment dominate this consumer market, but there is also a tendency towards high-performance industries like the army and professional sports. In a clinical context it focusses on treating anxieties and social disorders. EEG and fNIRS are used to register activity and allow for biofeedback training. tES can be used too to enhance useful traits (van Erp et al., 2012, Filmer et al., 2014).

Brain signals can also be used to control external events. Such systems specifically are referred to as Brain Computer Interfaces (BCI), though this term could apply to any neurotech system. Its relevance stretches from gaming applications to the control of prosthetics for the physically impaired.

The summarized typical/interesting contexts for wearable neurotechnologies at this point are listed in the Table 6. The relevant technologies for these scenarios are included.

<table>
<thead>
<tr>
<th>Usage application</th>
<th>EEG</th>
<th>fNIRS</th>
<th>tES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnosis of brain trauma</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patient monitoring (e.g. Epilepsy)</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sleep monitoring</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neurorehabilitation</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Treatment of psychological conditions (e.g. depression)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Treatment of physiological conditions (e.g. Alzheimer’s)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Contextualized research</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neuromarketing</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mental state recognition</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mood Alteration</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Neuro(bio)-feedback training</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(High) Performance monitoring</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cognitive enhancement</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Environmental Control</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

X = technology plays a major role for such applications.

x = technology plays a minor role for such applications.
2.4.3. SELECTING FOCUS APPLICATIONS

VALUE CREATORS OF THE FUTURE PRODUCT

Three main qualities of the future product are already included in the assignment: adaptable functionality, adaptable fit and a positive user experience. These are analyzed in relation to the VPD framework in order to understand the ways in which they can create value. For example, an adaptable functionality is valuable in scenarios where the initial functional requirements are ambiguous. A total of 12 of such characteristics of interesting scenarios were formulated after clustering a longer list. These 12 are listed in Table 7.

<table>
<thead>
<tr>
<th>Adaptable function is valuable if...</th>
<th>Adaptable fit is valuable if...</th>
<th>Good user experience is valuable if...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different applications are foreseen to be used</td>
<td>The product needs to service multiple users</td>
<td>The product is placed in a commercial market</td>
</tr>
<tr>
<td>Unique or personalized setups are desirable</td>
<td>Accuracy is important</td>
<td>Usage in daily life and social settings occur</td>
</tr>
<tr>
<td>Initial requirements are ambiguous</td>
<td>Repeatability is important</td>
<td>Delicate user groups are involved</td>
</tr>
<tr>
<td>New knowledge is of interest/developed</td>
<td>Shorter set-up can lead to significant gains</td>
<td>There is repetitive or prolonged use by a user</td>
</tr>
</tbody>
</table>

FOCUS APPLICATION SELECTION

The 14 application scenarios from Table 6 are evaluated with respect to the 12 characteristics of Table 7. For each of the scenarios (e.g. 'Diagnosis of brain trauma') a score was attributed to the applicability of the characteristics (e.g. Usage in daily life settings is not applicable (= 0), and Shorter setup time can lead to significant gains is highly applicable (=3)). These assessments were done based on careful deliberation. An extra weight factor was assigned to those characteristics that are believed to be unique. Figure 22 depicts the total cumulative evaluation scores on the y-axis after judging all 14 scenarios (x-axis) on the 12 value characteristics. The cumulative score can be interpreted as a metric of expected value of modular headgear. The details of this assessment, including the weighing factors, are included in Appendix III.

The results should not be interpreted as true relevance scores, but are a tool in decision making. With that in mind a selection is made of a primary focus group for the new product proposition. This selection includes: Neurorehabilitation, neurofeedback and cognitive enhancement. Mental state recognition—which also scored high—is not selected. It is considered a part of neurofeedback that on its own has a limited functionality. The focus on these applications does not exclude the others but merely helps to shape the design requirements.

Neurorehabilitation, neurofeedback training and cognitive enhancement are focus areas for the headgear design optimization.

2.4.4. DESCRIPTION OF THE KEY SCENARIOS

INTRODUCTION

The three selected focus applications are explored more deeply. The presented information is in part derived from a visit to the Rijndam revalidation centre (19 Jan 2016), to neurofeedback practice Mind Alive (21 Jan 2016) and interactions with neuroenthusiasts and experts such as at the Hack the Brain 2016 event (24-26 Jun 2016) and other meetings. This is complemented with relevant literature.

The user characteristics are summarized in three representations of expected users. The VPD framework is used to identify relevant traits of the users (goals, pains and gains), which are included in these representations and can help to understand who these users are.

Common setups of the neurotechnology in the focus applications will be discussed. A list is compiled of possible setups that are found in at least one of the three scenarios (see Appendix IV). A selection of most common and interesting setups is illustrated in the following sections.
I am Arman Gazi, a 59 y.o. father, husband and store owner. Motor impairments due to a stroke.

“I am just doing the best I can to get better fast. I follow all advices and cooperate.”

Context description
Neurorehabilitation is the process of recovering from injury to the nervous system. The programs include physical, cognitive and emotional training. Neurotechnology is deployed to monitor and improve the progress. An EEG evaluation can be used to tailor the program contents and the exercises can be enhanced with TES protocols. It is set mostly in rehabilitation centres, but recovery often continues at home.

Audience description
Stroke survivors form the largest group in this scenario. The risk of stroke increases drastically after age 55 and is related to ethnicity and gender. Men are 25% more likely to have a stroke than women and people of African or (South) Asian origin have a higher risk of stroke compared to Caucasians. This could affect the optimization of the future headgear. Some of the most common effects of stroke include weakness of arms and/or legs, visual problems, facial weakness and aphasia (Stroke Association, 2016), which all originate in different regions in the brain.

Many patients suffer from fatigue and emotionalism. They report to lack confidence and feel they are treated differently. Almost half of stroke survivors indicate they want more support after going home. The emotional impact of stroke not always receives the attention that it should (Stroke Association, 2013). It is important that the headgear contributes to a feeling of independence rather than dependence.

Experience
Seeing the relevance of the task, users are willing to compromise on their qualitative experience if that benefits functionality or reliability (Holz et al., 2015). This can directly link to the choice of EEG electrodes. Still, research shows that more aesthetic designs of EEG caps would be appreciated by such users (Holz et al., 2013, Blain-Moraes et al., 2012). Other bottlenecks that prevent neurotech to be used in a daily life setting are set-up time, clean-up time, discomfort and restricted mobility of the current systems (Kübler et al., 2013). The weight of elaborate EEG systems that are worn on the head can cause discomfort (D. Hairston et al., 2014) and should be kept under 250 gr. to prevent this (Ha et al., 2016). These matters should be kept in mind during the conceptualization and evaluation phases in this project.

Setups
The complications originate in different parts of the brain, resulting in different areas of interest during recovery. The central region and its 10-20 sites are associated with motor functions and is the most common target. Areas related to language and swallowing correlate with temporal sites of the extended 10-20 system. Advanced computer algorithms can generate setup complex channel configurations tailored to ones specific conditions.

» The design should be usable during low intensity activity (training).
» It should be possible to use the headgear daily for 60 minutes a day.
» Elderly should understand and use the headgear without much assistance.
» The headgear can be optimized for male and african/south asian head forms (when needed).
» The design should not compromise the functionality and reliability over the experience.
» The weight of the headgear should be under 250 gr. (for parts that are worn on the head).
» The headgear should target any two 10-20 sites and popular sites from the 10-10 system.
» The suitability for complex setups (odd sites, high channel count) should be explored.
NEUROFEEDBACK

Context description
Neurofeedback (NF) systems target brain disregulations such as anxieties, depression and attention disorders. In NF training, the brain of a user is monitored and audiovisual content is adapted on this basis. For example, desirable activity makes a video play and undesirable activity makes it interrupt. The neuroplasticity of the brain allows for the desirable activity to take hold. Usually people follow training sessions weekly at a clinician for about 15-45 sessions for the effects to take hold. Yearly the person can undergo a few ‘boost-up sessions’ if needed. Next to clinical use, this is also possible at home (Zengar institute inc., 2013).

Audience description
People of all ages tend to neurofeedback for a wide variety of purposes. The main focus here will be on the therapeutic use (since non-therapeutic use can be included in scenario 3). Compared to other applications, children are an important user group in this scenario. Attention deficits are a growing issue and parents look for ways to treat their children without medication. The NF protocols for these purposes are also most well developed and studied. Other than highlighting children, the user group is very diverse and can not really be labelled.

Experience
Though in rehabilitation scenarios the functionality is paramount, in this scenarios this might well be different because the ‘task’ of the neurotechnology is less crucial. D. Hairston et al. (2014) argue that peoples concern of neurotech systems is pointed towards ease of set-up and comfort. In this project that means that the modularity of the headgear should not impact the ease of set-up. This seems in line with Cafazzo (2013) who argues that product complexity and user responsibilities of EEG systems should be reduced for a better experience. Interestingly clean-up does not seem to be a very big deal, so gel based electrodes are not per se outruled.

Setups
Hemispheric symmetry in brain activity is considered healthy and basically all symmetry setups (e.g. T3/T4, F3/F4 etc.) can occur in neurofeedback protocols. These can be 2 or 4 channel versions. A lot of single site setups also take place, mostly around central and frontal regions. The central region can be associated with hyperactivity, while the frontal regions contain relevant cognitive abilities like reasoning and focus. The setup is then complemented with a neutral channel on the earlobe, arm or cheek (e.g. C4+earlobe).

Next to EEG or fNIRS there can be other technologies included such as monitoring of heart rate, respiration, blood pressure and galvanic skin response. This can help to enhance the functionality of the product and provide more data for the user or therapist.

» The headgear should be suitable to be offered as service (usage intensity and quality need).
» Integration of headphones in the headgear design should be considered.
» The headgear should be usable by children from about 10 y.o. with assistance from a caretaker.
» The perceived ease of setup of the headgear should be high.
» Setups that should be included are all 10-20 single site setups and all (double) symmetry setups.
» Technologies such as monitoring of heart rate and respiration could be included.
» Audio functionality could be included.
COGNITIVE ENHANCEMENT

Context description
Both neuro-monitoring and modulation are used for cognitive enhancement. With neuro-monitoring this is very similar to the neurofeedback context. For neuro-modulation there is also tES involved to artificially evoke (or inhibit) the target activity. Different goals can be achieved with different technologies and protocols. It can be done during activity (e.g. practice piano during stimulation for finger movement) or the user can be passive. The most common reported use is to improve attention (72% of respondents), learning abilities (68%), working memory (67%), long-term memory (41%) and perception (33%) (Jwa, 2015).

Audience description
Users often gather in online communities. The study by Jwa (2015) describes the main characteristics of one of such communities. The audience here is predominantly male with a slightly higher than average education level. The group includes both students and professionals and therefore the income levels are both very low and high.

Experience
In a study of Nijboer et al. (2015), ease of setup and appearance are said to be most influential on the experience of end-users of neurotech systems. They recommend to design systems that leave hairstyles intact and visible and that avoid or minimize materials on the face. While the Emotiv EPOC (see Appendix I) is often perceived as uncomfortable, it is still widely used due to its good traits on these aspects. Its complete setup time is generally between 5-10 minutes. Furthermore, while most tES devices are completely flexible in their configuration, the fixed setup floc.us headset is the most popular device (Jwa, 2015). It is another strong example of the importance of ease of set-up.

Setups
Targeting more than two lobes concurrently is very rare for setups in this scenario. Actually, almost all protocols only prescribe 2 channels. These can both be placed on the scalp, or one is placed on the scalp and the other at a neutral site. The frontal region contains most relevant cognitive abilities, but (fronto)temporal regions are also common. In some cases the exact location of a target site is not prescribed. The one electrode location will for example be assigned to site C3, while the other electrodes location is simply referred to as ‘right supraorbital’ (meaning above the right eye, corresponding to a larger area around Fp2) or ‘right dorsolateral-prefrontal’ (an area corresponding to F4 and adjacent sites). Since in tES it is common to use quite large electrodes, such instructions can be sufficient. Also, since users are applying this at home, they likely do not know the exact locations of target site anyways.

Goal: Outperforming others in everything.
Gainpoint: Best return on investments.

“...My own experience has been satisfactory, but I know there are a lot of unknowns...”

* The headgear should be affordable for students, presumably below 300$ (like competitors).
* The headgear should be perceived as attractive by (young), well educated men (and women).
* The headgear should leave hairstyles mostly intact and avoid materials on the face.
* The headgear should be able to target any two sites of the 10-20 system concurrently.
* The headgear can be optimized for frontal locations.
2.4.5. DISCUSSION AND CONCLUSION

This chapter has explored the different possible users and contexts of the future product. The usage domain is narrowed down to a focus on neurorehabilitation, neurofeedback and neuroenhancement, for the product proposition is expected to be most valuable there. Below it is described how this is envisioned.

- **Neurorehabilitation**: The product can play a role in the at home training and remote monitoring of stroke survivors, which is the later stage of their recovery process. The patient can be familiarized with the product in the rehabilitation clinic.

- **Neurofeedback**: The product can be used by patients under the prescription and (remote) supervision of clinicians. Either the clinician or the user can be the product owner. Attention deficits from children are a main focus area.

- **Neuroenhancement**: Learning and memory improvement are considered to be interesting for a wide target group, and distinct from the other two scenarios. The product is envisioned to be suitable for both at home and institutional use.

The different setups of neurotechnology in these focus applications are presented. These are requirements for the possible configurations of the future headgear design.

Some general requirements are brought forward that apply to all users. Ease of set up seems to be one of the greatest factors influencing the evaluation of users. This is very relevant in this projects’ context of modular headgear. There is an inherent tension between the modularity and ease of setup. This is an interesting design challenge for the Conceptualization phase. Other aspects such as aesthetics and comfort depend more on the specific context.

There are distinctly different user and context characteristics in the focus applications. The potential user group includes children and elderly. In the middle there is a target group of vital youngsters. This brings design challenges along regarding the contradicting requirements of the users.

An overview is made of main characteristics from these different users and context. This list is included in Appendix V. In this list the contradicting characteristics were identified and clustered. The result is the identification of six clusters of how modularity can be deployed to meet the contradicting needs of the different users and contexts. The end design could be made truly versatile by offering adaptability in all these clusters. These are:

- Adapting for different target user(groups) (specific - general)
- Adapting for different desired functionality (basic - elaborate)
- Adapting for different product appearance (calm - bold)
- Adapting for different usage contexts (passive - active)
- Adapting for different quality demands (price driven - quality driven)
- Adapting for different sales channels (B2B - B2C)

**List of formulated requirements**

- The headgear should be able to target any two sites of the 10-20 system concurrently, including symmetry setups.
- The headgear should be able to target all 10-20 sites and popular sites from the extended 10-20 system.
- The suitability of the headgear for complex setups (odd sites or high channel count) should be explored.
- The headgear should be affordable for students, presumable below 300$.
- The design should be usable during low intensity activity (training) such as walking 3km/h or exercises on a crosstrainer.
- It should be possible to use the headgear daily for 60 minutes a day over a period of several months.
- The headgear should be suitable to be offered as service, resulting in higher usage intensity, adaptability and quality demands.
- Elderly should be able to understand and use the headgear without much assistance and preferably independently.
- The headgear should be able to be used by children from about 10 years old with assistance from a parent or clinician.
- If need be, the headgear can be optimized/focussed on targetting male and/or african/south asian head forms.
- Integration of headphones in the headgear design should be considered.
- Technologies such as monitoring of heart rate and respiration can be considered for implementation in the system.
- The perceived ease of setup of the headgear should be high.
- The headgear should be perceived as attractive by the various user groups.
- The headgear should leave hairstyles mostly intact and materials on the face should be minimized.
- The weight of the headgear on the head should be kept under 250 grams.
2.5. Conclusions

2.5.1. CONCLUSION ON THE THREE MAIN THEMES
The assignment is to design of a novel modular headgear concept for neurotechnological applications. The goal is to find a better balance between functionality, fit and experience. This Analysis phase was set out to get a better understanding of the further interpretation of this through analysing the three main themes.

The following conclusions can be drawn:

The technical product functionality
The new headgear should adaptively integrate EEG, fNIRS and tES technologies. Different setups and configurations should be allowed. A type of adaptable channel count and adaptable channel positioning can be implemented in the design to allow for that variety. The placement should be stable (correct pressure regardless of the configuration and user) and the scalp contact should be clean.

Anthropometric and technical fit on the head
The Analysis resulted in the formulation of a design range that needs to be covered by the product. It covers the expected differences in size and ratio of the heads of the adult international population. Subtle variations in the head surface should be accounted for to ensure skin good contact. Furthermore a benchmark is set at an accuracy within 25mm and a repeatability within 12.5 mm.

User and context of the headgear
The usage domain will be focussed on neurorehabilitation, neurofeedback and cognitive enhancement. Six clusters are identified through which modularity could help to cover the variance of key scenario requirements. These are: adapting for different targetgroups (specific-general), functionalities (basic-elaborate), appearances (calm-bold), usage contexts (passive-active), qualities (affordable-high end) and saleschannels (B2B - B2C). Furthermore, ease of set up seems to be one of the greatest factors influencing the experience of users.

2.5.2. FURTHER INTERPRETATION OF THE PROJECT
VISION
The new headgear design will be the most versatile product in its sort, allowing for customizable configurations, keeping an easy setup and achieving a technical fit that matches current standards. With its fully adaptable build-up, it is a future proof system for any professional or end user.

The design can be used in differenct scenarios that lie at the junction of consumer and R&D oriented systems. The users can benefit from the ‘best of both worlds’: a wide range of capabilities in an accesible design. Key applications include at-home rehabilitation, neurofeedback therapy and cognitive enhancement. This can be done through combining EEG, fNIRS and tES technologies.

APPROACH
It is believed at this point that it is interesting to see this future product as an adaptable mounting frame for different technologies. In this way it can leverage on existing hardware and anticipate on future developments. The relevant electronics can be attached to the frame; the probes are placed on the specific target sites and the other electronics can be palced on a central unit on the head or elsewhere on the body. In this way, the adaptability of the product is highest.

A good quality on the three main elements in the assignment will be achieved through:

Functionality: by offering multiple technologies in changeable setups with good scalp contact;
Fit: through an adaptable size and shape and an accurate and consistent targeting of scalp sites;
Experience: by ensuring an easy setup, a good appearance and adaptation possibilities to the context.
MAIN DESIGN CHALLENGES

Four challenges are formulated that should be addressed in the conceptualization. These are:

1. Introducing a configurable setup without critically affecting the perceived ease of setup;
2. Achieving clean contact for all target sites while leaving hairstyles mostly intact;
3. Adapting for different head shapes while maintaining the desired pressure and accuracy;
4. Offering a product appearance that is satisfactory for the different described target groups;

2.5.3. PROGRAM OF REQUIREMENTS

The total list of (preliminary) requirements is listed below. Not all information presented in this report has been directly translated to requirements. Some content (such as the user representations) have a more subjective role in the product development and evaluation.

1. The headgear should be able to adaptively integrate EEG, (CW-)fNIRS and/or tES technology.
2. The headgear should incorporate adaptable channel positioning on different target sites on the scalp.
3. Combinations of EEG+tES and EEG+fNIRS should be possible. Other combinations have less priority.
4. The headgear should be compatible with different types of electrodes/probes, including [1] wet gel cup style EEG and/or tES electrodes of about 1-3cm² [2] self adhesive EEG and/or tES electrodes of about 1-3cm²; [3] dry flat and brush style EEG electrodes of about 1cm² and height up to 2cm [4] sponge pad electrodes of sizes at least up to 20cm² and height up to 2cm [5] Custom, shielded, LED and SPD arrays with a spacing of 25-40mm; [6] hybrid probes (optional).
5. The sensors should be placed perpendicular to the scalp in order to achieve the best signal quality.
6. Different hair styles should not hinder the functionality. Assistance to move hair aside could be integrated.
7. The headgear should have an adaptable channel count between 1 and 8-10 channels. This can be less when using larger fNIRS probes or tES sponge pads.
8. A pressure of about 100 gr/cm² should in all cases be present on the target sites.
9. Open source hardware (OpenBCI, OpenNIRS, OpentDCS) can be implemented in the design.
10. The headgear should be able to target all 10-20 sites and popular sites from the extended 10-20 system.
11. The earlobes, mastoids and shoulders need to be included among the headgear target sites.
12. The headgear should be able to target any two sites of the 10-20 system concurrently, including symmetry setups.
13. The suitability of the headgear for complex setups (odd sites or high channel count) should be explored.
14. The headgear design should aim to include all different head shapes, without the need of a sizing system.
15. The accuracy of the product when targeting 10-20 sites needs to be below 25mm, averaged over all sites. Ideally it would equal medical systems with an accuracy of 17 mm.
16. The maximum average accuracy discrepancy of a 10-20 target site needs to be below 50 mm.
17. The headgear should assist the user to align it well with occipital and parietal regions.
18. The average repeatability error of the product should be below 12,5 mm, averaged over all sites.
19. The maximum average repeatability error of a 10-20 target site needs to be below 25 mm.
20. The headgear can be optimized/focussed on targeting male and/or African/South Asian head forms (if needed)
21. The headgear should be affordable for students, presumable below 300$ (similar to competitors).
22. The design should be usable during low intensity activity (e.g. exercises on a crosstrainer, walking 3km/h).
23. It should be possible to use the headgear daily for 60 minutes.
24. The headgear should be suitable to be offered as service, resulting in higher usage intensity and quality demands.
25. Elderly should be able to understand and use the headgear without much assistance.
26. The headgear should be able to be used by children from about 10 years old with little assistance from a caretaker.
27. Integration of headphones in the headgear design should be considered.
28. Technologies like monitoring of heart rate and respiration can be considered for implementation in the design.
29. The headgear should be perceived as attractive by the various user groups.
30. The headgear should leave hairstyles mostly intact and materials on the face should be minimized.
31. The perceived ease of setup of the headgear should be high and setup time within 5-10 minutes.
32. The weight of the headgear on the head should be kept under 250 grams.
3. Conceptualization
3.1. Introduction

The Analysis chapter is concluded with the formulation of a design vision, requirements and four main challenges. These challenges provide a basis for the ideation process that will be described in this part of the report. This phase has the characteristics of a Fish Trap Model; a process of working on three subsequent levels of detail (Muller, 2001). This process is captured in Figure 29. The three subsequent levels are:

- **Topological level** Concerning spatial ordering of components;
- **Typological level** About form, construction and interaction;
- **Morphological level** Detail solutions, materials & production.

Within this project that division stays largely intact, notwithstanding that parts of each of these levels can also be seen in the other two. The Fish Trap Model furthermore emphasizes the exploration of the design space with visuospatial techniques such as sketching, collages and mock-ups. This will be brought forward in the individual chapters.

In Chapter 3.2 an exploration is presented regarding the possible product architectures. A few elements will always be present in the headgear design and there are different ways to relate them to each other. Alternatives of their relations are generated and an evaluation is done to find the most promising direction for further exploration. This is called the Structural Concept. The main design challenges that are addressed in this section are number 1 (*introducing modularity without critically affecting the ease of setup*) and 3 (*adapting for different heads while preserving pressure, accuracy and comfort*).

The purpose of Chapter 3.3, is to create a product proposal that gets real close to its definite form in terms of construction, working principles and shape. The subcomponents of the Structural concept will be dealt with one by one in order to investigate the different ways they can fulfil their function. In this section all four main design challenges will be addressed. Besides that there are many other challenges that need to be resolved.

The third level of detail, the Morphological level, deals with the further detailing of the proposal in terms of dimensioning, materials and manufacturing. This is included in the next section, Detailed Design.

![Fish Trap Model](image)

**Figure 29**: Fish Trap Model (after Muller, 2001).
3.2. Structural concept

3.2.1. INTRODUCTION

The purpose of this section is to come towards a Structural Concept of the headgear in which the spatial ordering of main components is defined. This is done in three steps.

First a preliminary exploration is done (Section 3.2.2). The goal of this is to freely research the different solution directions that arise, without much directed effort. This is done with sketches and 3D mock-ups. It is a designers’ equivalent of free-writing; all ideas one has or that arise at the start are simply put to paper. These raw ideas do not have to be relevant or logical. It merely allows one to ‘empty the head’ and limber the thought process. Afterwards one can take a step back to make up the larger picture. Doug Hall conceptualized this process as a ‘Mind Dump’ (Hall, 2007).

In this case the preliminary exploration leads to two types of results. Firstly through this exercise the designer becomes familiar with the practicalities of designing headgear products. Secondly it allows for the first insights, solutions and criteria to arise that can later be further attended to.

The second part of this cycle (Section 3.2.3) has a more intentional nature and builds partly on insights from the previous exploration. Here the solution space is mapped out and explored through a number of creativity techniques and methodologies. The main design challenges 1 and 3 are herein addressed. This leads to the generation of multiple concepts of the main product architecture. These are discussed in respect to their envisioned properties, benefits and deficits.

Lastly a selection is made of most favourable sub solutions from the generated concepts (3.2.4). This selection is done based on the discussion and further evaluation of the concepts on a number of criteria. The selected sub-solutions are then combined into a final Structural concept proposal to conclude the Conceptualization phase (3.2.5).

3.2.2. PRELIMINARY CONCEPT EXPLORATION

In line with the Fish Trap Model philosophy, the solution space is explored with sketches and quick 3D mock-ups. Styrofoam head models were used to visualize and assess some of these raw ideas. As explained in section 3.2.1, the purpose of this exploration is mainly to loosen and lumber the mind for later efforts. As such there are no formulated intentions at the start. In hindsight some streams of thought can be extracted from the efforts. These are included alongside Figure 30.

**Findings**

Despite the laxity of this activity, it led to valuable insights that can be used in the next phase. Some of these are implicit and relate more to a growing gut feeling. Others are in the form of more concrete leads. These are listed below.

- Some components are nearly always present in the product build up. These are: (1) interaction channels on the scalp, (2) a form of embodiment to wear on the head, (3) a means of connecting the interaction channels to this embodiment, and (4) a technical unit for signal processing. These components can be used as starting points for the next diverging design exercise.
- The ears form a crucial point for many product propositions. This has various reasons, starting with their location in the 10-20 system. (1) They are halfway between the front and back halves and situated on the left and right halves of the 10-20 system layout. This makes that it is a ‘strategically interesting’ position to target other sites from. (2) Furthermore, they contain two of the 10-20 system fiducial points, which can help to provide accuracy. (3) The geometry of the ears can make it is easy to place products on/around them and this is also socially well accepted (think of hearing aids, headsets, headphones). (4) The bony tissue around the ear (above and behind) is not so sensitive to pressure as
temporal and frontal regions. (5) Additionally part of the embodiment can stay out of sight if it is run further behind the ear or neck. A stronger emphasis on solutions that situate around the ear can be taken in the next phase.

- The use of elastomers in the headgear design should be considered. It is currently not addressed by EEG headgear products, as they try to move away from ‘clumsy’ head caps. However, an elastomer can solve multiple issues at once: it can take care of the proportional distribution of the interaction channels; it can deliver pressure on these channels for improved signal exchange and it automatically adapts for major and minor head shape variations, keeping the channels correctly aligned to the scalp surface.

- Many of the generated raw ideas have some degree of segmentation. This can be very little or very large. It is quite clear that this will play a role in the headgear design in some way. It is a very logical way to provide adaptability in e.g. dimensioning, configuration or aesthetics. Different levels of segmentation can be explored to find a right balance between adaptability and the increasing complexity.
3.2.3. DELIBERATE CONCEPT GENERATION

STARTING POINTS
The divergent creative process starts from the assumptions made on the basic elements of the new headgear design. The functional components that will always be present in the basic product architecture (as taken from section 3.2.2) are thought to be:

- **Main frame** – A part of embodiment used, among others, for overall product-on-head placement, stability, comfort and possibly for increasing accuracy and/or precision;
- **Probes** – Elements placed on target sites on the scalp and enabling EEG/tES/fNIRS;
- **Probe support** – Physically linking the probes to the main frame and exerting pressure;
- **Technical unit** – Data processor, battery unit and communication module for signal processing.

Together they should be combined in a new type of embodiment. It is important herein that (challenge 1) the placement of probes is adaptable in such a manner that it can cover the setups brought forward in the Analysis phase; and (challenge 3) the main frame is made suitable to correctly fit different head shapes. This forms the starting point of the diverging design exercises in the following sections.

MORPHOLOGICAL CHART
The solution space is systematically explored. A type of Morphological Chart is used in which the sub solutions to functions of the product are listed. The chart in Figure 31 was composed to grasp this solution space. It is used to more systematically explore the possibilities. Different (sub-)solutions for specific functions are listed. Interesting combinations are sought through reasoning, sketching and rapid prototyping.

The principles in row one and four largely came forward in the Preliminary Exploration. The content of row two originates from section 2.2.7 on page 13 in the Analysis phase. Further elaboration on these earlier findings are done using TRIZ methodology (Altshuller, 1984). Row three lists ideas that came from both TRIZ and from the Preliminary Exploration. The solutions that are included are formulated in a quite general fashion. This leaves room for interpretation and inspiration when they are combined. The next section presents concepts that are composed. Their origins are indicated in the chart colours.

GENERATED HEADGEAR CONCEPTS
A selection of the generated concepts is presented in Figure 32-Figure 36. Their main working principles, shortcomings and advantages are discussed below. The variety of the concepts and considerations that further shape the final direction are captured in this. Together these figures represent the solution space.

TRIZ
Altshuller (1984) believed that every problem has already been solved in a way before. Therefore they studied recurring patterns in inventive problem solving. The reappearing solution principles have been summarized into forty general principles of problem solving that can be applied to new situations. They also found that many problems are essentially contradictions, and mapped out elements that are the subject of such contradictions. Since the design challenges that are formulated in this project already have the nature of contradiction, it was considered interesting to use TRIZ methodology while completing the morphological chart.

Example
Design challenge 1 was formulated as: *Introducing a configurable setup without critically affecting the (perceived) ease of setup*. Following the TRIZ contradiction matrix, this can be generalized to a contradiction between features (35) *adaptability* and (33) *ease of operation*. Subsequently the solution principles 15, 34, 1 and 16 are suggested in their documentation. Those respectively represent principles Dynamics, Discarding & recovering, Segmentation and Partial/excessive actions. These four are processed in row two of the Morphological chart: 2c and 2d cover Dynamics, 2a and 2f implement Discarding/recovering. 2a relates most to Segmentation and 2b deals with Excessive actions.
Figure 32 shows a ‘moonlander’ inspired concept. A freely moveable element can be placed on the scalp at any desired site. The required technology could be (re)placed in the body of the unit.

**Pro’s:** It is not the intention to hide this design; a distinct shape could even make it a high-tech fashion accessory. It provides endless freedom in positioning, is lightweight and possibly quite robust.

**Cons:** It requires quite some effort to obtain accuracy/repeatability in setup. The design also has challenges when it comes to targeting multiple sites (with multiple independent units) or maintaining stability.

What was envisioned in Figure 33 is a design with such a characteristic shape that simply by placing it on the scalp in different orientations, the user can set up any needed combination of target sites. Different shapes were explored using head models and iron wire. The presented form is what came closest to what was intended. The probes are moveable in small slots that cover the anthropometric variance.

**Pro’s:** Such a unique shape might be the holy grail of simplification for a designer and the ease of setup is potentially very high.

**Cons:** On the usability side there are quite some shortcomings. The actual benefit of the user does not have to be high. It might actually lead to confusion during set up. Some of the orientations will look odd (with the legs for example looking like sideburns) and the repeatability can be hard to provide.
From this rather odd shape, a simple circumferential design can potentially look more serene. A concept is presented in Figure 34 of a partly flexible headband. All sites in the circumference are integrated as connection points for either probes or for ‘extensions’ to reach other sites. These extensions in this sketch would always connect two opposing sites so enough pressure can be exerted on the probe underneath.

**Pro’s:** The setup is really intuitive and the headgear design can in this way count on high acceptance. The design is also expected to be quite stable.

**Cons:** When it comes to targeting sites on the top of the scalp, it is difficult keep the serene quality. The shape simply does not lend itself well for that. Furthermore it is simply not so unique as the other directions.

Designs that already have a ‘fuller’ main frame do not encounter that difficulty when targeting higher sites. Two raw ideas are presented in Figure 35. The left proposal has two arcs that can be rotated to target different underlying sites.

**Pro’s:** This idea could perform pretty well overall in terms of aesthetics, accuracy, ease of setup, head adaptation and stability.

**Cons:** Though most setups include only sites from two lobes of the brain, there is limited freedom in the different combinations.

The sketch on the right captures some loose ideas. It starts from the figment that it could be interesting to use the brain in the form language. A ‘cerebellum’ could be placed at the back of the neck, housing all technical components. A subtle frame accents the edges of the brain along the circumference and over the hemispheric middle line. From this frame there are different ways to target the sites therewith. Extending the metaphor further this could be done through organically folded and deformable offshoots.

**Pro’s:** It is easy to approximate all sites. It is quite unique, also when the subcomponents are assessed individually.

**Cons:** The danger is of course that one ends up with a product that is equally obtrusive as current solutions due to its extensive embodiment. Setting up the product with the right accuracy is also challenging.

A strategy to prevent elaborate designs is to discard parts that are obsolete in ones desired application. This is captured in the concept in Figure 36. This proposal has a main technical unit at the back of the head. Different modules with varying numbers of connections can be attached to this to create different setups.

**Pro’s:** With this segmentation it is possible to keep the headgear as minimal as possible, which can benefit the aesthetics, dimensioning and ease of setup. Adapting for head shapes is also easily facilitated.

**Cons:** A user would be bound to the module(s) he/she possesses, limiting the modularity at the user level.

The proposal in Figure 37 builds on the familiar shape of a headphone. This concept innovatively incorporates elastomers to adapt for head shapes. The two outer rigid arcs running over the head can move outwardly. The spanned elastomer then proportionally adapts the spacing between the points on top.

**Pro’s:** Leveraging on this existing product can be convenient for the acceptance. Adapting for different head shapes is incorporated well, and the ease of setup is high.

**Cons:** The design is challenging when it comes to repeatability. Furthermore, when lower sites (i.e. those in the circumference) need to be targeted, additional solutions need to be incorporated.
Figure 34: Elastic band concept, using sub solutions 1c,2e,3a,4e.

Figure 35: Frame design concepts, using 1a,2e,3a,4a and 1e,2c,3c,4e. NB: These drawings also include ‘typological’ and ‘morphological’ features. However they should be interpreted at this point merely on their topological properties.

Figure 36: Segmentation concept, using sub solutions 1a,2f,3a,4a.

Figure 37: Headphone concept, using sub solutions 1a,2a,3f,4a.
CONCLUSIONS
Different concept proposals are done based on combinations from the morphological chart. All of the concepts have their own benefits and deficits, as discussed in the explanations. Together these presented concepts capture about the complete presented solution space. This does of course not mean that other distinctly different concepts can still be made from this chart, or beyond it. Other ideas are also developed during this deliberate exploration, but it is impossible and beyond the goal of this report to present all of them. From the selected proposals and their explanation it can be concluded that, though there are points for improvement, there is enough reason to build further on these directions towards a final proposal.

3.2.4. FINAL DIRECTION

EVALUATION PROCESS
A final selection is constructed through three pathways: (1) the scoring of sub-solutions on evaluation criteria, (2) discarding directions through reason/deduction and (3) building on preference, intuition and experience gained in earlier efforts.

Twelve evaluation criteria are formulated and are listed below. They emerged from the Analysis phase (program of requirements) or came about as insights during the conceptualization. It is decided to use these criteria to evaluate the sub-solutions, rather than the presented concepts. This is preferred because it can leave more room for a new, ideal, combination to arise based on the gained insights. A final Structural Concept is then created through combining favorable aspects of multiple of the presented proposals.

A list is made of main apparent deficits and benefits of the presented sub-solutions. The properties are in this way detached from the concept proposals and brought back to the sub-solution level of the Morphological chart. Still, one can trace back the evaluations in this phase to the discussions in the previous section. This list is included in Appendix VI.

After this dissection, the sub solutions are scored on the relevant criteria. Not all twelve criteria are applicable to all rows of the morphological chart. The scoring is done on the basis of subjective experience of the designer, using scores 0 (low), 1 (medium) 2 (high). At the foundation of this are thus discussions of the different concepts of the exploration.

The complete score-chart is included in Appendix VII. Figure 38 includes the cumulative scores and key positive and negative factors of the sub solutions. It is important to understand that this evaluation exercise is merely a tool and its results are not absolute.

- **Aesthetics** - The expected attractiveness of the solution;
- **Acceptance** - Likelihood of being perceived as adequate;
- **Placement** - Anticipated influence on the accuracy;
- **Repeatability** - Anticipated influence on the test-retest reliability;
- **Approximating** - Foreseen ease of using different setups;
- **Technologic** - Suitability i.r.t. technical requirements;
- **Dimensioning** - Potential for favorable size/weight/form;
- **Ease of setup** - Simplicity of installation;
- **Modularity** - Potential to be adapted for different needs;
- **Stability** - Performance relating to ‘technological fit’;
- **Headshapes** - Ability to correctly fit different heads;
- **Uniqueness** - Inventiveness of the solution.
From the evaluation it appears that it is most interesting to consider a basic product architecture that focusses on the space behind the ears and/or neck (1a) or is circumferential (1c). The former is preferred since it leads to more unique product propositions (which is strategically interesting) and can more easily be used to target other sites. In the Preliminary Exploration it had already become clear that the ears would be a key point for many product propositions. Almost all listed ‘basic architectures’ run along the ears. Making the main basic product architecture situated here, therefore, in a way, means that it still contains a small part of the other architectures.

The solution that stands out in row two is segmentation and altering build up (2a). What is strong here is the flexibility: it leaves room for personalization, optimization, replacements, maintenance and upgrades. Additionally, modules around the ears can be ‘upgraded’ to form other basic architectures (i.e. the ear module can interpreted as a segment of a headphone, headband, etcetera).

For the other two rows the differences in total scores are not high enough to select a best direction. The general formulation of the sub-solutions makes that there is a lot of room for interpretation here. What is most important is the suitability of the solutions to be combined with the emerging concept direction. Following the focus in rows one and two it seems natural to implement sub solution 4b (repositionable arms) and possibly 4e (clamping of probes between points) in the structural concept. They best fit with the principle of segmentation. It is important to pay attention to their main deficits that relate to the product appearance: making the product appear as a whole, instead of a collage of elements.

Then, at their turn, this selection gives direction to the decisions regarding row three. Two of the subsolutions are viewed as not suitable to be combined with the current selection (3b, 3c). Though 3b is still relevant, it moves away from the original ‘fit for all’ vision. In regard of the project scope and the product direction it is hence too discarded (and could be seen as a point further on the timeline). What then remains is the final selection in which both flexible materials (3a) (possibly merged with 3f) and mechanical expansion (3d) are envisioned to play a role.

The next section discusses the envisioned Structural Concept based on this selection.
3.2.5. CONCLUSION

What is envisioned is the design of a module that will be placed at the ear of the user, targeting the approximate location of T3/T4 of the 10-20-system. Different arcs can be connected to this unit, as shown in Figure 39 (the red and green straps over the scalp). By doing so the product can be stably placed on the head. Tightening of these arcs should be possible in order to fit different heads. These arcs not only serve a purpose of stabilization of the product, but can also be used to target the 10-20 sites that lie on these paths. For example, frontal sites can be targeted by clamping a probe underneath the green arc in the image, and occipital sites can be targeted with the red arc.

Next to this, the 10-20 sites can also be targeted with a repositionable arm that is connected to the central unit at the ear. This arm can be placed in a number of positions so as to reach the relevant points of the 10-20-system that are not covered by the arcs. It can be preferred to use the arms rather than the arcs to prevent complications such as discussed with the concept presented in Figure 35 (left). It can also be favoured for its more minimal dimensioning and aesthetic. By implementing flexibility at the end of these arms they should follow the contour of the head.

Design challenges
1: Introducing a configurable setup without critically affecting the ease of setup.
The segmentation of the product definitely has its impact on the ease of setup when starting blank. In that case multiple actions have to be undertaken set up the desired configuration. For an experienced user this is expected to be quite simple, but for new users or impaired users within the target audience this can be challenging. However, when the headgear is set up, it can be kept in that position and no real efforts for installation have to be undertaken. Since this will be the case for many applications, it is considered to be adequate. Any further efforts that can be done to assist the user in initial installation are welcome.

3: Adapting for different head shapes while maintaining accuracy, comfort and pressure.
The current proposal is believed to be able to successfully adapt for different heads. Especially the issues regarding accuracy and comfort can (potentially) be resolved through the combination of the arcs and arms. More effort is needed to ensure a constant pressure. This will be attended to in the next phase. A type of adaptable pressure feature can be sought after.

Figure 39: Representation of final selection for the Structural concept.
3.3. Formal concept

3.3.1. INTRODUCTION
The following sections discuss the creation of a Formal Concept, based on the concept that is laid out in Section 3.2.5. What is meant by a Formal Concept is a product proposition in which the overall form, working principles and interaction get very close to their final design. This stage is worked to using a number of divergent design phases for the different headgear components. The possibilities in here will again be explored with visuospatial techniques. The starting points for this cycle are:

• Using the space around/behind the ears as location for the 'fixed' embodiment of the headgear;
• Include segmentation and altering build up in order to adjust the configuration through repositionable arms and different arcs that can be connected to the main unit;
• Probes can connect to the repositionable arms or be clamped underneath arcs to target 10-20 sites;
• Implementation of elastomers, intermediaries or mechanical expansion should adjust for head shapes.

The remaining design challenges will also be addressed. At times this will be done explicitly, at other times they are taken into account implicitly. At the start of this phase a moodboard is presented that can be used during further design efforts (3.3.2). This moodboard directly relates to design challenge 4: creating a product aesthetic that suits the wide variety of users and usage situations. In the later stage this effort can be finalized through the selection of materials, finishing and colours.

After setting this stage, all the components of the system will individually be attended to. This starts with the design of the main units situated at the ear (3.3.3). An exploration will be presented on how they could facilitate their envisioned function best. This is done through a series of sketches and quick mock-ups. Subsequently the other components of the headgear are explored, which are the arms and probes (3.3.4), arc (3.3.5) and technical unit (3.3.6). This phase is concluded with the formulation and presentation of the Formal Concept and a record of the state of affairs regarding the main design challenges (Chapter 3.4).

3.3.2. MOODBOARD
A moodboard is created to describe the intended style of key appearance of the future headgear. This includes colours, materials, forms and ratios. It is attempted to capture an aesthetic character in between medical and consumer products, envisioned to satisfy main design challenge 4. Products from both of these categories are therefor included in the collage of Figure 40. Important in the selection was to capture a calm and trustworthy appearance, but also a unique contemporary character. Some findings that can be taken from this are formulated. Things that are for example considere to be interesting are:

• Using rounded, organic shapes with a medium complexity;
• Using mostly white, sometimes grey and bright (playful) colours;
• Highlighting specific functions of the product through colour, offset or material.
• Implementing symmetry in different parts of the design;
• Choosing a soft, matte, appearance/finishing of the materials.

Figure 40: Product moodboard, included in large in Appendix VIII.
3.3.3. MAIN UNIT

IDEATION

There are many ways to model the main ‘ear’ unit. Its shape depends mainly on how it facilitates the placement of the replaceable arms and arcs. When this functionality is accomplished, there is freedom to change the exact form language to match the intended style. The following points discuss a number of undergone iterations (alongside Figure 41).

1. It was decided first that sites on the circumference and in the middle of the head should be targetted with arcs. This reduces the sites to be targetted with arms to three on either side. This makes it more manageable and comprehensible for the user. Concomitantly it is decided to work with fixed-length arms. Adaptation for different sites and head shapes can then be done on the main embodiment. In order to keep the ear units small and lightweight, the technological components are from here on envisioned to be placed extracephalic.

2. A second simplification that was envisioned was the reduction from three to two arm-connection-points. If these two points are located at equal distance from two target points, they can together reach all three (see top view sketch). This concept was explored for a while. Multiple ideas were developed in which the main ear unit of the product derives its final shape by setting the arm connectors in one’s personal set-up.

3. The idea was later let go of for several reasons. The main reason were the different angles of the arm when targeting location A or B. Not only would it be difficult to design the product in such a way that it would correctly adapt in this way for all headshapes, the total assembly of the product also gets quite an odd shape in many setups and that is undesirable.

4. The new direction uses the same system of repositionable arms, but points them directly towards the target site in a straight line from T3/4. With only two arms it should still be possible to configure the product to any of the required configurations. Another third connector is hence still not needed. The product now centers fully around T3/T4 and feathers out from there.

5. Initially it was envisioned that different arcs could be connected to form either a ‘back of the head’ ‘headphone’ or ‘tiara’ setup. This would require the design and manufacturing of multiple arc elements. Based on the explorations it is found to be preferable and possible to offer one single arc that could fulfill all of these roles. In this way the costs could be kept lower and the simplicity could be increased (when done successfully). This means there is only 1 arm and 1 arc design needed.

6. The efforts culminated to an initial formal concept as illustrated at the bottom of Figure 41. The design centres around a point with two stubs can move ‘in and out of the embodiment’ and have some rotational freedom. Longer arms can be connected here to target the 10-20 sites. In the side of the product there are slots (visible in backview detail) that can be used to connect.
the arcs that run over the head. Some issues that are still unresolved at this point included the actual dimensioning, the pressure distribution, the aesthetics of the total assembly and the usage concurrent with glasses or hearing aids. Following discussions with people from inside and outside the team, a final iteration is hereafter made.

**FINAL ITERATION**

7. The key step that is made in the final iteration is another segmentation step. The point with rotating arms is isolated from the part that wraps around the ear. This provides benefits, such as:
- The ‘mechanical’ part is transposable between left and right (reducing costs);
- The part around the ear could be personalized (3D printed) when desired;
- Different designs for the ear part are possible so as to make it useable concurrently with glasses, hearing aids or other obstructions to the regular application. It can also be equipped with electronics such as an integrated reference electrode, heart rate monitoring or possibly audio functionality (which is interesting for neurofeedback applications).

This update is accompanied by a number of other changes to the product. The arms are now directly slid into rotating sections instead of connected to the movable stubs. The arms (and arcs) are longer and are allowed to stick out of the product when it is adjusted for smaller heads or closer sites. This visual feature was at first avoided. In hindsight it is believed that this is not necessarily disturbing and that it can deliver a more convenient workflow and more freedom in dimensioning.

What else is new about this iteration is the number of connection points for the arc. It is envisioned now that the slots in the side of the product are reduced to only 2; one on either side. In this way the arc can be set up for the frontal and occipital position. The arc can still be placed in other orientations too (e.g. over the top of the head), by inserting it in the rotating elements (i.e. the arms and arcs are interchangeable).

The result is a more miniature embodiment, more freedom in the design of the embodiment, fewer steps in setup, more comfort in installing the arms to their right positions and more freedom in positioning of the probes. On the other hand the freedom can lead to higher perceived complexity. The increasing segmentation can lead to an increased chance of failure from wear and tear. The decrease in dimensioning can result in a lack of ‘body’ of the product. This should be considered in further detailing.

![Formal concept proposal of main unit.](image)
3.3.4. ARMS AND PROBES

STARTING POINTS
The arms and arcs have already gotten some attention whilst designing the main embodiment. What is clear is that the ends that connect to the ear unit will be a simple strip with a type of serrated surface so as it snaps into pre-defined ‘positions of extension’. In this way it can quite easily be configured for different headshapes. The arm and arc need to have the same connection so that they can be placed in each others locations when desired. The design of the other ends of the arm are still unresolved and depends on the probe. A few functionalities are important to consider here:

• It is adaptable for various EEG/fNIRS/tES technology setups (challenge 3);
• The probe must have some angular freedom so it can stay tangential to the scalp;
• The pressure that the arm exerts on the scalp needs to be adjustable (challenge 4);

EXPLORATION

Adapting for different technologies with some angular freedom
Traditional research systems often use snap connectors as flexible electronic contacts. An EEG/tES electrode is placed underneath a headcap with a little snap connector protruding through a hole. A wire snaps on top of that (see Figure 43). This principle is also very suitable for this project. It is an easy way to implement flexibility and build on existing habits. Though to the best of the authors knowledge this system is not yet used in fNIRS research, it should be possible to use this exact same principle (at least with CW-fNIRS).

Different solutions were explored regarding the desired angular freedom. The most obvious solutions seemed the use of a type of ball joint between the arm end and probe. Other options could be found in using a gyroscopic construction or embedding flexibility in between the two parts (such as with foam or a minuscule spring system). Upon inspecting some snap connectors it was envisioned that these can actually be used as ball joints, killing two birds with one stone.

The end of the arm that is placed on the scalp has been shaped in such a way that it is believed to fit many different probe designs, especially for EEG and tES systems. Tailor made extensions could be produced and added to the arm-end to adapt it for other requirements from specific manufacturers or applications. This is also where the snap-connector ball joint could be used as bridge between the regular electrode and wire.

Adaptable pressure
What remains is the adjustment of pressure. The ‘easy’ solution is to design a system with compression springs (like the UltraCortex or imec headset in Appendix I). This is however believed to be not very sophisticated. Ideally the pressure functionality does not affect the appearance of the arm much, keeping the design as minimal as possible. The arms of the Emotiv EPOC are from semi-rigid plastic. When it is put on the scalp they exert pressure as a result of their strong inward curvature. What needs to be made possible is to create an increase or decrease in the curvature of the arm to adjust this pressure.

A number of ways were explored to accomplish this (e.g. temperature, plasticity, include a hinging point, change the orientation at the rotating origin), but eventually the choice was made to implement the working principle as shown in Figure 45: a metal spring strip that runs along the plastic arm. By changing the point of engagement of the spring force, one can adjust the curvature of the arm and with it the force that is exerted on the scalp. This can be done by moving a slider (in blue) up and down the two strips. This principle was believed to contain an interesting interaction and aesthetic. Through some iterations on the exact form, the shown design has come about in which a rounded (plastic) inner and a more angulated, spring steel, outer shape are combined.
Figure 44: Sketches and Formal concept proposal of the arm end and probe setup.

Figure 45: Exploration and Formal concept proposal of the arm.
3.3.5. ARCS

STARTING POINTS
For the arcs it is already clear that the ends on left and right will be the same as those of the arms. In this way they are interchangeable if that is desired by the user. Other important functions of the arc are:

- Exert clamping force on ear units to stabilize the product (yet not be uncomforable);
- Allow the placement of probes at locations: 40%, 50%, 80%, 100% of the ear-to-midline distance (both left & right), this corresponds with F7/F8/P7/P8, C3/C4, Fp1/Fp2/O1/O1 and Fpz/Oz/Cz;
- Exert correct pressure on the probes in all arc positions and for all headshapes;
- Allow the use of snap connection style connectors for the probes.

EXPLORATION AND FINDINGS
It would be elegant to embody the same working principles in the arcs as in the arms. The pressure application in the arc is however much more complex. There is not just one point that needs to be serviced, but there are seven points along the complete arc. This makes it very hard work with the same principles whilst preserving the qualities in usability and aesthetics.

The constant ratio between target locations makes it interesting to implement a type of constant expandability, for example through use of an elastomer. In order to keep the desired clamping force on the ear units, these expandable solutions could be ‘the inner lining’ of a more rigid arc, following sub solution 3f of the morphological chart. Alternatively one could think of other systems such as compression spring loaded units that can be moved in a slot in this rigid arc.

Three proposals have been developed. The first makes use of the same principle as the arms. However, some simplification steps have been implemented. The design will no longer target the 40-50-80-100, but uses one large element in the middle (serving 80-100-80) and two adjustable units on the sides (serving 40-50). It might require some effort for correctly installing all right properties, but it makes it more manageable in the end.

The second design makes use of an elastic inner strap. This strap directly takes care of distributing the probe locations correctly and adding pressure. It can be seen as the ‘automatic’ version, the other designs being manual. Different elastics could be supplied for little, medium or tough pressure. The third design makes use of freely moveable elements with a compression spring system.

Figure 46: Ideas, evaluation and design of the formal concept or the arc. The three shapes on top are the contours of the arc with the other functional components. An evaluation is shown underneath. The bottom drawing is the formal arc concept.
DECISION
In terms of usability it seems that the second proposition is most desirable. Still, a feeling dominates that this is not the most optimal solution. It should be possible to distill the arm’s working principle to a more minimal version, but efforts doing so have not been successful. Therefore for now the design of the arc is kept as shown, and updates to this design could be done in a later version based on the experience gained with this version.

3.3.6. ELECTRONICS
It is formulated in the Design Vision that many electronics could be located extracephalic (not on the head). There is a number of arguments why this is considered interesting.

• It can be hard to operate a product that is located on the head (especially for challenged target groups). It will be easier if this is done more in the line of sight and reach of arms.
• In this way the visual ‘disturbance’ on the head is kept at minimum, as well as the weight that needs to be carried by the neck. This is believed to be no issue for wearing it on other bodyparts.
• Some setups include locations outside of the head (EEG can require a ref/gnd on the arm, tES can require an electrode on the arm). In this way those positions can also more easily be targeted.
• By creating this split-off between the headgear and the electronics, the headgear automatically becomes ‘open’ for every type of electronics at hand; i.e.: It can be combined with high grade medical systems, lower grade consumer electronics or -in the future- hardware that is specifically designed for this headgear.

Seeing the scope of the project it is decided that not much attention will be put on the design and characteristics of this unit. Only a rough suggestion will be done to communicate how it is envisioned.

Figure 46 displays an impression of a wearable arm strap to which hardware from different suppliers could be connected (with screws, bands, clips). Additionally it allows for the placement of a probe that is then pressed to the skin by the band. A user is free in its decision to use such a band or other intermediaries to connect the hardware to e.g. the belt, collar or chest pocket.
3.4. Conclusion

INTRODUCTION
This design cycle started with the general product architecture as a given. The overall form, working principles and interactions were explored. This has lead to a Formal Concept in which many decisions regarding the product properties have been captured. Some of these decisions are intermediary and can be subject to adaptations in the next cycle. This especially applies to dimensioning. The exact form of the product will depend largely on the dimensioning that is required from a technical and anthropometric perspective. This chapter has set the stage for such further detailing and engineering of the proposal.

PRODUCT DESCRIPTION
The Formal Concept proposal is illustrated in Figure 48. It is an adaptable mounting frame for neurotechnological systems. It can be used to place and keep the electronics on the heads of the users. The design contains of different separable parts that can be recombined, pivoted and extended to form various setups and fit various head shapes. It can be configured for basic set ups that use only 1 or 2 sites on the scalp, or it can be expanded for higher complexity. The segmentation of the different components can make it possible in the future to offer an expanding portfolio of parts; users can select and combine their own product completely based on their wishes and requirements.

In all further detailing and discussion of the proposal, only the basic versions of its components will be considered. This also means that for the full setup, it is assumed for now that users wear a similar unit at both their left and right ear. This is something that does not have to be so in the future.

COMPONENTS
The Formal Concept contains the design of six main product components, starting with the main unit that is located at the ear. An important sub component hereof is the cassette of rotating discs where arms and arcs can be connected to.

A holder helps to position it all at the ear. It follows the (average) shape of the skull and distributes the pressure of the clamping force. Next to a basic design such as illustrated, there is a possibility to add other versions to the product portfolio later.

An arc can be connected to the main unit, either by inserting it to the cassette (left and right) or by sliding it in the side slots that point to the front and back. The arc has an elastic inner strap to which electrodes can connect. The strap exerts pressure on the scalp, distributes the electrodes and adapts for head shape variations.

The arm is a fixed length element that can be inserted in the cassette at approx. T3/4 and reach other sites from there. A simple spring strip system can adjust the curvature of the arm to add pressure to the end that touches the scalp. This end is designed in such a way that neurotech probes from different suppliers can fit onto it. Be it for EEG, tES or fNIRS.

Different arm-end extensions can help to enhance the capabilities of the arm. A novel ball-joint snap-connector can be used to increase the angular freedom of the probe. Other types of extensions can allow for different interaction technologies to be placed concurrently, such as fNIRS+tES.

The wires of the electronics can be pushed in between two ribs that run under the arm (and arc). In this way they can be safely guided away, from the scalp, over the main unit and behind the ear. Somewhere away from the head (the arm, chestpocket, at the belt, etc.) there is a technological unit that contains the electronics and interfacing that are needed for data processing. This is considered to be outside the scope of this project and no further attention to this is given in the next phases.
Arms and arcs can connect to this cassette where rotation and extension of them is possible.

The strap can be attached to a pin at the back of the main unit.

The strap has indications for the locations of target sites.

Slots in the left and right side of the main unit can be used to insert arcs or arms.

For now it is assumed that there is always a main unit at either side of the head, though this does not have to be the case.

The electronics can be connected to the 'open' arm end. It is also possible to extend these arms for other functions.

Wires can be pressed between ribs under the arm and arc.

This slider can be used to adjust the pressure on the scalp.

Arms and arcs can connect to this cassette where rotation and extension of them is possible.

Figure 48: Total Formal concept proposal; its components and its features.
4. Detailed design
4.1. Introduction

In this chapter the presented concept will be brought from sketched impressions to 3D models. All components of the system will be detailed in terms of (anthropometric) dimensions, material selection, detailed design solutions and manufacturing. Within the Fish Trap Model (Muller, 2001) that is presented at the start of the Conceptualization phase, the end result of this section is referred to as the Material Concept. The goal is to develop a proposal with sufficient level of detail and substantiated in such a way that it can be said with certainty that the proposal is realistic.

The following sections will one by one discuss the detailed design of the product components. Their main functionality will be described and their dimensioning will be established based on anthropometric and technical requirements. The envisioned material and manufacturing properties are then selected. The different parts that are included in this are: the main unit (4.2), which is actually a sub-assembly of a number of other components, the holder (4.3), the arc (4.4), the arm (4.5) and the extensions of the arm-end (4.6).

After this discussion, the complete product is presented, including a cost price estimation and assembly steps (4.7). To bring the design to full completeness a first branding suggestion is done. The detailed design phase sets the stage for the evaluation of the design proposal in the phase thereafter.

A batch size estimation is done to estimate the production costs and select materials and processes accordingly. In practice the actual applications context depend on the partnerships that can be set up with different parties in the industry. The calculation that is done here is purely hypothetical, assuming that relevant partnerships can indeed be established for the selected key application scenarios. Following the estimations, a first batch size is set at 6000 pcs. A worst case scenario is set at 2000 pcs, which can be used when making decisions on the pricing.

### Batch size estimation

**Neurorehabilitation**

- 46,000 People get a stroke in the Netherlands per year (Hartstichting, 2015)
- 41,400 90% of people survives a stroke (Stroke Association, 2016)
- 14,490 35% gets Early Supported Discharge (Stroke Association, 2016)
- 7,245 For 50% of these patients it is interesting to use the headgear*
- 362 5% of this group will actually use the product*

**Neurofeedback**

- 4x10⁶ People that are within age 10-30 in the Netherlands (CBS, 2016)
- 60,000 1.5% suffers from AD(H)D (conservative estimation)
- 600 1% of those will use the product*
- 1,200 Only half of the NF use will be by AD(H)D patients age 10-30*

**Cognitive enhancement**

- 250k Number of students on Dutch universities (DUO, 2016)
- 125k Number of male students*
- 12.5k 10% of those are interested in the product*
- 125 1% will acquire the product*
- 250 Only half of the users will be male university students*

**Total**

- 1,812 Total number of estimated users from three focus application
- 2,416 75% of sales in Netherlands, 25% is from other countries*
- 3,221 75% of sales is for key scenarios, 25% is for other applications*
- 6,442 The first production is for 2 years of sales*

Items marked with an asterix (*) are assumptions.
4.2. Main unit

4.2.1. Introduction
The main unit of the product proposition is the part that is located at the ear. In this section it will be discussed in two separate sections: the cassette, the embodiment (see Figure 50).

4.2.2. Cassette

Starting Points
The cassette is the rotating part on the main unit. Its functionality is to allow the (concurrent) placement of two elements (arms and/or arcs) in variable angular orientations and degrees of extension in relation to the rest of the product.

It was envisioned that this part would be a number of stacked discs that snap into one another. The arms can slide into slots in these discs. The snap connection should still provide rotational freedom between the different discs and between the cassette and the main embodiment.

Other requirements that are taken into account during the detailing of this sub assembly is that the number of individual parts and their complexity should be as low as possible in order to keep production costs low.

Detailed Design Description
An exploded view of the detailed design is shown in Figure 49. The sub assembly consists of three components. The bottom two deliver the main functional properties. They have a technical appearance as a result of the effort to include all functionality yet make production easy. The third component is a cap that tops off the discs and ‘cleans up’ the appearance.

Figure 50: Components of the main unit in the concept design

Figure 49: Exploded view of the detailed design of the cassette
The bottom component has snap fingers that connect to an opening in the main embodiment (a) and that connect to the middle disc (b). The large flange lies on top of the supporting embodiment. It contains a slot in which the arms can slide (c) that are clamped both at top and bottom. There are two circular shapes that guide the movement of this disc in the main embodiment (d) and the rotation of the overlying disc (e). The small bridge in the middle (f) serves as support for the second arm when the assembly comes together.

The middle disc starts with a ring on which the snap fingers from the underlying part land (g). It also contains openings for the top cap to snap into (h). The other openings in the side are for the second arm to slide through, that again are clamped on top and bottom (i).

The top cap then contains the snap fingers to connect to the second disc (j) and its bottom surface is shaped as such to form the slot that guides the second arm (k). The top surface is dome shaped and tops of the stack with a clean look (m).

It has deliberately been chosen not to integrate a ‘lock’ feature in the design. Ideally the arms stay in place much like the microphone arm of air traffic controller headsets does. An alternative (extended) proposal has been developed for if this turns out to be unsuccessful. This is included in Appendix IX.

ANTHROPOMETRIC AND TECHNICAL DIMENSIONING
This component has technical dimensions only and anthropometry does not play a role in the dimensioning. The final design is established through different iterations. It has been optimized for production. All parts can be made with simple two part molds with a flat parting line. The tolerances of the cassette are the most critical of all the parts of the product. These should be established together with a specialized production engineer.

MATERIALS AND MANUFACTURING
The parts of the cassette should be produced with a bearing-grade, wear resistant plastic. Nylon (PA6) is the most widely used plastic for bearing applications. It has low friction, a low wear rate and does not need lubrication. It can also be produced with high tolerances. POM can be an alternative choice that is a little less wear resistant but should be suitable for low-load applications such as these. The higher Tensile Strength of Nylon makes that for now that is the material of choice (Figure 51) (KMS Bearings, 2016).

The design of the components is optimized for injection molding. The components can be produced in a single injection by making multiple cavities in one blank. This helps to limit the operational costs and can make it possible to use injection molding with a low batch size. These parts have a very low depth and only little tooling is needed to produce the mold. The low production size also allows the use of molds that have a shorter lifetime.

![Figure 51: Comparison of different bearing grade plastics (After KMS Plastics)](image-url)
4.2.3. MAIN EMBODIMENT

STARTING POINTS
The main embodiment refers to the supporting housing for the cassette, i.e. that in which the cassette is placed and wherein it can rotate. The main functionalities that this part fulfills are:

• It facilitate the placement of cassette at site T3/4 from the 10-20 system;
• Allows placement of arcs (+ elastic strap) in front and rear positions;
• Allows placement of probe behind the unit to target T3/T4 when desired;
• Connects to holders at the ears;

The proposed design is build up of two parts: a front and back cover. The shape is derived from its functionality: a circular shape under the cassette is extended downwards to connect to the holder. On the sides it has slots for the arcs to slide into between the two covers. The design is symmetric so that it is suitable to be used for both left and right side.

DETAILED DESIGN DESCRIPTION
The front cover has a big opening in which the cassette can snap (a). The front plate (b) extends downwards and connects after a shape transition (c) to the holder. A small protrusion in the middle (d) will snap into the holder to fix it in place. Testing should prove later if this is sufficient or not. The back of the front cover shows ribs (e) that also serve as guide for the arc that slides in the openings left and right (f). Three cylinders allow screws to connect the front and back cover (g).

The back cover captures some more functionality. The back plate (h) is curved so that it makes better contact with the scalp. Three openings (i) allow the screws to go through and into the front cover. This back plate and the screws will be covered with a 2mm thick padding, that leaves the middle open. In the middle there is an circular indentation that allows for an electrode to be placed underneath the product (j), approximately at T3. The wire can run off via the slots that go to the left and right (k). These slots are also used for the elastic strap of the arc, which can connect to the middle pin (m). The inside of the back cover is simply the negative of what was just described. The plateau that forms as a result of (h) is situated just behind the cassette and can be used for the alternative cassette proposal. The shaft that leads downwards (o) is used to strengthen the connection to the holder, to provide more room for underlying electrodes and to clamp the legs of the arc as they slide between the shaft and the front.

Figure 52: Renders of the 3D models of the main embodiment parts (front and back cover).
ANTHROPOMETRIC AND TECHNICAL DIMENSIONING

There is a number of dimensions for which anthropometric data are used. A first feature that is adapted based on anthropometric data is the curvature of the back plate that touches the scalp. This curvature is approximated by analyzing the horizontal distance from the scalp at a 20mm distance from T3, both in depth and height. This was done for different head shapes. Appendix X explains this process, the simplifications and calculations. Figure 53 displays the suggested curvature as modeled in CAD software. Foam padding of 2 mm will be added between the scalp and the main embodiment to account for the variation of the scalp surface and to provide comfort.

The front cover of the embodiment is placed under an angle in relation to the midsagittal plane (which devided the body in left and right). Due to this angle the arms move towards the middle when they are extended from the cassette. Sites that are further from the ear in side (requiring a larger extension of the arm) typically also are located further towards the middle. This is so for different sites on one head (C3 compared to F3), but also for the same site on different heads (C3 on different head shapes).

The pressure-adjustment-feature (as proposed in section 3.3.4) can also be used to move the tip of the arm towards the middle, but this process is aided by placing the front face of this embodiment (and hence the cassette) under an angle. A simplified calculation is done to evaluate the horizontal distance of C3 in relation to the ear for different head breadth extremities. There appears to be a possible variation of about 15 mm. As a result it is decided that a 10 degree angle could be a good starting point to achieve this horizontal translation of the arm end. The calculations are included in Appendix XI.

Another relevant metric is the distance between T3 and the location where the ear attaches to the scalp, known as the otabasion superius. Ideally the cassette is placed directly over T3. The necessary anthropometric data is to the authors best knowledge missing. This could be a point for future research. In order to get a first rough impression of this data, a small study with 4 subjects was done to estimate this distance. This study indicates that the distance between T3 and the otabasion superius is about 12 mm on average. For the placement of the cassette this could be a little too tight of a fit. It is decided to place the cassette slightly above T3 (which can be compensated for during repositioning of the arms and arcs). The details of this study can be found in Appendix XII.

MATERIALS AND MANUFACTURING

There are no really unique requirements for the materialization of these parts when compared to other, regular, plastic product embodiments. The part will be subject to different forces (via the arms, arcs, cassette and holder) so it is important that its material quality is relatively high. ABS is a widely used plastic for product housings. It is known for its good mechanical properties in relation to price and weight. It also has good machining and aesthetic properties (CES, 2016). Furthermore, the embodiments of other neurotech products such as the Macrotellect Brainlink are also made out of ABS plastic (MindtecStore, 2016). It is therefor selected as first material of choice for these parts of the product.

The parts are suitable for production by injection molding. Again, the batch size is rather low for such a production process, but alternative production methods like additive manufacturing might not deliver the aesthetical and material quality that is desired. Low cost injection molding should be possible by using aluminum molds and rapid tooling. The parts are designed so that no use of slides or side cores in the mold are needed.

Figure 53: The modelled averaged head surface that was used to shape the back plate of the main embodiment.

Figure 54: Side view of the front cover, displaying a 10 degree angular orientation.

Figure 55: A schematic illustration of the expected distances between points of the product and the body.
4.3. Holder

STARTING POINTS
The holder is the part that actually wraps around the ear. As mentioned in section 3.3.3, many different versions of this part are possible within the product portfolio. Most interestingly it can be personalized for an optimal fit (3D printed) and minimized to be compatible with hearing aids and/or glasses. It also holds the opportunity to integrate electronics such as reference electrodes, heart rate monitoring or audio. These are scenarios that can be subject of future design efforts. In this stage what will be developed is a first design proposal that captures the basic functionalities in a ‘fit for all’ design: The functions are:

- Connect to the main embodiment;
- Wrap comfortably around the ear towards mastoid;
- Distribute pressure over a larger surface.

A proposal is developed that breaks down the holder into two components: a shell and a cushion part. The shell is a piece of plastic embodiment that gives the main form and rigidity. The cushion is placed inside the shell and touches the scalp where it adapts for head shape variations and provides comfort. It is replaceable in order to ensure hygiene.

DETAILED DESIGN DESCRIPTION
The holder design has quite an intricate, 3D curved shape. At the top there is a cavity in which the main embodiment with the cassette can be placed (a). The protrusion from that front cover will snap into an opening in the holder (b). To the left (in this image) goes a curved leg behind the ear (c), following the head surface curvature that was generated earlier for the back cover. The front face of it has an inward bend towards the scalp (d). The outside edges of the holder are quite thick but the inside edges are thinner (e) so that it is the cushion that is in touch with the ear rather than the holder. The cushion has a ‘bump’ on the bottom (f) that ensures that it sufficiently touches the scalp at that point. Other than that it is simply the exact negative of the holder part and the little edges (g) make that they line up perfectly (assuming the cushion is injection molded rather than stamped).

Figure 56: Renders of the 3D models of the holder.
ANTHROPOMETRIC AND TECHNICAL DIMENSIONING

The ear and surrounding surface is a very complex piece of geometry. This makes it difficult for researchers to acquire 2D and 3D data. Many studies focus only on global ear dimensions such as the total length and width. The detailed data that would ideally be used in this project are difficult to come by. A recent study by Lee et al. (2016) aims to provide such data of the ear.

The data that they have generated relate (e.a.) to the human ear root (the shape of the attachment of the ear to the scalp). The actual dimensions of the ear root are not publicly available, but the average contour is provided. This was used to design a sensible shape of the holder proposal. This process is described in Appendix XIII and results in the basic shape as shown in the Figure 57. Since the holder in this case does not actually carry the complete product (the product is clamped to the scalp rather than carried on the ear), the exact fit is arguably less critical than in other devices that are coupled with the ear.

A second relevant metric is the protrusion of the ear from the scalp. The thickness of the product will be adapted for this. The data is obtained from Lee et al. (2016) and Kalcioglu et al. (2003). The ear protrusion is larger behind the ear than on top of the ear, so only we will look at the top only. Where Lee and associates note an average protrusion of 17mm, the data of Kalcioglu and associates indicate about 12.8 (both have a standard deviation of about 3 mm). A product thickness of 10 mm would allow 95% of the subjects from the study of Lee and 85% of users from Kalcioglu to use it without pushing the pinna of the ear more forward. This is set as target and used in the design.

MATERIALS AND MANUFACTURING

The material selection of the shell of the holder is done first. A material property that is envisioned for this part is deformability under moderate heat. Similar to the frames of glasses, the shape of this part can then be adjusted (after production) to fit ones specific head shape better. This is done by heating the part in hot water or with a hair dryer. After several minutes, it can be slightly deformed under pressure. In this way the comfort and stability can be increased by making it fit better on the scalp.

The material that is commonly used in the frames of glasses is Cellulose Acetate (CA). Actually the designs are comparable in many aspects. Not only the envisioned deformability, but the whole shape, placement and interaction with the holder are similar to glasses. CA is therfore found to be the most logical material selection if the envisioned deformability is persisted. If after testing this turns out to be unnecessary, this part can be made out of ABS plastic, in line with the main embodiment.

The cushion should be made of some type of foam. It is important that it feels comfortable to the skin, it can have sufficient rigidity and that its moisture absorption rate is low. Ethylene-vinyl acetate (EVA) has a rubber-like appearance and is known for its use in e.a. yoga mats and various sorts of padding in sports equipment like goggles and boots that are in contact with skin. It is water proof and can be made in different grades of flexibility. It is suitable for molding and stamping and is hence the material of choice for the cusion in this part (CES, 2016).

Ideally both parts are injection molded. The design of the shell requires a two-part mold with one side core that shapes the cavity where the main embodiment fits into. This results in slightly higher mold costs, especially since designs for left and right ear are necessary. The cushion has a lot less critical tolerances and finishing, and does not need the side core.

When production numbers are still low, it could be interesting to consider 3D printing the shell part. This is not possible in CA but could be done in ABS plastic. The loss of the deformability can easily be compensated for with personalized 3D printed designs. This is a point of further investigation. The cushion can alternatively be cut out of flat sheet (stamped) in order to reduce investment costs.
4.4. Arc

STARTING POINTS
This section deals with the further detailing of the design of the arc element of the product proposal. The starting points from this section can be taken from section 3.3.5 on page 44. The most important functionalities and properties of this arc are the following:

• Exert sufficient clamping force on ear units to stabilize the product during use;
• Exert pressure on probes in all main positions and for all head shapes;
• Properly guide the elastic inner strap during product application.

A design proposition is made that contains one additional feature compared to the earlier presented impression: three slots over the arc length are created to provide extra room for underlying probes. Furthermore they can bring more ‘lightness’ to the aesthetics of the product.

DETAILED DESIGN DESCRIPTION
The design consists of a rigid arc (a) and an elastic inner strap (b) to which the probes connect. Three openings (c) are created in the rigid arc so as to create extra room for underlying probes. The outer edges of the arc are ribbed. This provides extra stiffness but also acts as cable tray (d) to guide the wires away from the head.

The elastic strap is guided at four places: at both sides from the middle (e) and just about at both ends (f) where the metal legs (g) have an opening at their end where the strap threads through. The elements at both sides from the middle have rotational freedom so that they can move inward and outward when applied on different head shapes. In this way almost the complete elastic strap can come in contact with the surface of the scalp, allowing for placement even beyond the target sites.

Figure 58: Render impressions of the final 3D design model of the arc.
The metal legs on either side that slide into the main unit. These metal legs should be suitable for an average head shape and can be deformed to adapt for smaller or wider heads when more pressure or comfort is desired. To facilitate this deformation, a small indent is made in the leg at the connection with the arc (h). The shape transition that happens where the plastic arc and metal legs connect (i) is so to allow more room for probes to be placed underneath the plastic part and to guarantee that the plastic does not scrape along the sides of the head. A small screw keeps the leg connected to the plastic part (j).

ANTHROPOMETRIC AND TECHNICAL DIMENSIONING
Different dimensions of the arc are optimized on the basis of anthropometric data. Because of the symmetry of the scalp, we here consider the left side of the head only, starting with the contour.

Many head worn consumer products simply follow a circular contour. This simplification often suffices, though it might not be ideal for heads with a low Cephalic Index (see 4.3 on page 54). Within this project however, the detailed contour of the arc is not critical. The reason therefore is that the elastic strap adapts for head shape variations and the arc doesn’t make full contact. It can therefore be said that a circular contour is in this case adequate and in line with current industry practices.

The arc will mainly be used in circumferential positions (front half or back half), or over the top of the head. The minimum and maximum distances of the underlying target sites in relation to the midline are calculated (various hea sizes). Based on these locations, the dimensions of the slots in the arc are determined. This is shown in Figure 59. Appendix XIV includes these calculations. An additional 10mm backlash is incorporated in the dimensioning of these slots. The length of the legs is also extended by 10 mm. A mm offset provides extra room for head shape variations and the body of the probe.

There is a 35 mm difference between the minimum and maximum location of T3 (at the ear). Including the 10 mm backlash this means the legs are 45 mm long. When adapted to the smallest head size they will stick out 5 mm (circumferential position) or 35 mm (using the cassette). This is not expected to cause any problems.

MATERIALS AND MANUFACTURING
The bending of the arc creates the clamping force that serves as product stabilization. It is very important that the tensile strength of the arc is high, so that it doesn’t break easily under this tension. The Cambidge Engineering Selector is used to select suitable materials (CES, 2016). The selection process shows that reinforced PA+PP would best satisfy the requirements (see Table 8), though this depends on the actual desired elasticity (Young’s modulus), which at this point is not known.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Glassfiber</th>
<th>Tensile Strength</th>
<th>Youngs mod.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA6+PP</td>
<td>30-35 %</td>
<td>122 - 149 MPa</td>
<td>7.3 - 9.1 GPa</td>
</tr>
<tr>
<td>PA6</td>
<td>30-35 %</td>
<td>90 - 132 MPa</td>
<td>4.7 - 7.9 GPa</td>
</tr>
<tr>
<td>PC+PET</td>
<td>20-30 %</td>
<td>72 - 122 MPa</td>
<td>6.8 - 9.0 GPa</td>
</tr>
<tr>
<td>PC+PBT</td>
<td>20-30 %</td>
<td>75 - 118 MPa</td>
<td>5.1 - 11.5 GPa</td>
</tr>
<tr>
<td>ABS</td>
<td>30 %</td>
<td>90 - 110 MPa</td>
<td>6.8 - 8.3 GPa</td>
</tr>
</tbody>
</table>

Table 8: Selection of materials from the Cambidge Engineering Selector (Granta, 2016). The selection criteria were the following: [1] excellent moldability, [2] Elastic Modulus <8GPa, [3] Yield Strength > 60MPa, [4] Contact with salt water is acceptable, [5] High fatigue strength (>40MPa), [6] Price < 5 $/kg. These criteria are based on the first guesstimated favorable product properties. The resulting 9 polymer grades are clustered in the five that are listed in the table.
A simulation using the Finite Element Method in SolidWorks (D’Assault, 2016) is performed to assess the internal forces in the part if it were made out of the PA+PP grade. In order to assess this a prescribed displacement of 25 mm was assigned to the arc end as illustrated in Figure 60. The middle of the arc is fixed. The highest stress that occurs is $1.9 \times 10^7$ Nm$^{-2}$, which is well below the elastic limit ($1.0 \times 10^8$ Nm$^{-2}$). With this simulation it seems that PA+PP can indeed be a suitable material choice.

Regular PU elastomer seems an interesting option; it is the strongest elastomer and has a high tear resistance. It can be fabricated with many different grades of elasticity. Silicone could be an equally good choice. Though it is typically weaker, that shouldn’t cause problems in this context (CES, 2016). The material quality of the strap is less critical than that of the arc.

A test with different elasticity grades should be set up in the future to select the optimum. A moderately high elasticity and elongation are desirable to easily cover a wide range of head sizes. The strap can simply be die cut out of sheet material.

The legs can be stamped out of metal sheet (aluminium or stainless steel). A design for the middle elastic guide element is developed, which can be produced with injection molding. If at first the startup costs need to be kept lower, this element can also be replaced with a bent aluminum or steel wire.

The most difficult part is the manufacturing of the arc. The part needs to be produced with injection molding, but in contrast to many of the other parts there is no simple split line. It should be assessed together with a production engineering specialist how this part can be best optimized for production in series.

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**Figure 60:** Von Mises Stress Plot of the simulation study.
4.5. Arm

STARTING POINTS
The arm is a subassembly within the product that is used to target the locations of F3/4, C3/4 and P3/4. It slides into the cassette and has freedom in rotation and extension. Furthermore a type of pressure adjustment feature is built in, by which the user can add or release the pressure that the arm exerts by moving a slider up and down the arm.

DETAILED DESIGN DESCRIPTION
The final design proposal is shown in Figure 61. The arm end is shaped as a kind of small claw with a circular inner contour (a). This was proposed in the concept phase. Different types of probes can be connected to this, often in a similar fashion as with traditional electrode caps. The arm has a shape transition at the end where it bends towards the scalp (b) so that it can more easily make contact without the other sections of the arm scraping the scalp surface. The opening of the claw extends upward over this shape transition and forms a slit through which wires can run (c). The wires can be pressed in between the ribs underneath the arm (d) that also acts as cable tray, next to providing rigidity. The slider (e) wraps around the edges of the plastic part of the arm (and around the metal strip), but doesn’t run over the ribs so to leave this cable tray open at all positions. The top surface of the slider is placed under a slight angle to make it easier to slide it forward with pressure (f). The shape is drop like, which is thought to be both more comfortable during use than straight designs and also more aesthetically pleasing.

The metal strip (g) follows a more angular shape than the plastic part and has two holes for screws (or rivets) to connect through (h) into the openings in the arm (i).

ANTHROPOMETRIC AND TECHNICAL DIMENSIONING
The dimensioning of the arm is optimized based on both anthropometric data and simulations of its technical performance.

There are two strips running along each other, a metal spring and a plastic part. Their contour is shaped based on the analysis of the digital head forms that were obtained (see section 2.3.5 on page 18). The coordinates of the target sites (F3, C3, P3) in relation to site T3 (at the ear) were noted for these head models. This was done on the plane that crosses both these target sites (so the y coordinates are actually on different planes). For example, site F3 on the ‘short/wide’ head model is located at 31x76mm (see Figure 62). This was done for all sites on all different models. The coordinates are plotted in one figure. The shape of the arm has subsequently been chosen as such that it is believed to be possible to target all these sites (with the aid of the pressure-adjustment slider). This is illustrated in Figure 63 on the next page. The coordinates of the target sites are included in Appendix XV.
When site C3 is targeted, the arm will bend outward during product application, i.e. it is under tension without any movement of the slider. When further sites are targeted (F3, P3), it will be necessary to use the slider in order to get the desired pressure. A SolidWorks Simulation study is done in order to verify that the necessary deformations and displacements are possible, to optimize the dimensions of the arm and to select the desired material qualities. The three tests that are performed are:

- Is it possible to create contact pressure on the head surface (using the slider) of at least 100gr/cm², starting from a 0 contact position?
- Is it possible to create a 10mm translation in horizontal direction towards the midline using the slider?
- Is it possible to create a -10mm horizontal translation (away from midline) using pressure under the arm within 0-150gr/cm²?

Appendix XVI describes the details of these simulations and the simplifications are made in the model. Through a series of iterations, the dimensions and material qualities of the metal and plastic parts have been optimized to pass the three tests. In its current design it can increase contact pressure to about 190gr/cm² (test 1), translate 8mm with 100gr/cm² pre-pressure (test 2), and translate 11 mm inward using the slider without any limiting surface underneath (test 3). With these results the validity of the proposal is confirmed.

MATERIALS AND MANUFACTURING

The material selection was also established during the simulations. First a pre-selection was made of sensible materials.

The metal strip will be made out of spring steel. A standard grade spring steel is selected: AISI1095. This grade is used in different spring-strips found by resellers (e.g. Spring Engineers Ltd.). The exact material properties can be altered by different heat treatments. Using simulations (with a fixed the strip thickness at 1mm), a grade of AISI1095 tempered at 205deg C. is finally found to have the most suitable elastic properties. This must later be tested in practice.

For the plastic strip it is very important that its Tensile strength and Yield strength are high, so that it doesn’t break or permanently deform during pressure application. In line with the material pre-selection for the arc, in Table 8, reinforced PA could be a good first choice. A benefit of PA is that its low coefficient of friction allows for a more easy movement of the slider element. Eventually, following simulation results, a glass fiber fill grade of 35% is believed to be most suitable.

A point of attention is the moisture absorption level of PA, which is rather high. The end of the arm could be in contact with moisture from the scalp or the probes (sponges). PA can be treated to lower the moisture absorption. A test should clarify if this is sufficient. A different material selection out of the table can otherwise be made. The superiority of PA grades in terms of tensile strength makes it the first material of choice.

The spring steel strip can be cut and stamped (press-formed) in the desired shape. The two plastic parts (the plastic strip and the slider) can both be injection molded with simple two-part molds. The strips are joined together with a screw joint at both ends.
4.6. Arm-end extensions

STARTING POINTS
At the end of the arm, different extensions can be placed to enhance the functionality. This is how the design can be tailored to specific requirements from different setups, suppliers or users. In principle, these extensions should be unnecessary for most scenarios. The arm ends and arc are usable with many regular probe designs. Within the scope of this project only a brief suggestion is presented for what could later be its own branch of research and development in collaboration with people from the field. Two designs are proposed here that allow for different functionalities, namely:

- An increase of the number of connection channels possibilities at the arm end;
- An increase in the angular freedom of the probe at the arm end;

DETAILED DESIGN DESCRIPTION
Both proposals are mentioned earlier in section 3.3.4. The designs of the extensions is shown in Figure 64. The first proposal is simply provides two additional circular connection points that can be used for EEG or fNIRS research alongside a tES probe in the middle. In the same fashion an extension can offer four extra points to allow the 4x1 ring setup (Figure 12 on page 11). These extension elements could fit tightly around the arm-end (‘claw’) to stay in place. The design that is shown has a quite strong curvature that will bend outward on the scalp under pressure.

The second design is that of a snap on ball joint module. It acts as a bridge between the probe and the wire so that extra angular freedom can be offered to the probe on the scalp. The design and manufacturing of this part should be outsourced to a specialist. Dimensional criteria will be provided based on the shape model that is presented below in Figure 64. The goal is to have a design with a flange on either side of the claw, connecting through the middle opening.

MATERIALS AND MANUFACTURING
The probe supports could be manufactured in various ways. Whilst the two presented proposals could be quite common, many other designs would be used only for a very limited number of applications. Additive manufacturing therefore seems to be a suitable production process for most of these extensions. The ball-joint element would be produced through a series of forming steps (die cutting, rolling, pressing). The detail design and manufacturing is considered to be work for experts. There are different suppliers that can design and deliver custom made medical/electrical snap fasteners (e.g. Romefast). Double sided snap fasteners are known as Gypsy studs in the industry. Though no ‘medical gypsy stud’ seems to be available at the moment, there is no reason to assume that this is not possible.
4.7. The complete product

4.7.1. INTRODUCTION
The following sections deal with the complete assembled product. What will be described here is the bill of materials, the assembly procedure and the estimated production price. There are many different configurations of the product possible. Depending on the user, usage context and application this means that the parts list is variable. All following sections will discuss the product in the context of an envisioned consumer purchase that could occur in focus scenario 3 (cognitive enhancement, page 21). This ‘consumer kit’ includes 2 arms, 1 arc, 2 holders (left + right), 2 main units, 2 straps (1 spare) and 2 extensions.

4.7.2. BILL OF MATERIALS AND COST ESTIMATION
The bill of materials is included in Table 9. The part numbers comply with the numbers indicated in the exploded view of Figure 65. The noted cost price per part is based on rough estimation and represent an upper limit guideline. The costs of injection molded parts are estimated with an online mold cost estimator (CustomPartNet, n.d.). Basic part information (envelope, projected area, complexity level) and basic process parameters (mold class, tooling) are filled in. The calculator gives an estimation based on industry averages. The investment costs are debited over the first batch size of 6000pcs. For all injection molded parts a cost distribution of: 50% mold, 30% processing, 15% material, 5% other is assumed (ACOMold, 2016). Following these and other first estimations, the product components costs are expected to be a maximum of 22.70$. Following more advantageous estimations (production overseas, longer write-off times) the total price of components could be as low as $10. Further details and argumentation of these estimations can be found in Appendix XVII.

Figure 65: Exploded view of the detailed design product proposition.
## 4.7.3. Assembly Process and Time

The assembly procedure is documented in Table 9. It is assumed that there are no transportation times between steps. The assembly can be performed by one individual in an assembly cell. Furthermore, it is assumed that this person is experienced in assembling this product and that relevant moulds or tools are used to align the components during the process. This is especially critical for the screw operations of the arm and arc (steps 3.1 and 4.2). The presented estimations are done based on the Methods Time Measurement (Karger & Bayha, 1987), yet these are very rough indications. A more detailed estimation that takes into account the actual tolerances and axis of symmetry should be done in the future. The current estimation can be seen as an insight in the order of magnitude of the assembly time. The total estimated time is 108 seconds. Taking into account various delays that can occur throughout the process, it is at this point thought to be possible to assemble 25 products per hour.

<table>
<thead>
<tr>
<th>#</th>
<th>Sub assem.</th>
<th>Part</th>
<th>Material</th>
<th>Production</th>
<th>Qty</th>
<th>Costs</th>
<th>Total</th>
<th>Notes</th>
</tr>
</thead>
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<td>1.00</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>Back cover</td>
<td>ABS</td>
<td>Injection molding</td>
<td>1</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>Cushion 1</td>
<td>EVA</td>
<td>Stamping</td>
<td></td>
<td>1</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>Screws</td>
<td>Stainless steel</td>
<td>-</td>
<td></td>
<td>3</td>
<td>0.01</td>
<td>0.03</td>
<td>ISO 7046-1 - M1.6</td>
</tr>
<tr>
<td>2.1</td>
<td>Cassette</td>
<td>Bottom ring</td>
<td>PA6</td>
<td>Injection molding</td>
<td>1</td>
<td>0.45</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>Middle ring</td>
<td>PA6</td>
<td>Injection molding</td>
<td>1</td>
<td>0.45</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>Top cap</td>
<td>PA6</td>
<td>Injection molding</td>
<td>1</td>
<td>0.45</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>Holder</td>
<td>Shell</td>
<td>CA</td>
<td>Injection molding</td>
<td>2</td>
<td>1.66</td>
<td>3.32</td>
<td>3D printing also possible</td>
</tr>
<tr>
<td>3.2</td>
<td>Cushion 2</td>
<td>EVA</td>
<td>Injection molding</td>
<td>1</td>
<td>0.92</td>
<td>0.92</td>
<td>Stamping also possible</td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>Arm</td>
<td>Spring strip</td>
<td>AISI 1095</td>
<td>Stamping</td>
<td>2</td>
<td>0.16</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>Plastic strip</td>
<td>PA6 (35% gf)</td>
<td>Injection molding</td>
<td>2</td>
<td>2.10</td>
<td>4.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>Slider</td>
<td>PA6</td>
<td>Injection molding</td>
<td>2</td>
<td>0.60</td>
<td>1.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>Screws</td>
<td>Stainless steel</td>
<td>-</td>
<td></td>
<td>4</td>
<td>0.01</td>
<td>0.04</td>
<td>ISO 7046-1 - M1.6</td>
</tr>
<tr>
<td>4.5</td>
<td>Extension</td>
<td>ABS</td>
<td>Injection molding</td>
<td>2</td>
<td>0.50</td>
<td>1.00</td>
<td>Different versions possible</td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>Arc</td>
<td>Middle arc</td>
<td>PA+PP</td>
<td>Injection molding</td>
<td>1</td>
<td>5.56</td>
<td>5.56</td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>Leg</td>
<td>Stainless steel</td>
<td>Stamping</td>
<td></td>
<td>2</td>
<td>0.16</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>Guide</td>
<td>PA6</td>
<td>Injection molding</td>
<td>2</td>
<td>0.66</td>
<td>1.32</td>
<td>Can also be a bend wire</td>
<td></td>
</tr>
<tr>
<td>5.4</td>
<td>Strap</td>
<td>PU elastomer</td>
<td>Stamping</td>
<td></td>
<td>2</td>
<td>0.50</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>Screws</td>
<td>Stainless steel</td>
<td>-</td>
<td></td>
<td>2</td>
<td>0.01</td>
<td>0.02</td>
<td>ISO 7046-1 - M2.5</td>
</tr>
</tbody>
</table>

Table 9: Bill of materials and cost price estimation. The part numbers correspond to Figure 65.

<table>
<thead>
<tr>
<th>#</th>
<th>Sub assem.</th>
<th>Qty</th>
<th>Description</th>
<th>Parts</th>
<th>Handling time (s)</th>
<th>Assembly time (s)</th>
<th>Total (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Main</td>
<td>1</td>
<td>Click to cap on middle ring</td>
<td>2.3+2.2</td>
<td>2</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>1.2</td>
<td>Main</td>
<td>1</td>
<td>Click middle ring on bottom</td>
<td>2.2+2.1</td>
<td>2</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>1.3</td>
<td>Main</td>
<td>1</td>
<td>Insert bottom ring into front</td>
<td>2+1.1</td>
<td>2</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>1.4</td>
<td>Main</td>
<td>1</td>
<td>Screw back cover onto the</td>
<td>1.1+1.2</td>
<td>2</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>1.5</td>
<td>Main</td>
<td>1</td>
<td>Stick Cushion 1 to back cover</td>
<td>1.3+1.2</td>
<td>2</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>2.1</td>
<td>Holder</td>
<td>2</td>
<td>Insert Cushion 2 in holder</td>
<td>3.2+3.1</td>
<td>2</td>
<td>1.5</td>
<td>7</td>
</tr>
<tr>
<td>3.1</td>
<td>Arm</td>
<td>2</td>
<td>Screw metal strip on plastic</td>
<td>4.1+4.2+4.4</td>
<td>3</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>3.2</td>
<td>Arm</td>
<td>2</td>
<td>Move slider onto metal strip</td>
<td>4.3</td>
<td>2</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>4.1</td>
<td>Arm</td>
<td>2</td>
<td>Insert guide into middle arc</td>
<td>5.3+5.1</td>
<td>2</td>
<td>1.5</td>
<td>7</td>
</tr>
<tr>
<td>4.2</td>
<td>Arm</td>
<td>2</td>
<td>Screw leg onto middle arc</td>
<td>5.2+5.1+5.5</td>
<td>3</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>5.1</td>
<td>Packaging</td>
<td>8</td>
<td>Place components in box</td>
<td>1+2+3+4+5</td>
<td>2</td>
<td>1.5</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 10: Assembly process and assembly time estimation. The part numbers correspond to Figure 65.
4.7.4. PRICING
The pricing can roughly be build up as follows:

<table>
<thead>
<tr>
<th>Conservative estimation:</th>
<th>Bold estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>22,70 material costs (maximum)</td>
<td>10,00 material costs (minimum)</td>
</tr>
<tr>
<td>1.00 assembly costs (25$/hr wage)</td>
<td>0.40 assembly costs (10$/hr wage)</td>
</tr>
<tr>
<td>1.50 packaging costs (estimate)</td>
<td>0.50 packaging costs (estimate)</td>
</tr>
<tr>
<td>2.00 shipping and other costs</td>
<td>1.00 shipping and other</td>
</tr>
<tr>
<td>Total = $ 27,20 (investments: $163,200)</td>
<td>Total = $ 11,90 (investments: $71,400)</td>
</tr>
</tbody>
</table>

These two estimations can be used to build a business model. When assuming a sales margin of 500% and 21% VAT, this results in a consumer price of 72-165$. The break even point would then lie at 1200 sales.

Setting a consumer price at $118,50 (mean), would result in a break even point after 1744 sales (worst case cost price estimation) up to 762 sales (bold cost price estimation) and a revenue of 400-500k. In both these cases the investment costs are debited over a production batch of 6000 pieces. A worst case estimation was set at 2000 users. This means that the break even point can still be reached, even when the lowest expected user group of 2000 people and the highest expected cost price are retained. It should be assessed later if users are indeed willing to pay $118,50 for the design.

Further decisions regarding the business model and pricing strategy would need to be researched later. All presented numbers just give an impression of what could be possible.

Next to the stated cost, the user would need the necessary electronics and possibly a type of arm or belt fixture (see section 3.3.6). Depending on the further detailing this could add another 5-25$ to the purchase for the arm strap, and 100-2000$ for the electronics.

4.7.5. BRANDING
A rapid exploration into the branding of the headgear is done. The goal of this was to find a sensible product name that can be used for future communications. The qualities that were tried to capture in this name are:

- The product interacts with your brain/mind/neurons;
- It is a technical product and the name should radiate such a meaning;
- It is a modular product that can be adapted;
- It should fit with many usage scenarios, from gamers to patients;
- It should be an ‘international’ name, it’s pronunciation not limited to language

With these drivers in mind a brainstorm was done. The final proposed name is: Nerva. The root of this name comes from the word nerve (or Latin nervus), the cells which build the brain and nervous system. The bastardization of the word transforms it into a brandname that is short, catchy and modern. Furthermore, the modularity aspect can be communicated through the adaptation <my>Nerva, the platform where everyone is encouraged to assemble their own (my) Nerva. With Minerva being the Roman goddess of wisdom, medicine and commerce, the resemblance here is of course not incidental.
Figure 66: Impression of Nerva headgear.
5. Evaluation
5.1. Introduction

At the start of the project the assumption was made that modularity could be a successful strategy to find a balance between the functionality, experience and fit of neurotech headgear. These 3 aspects were defined as follows:

1: The range of capabilities of the product and its suitability for a variety of applications;
2: The overall perceived quality of the interaction of the user with the product in context;
3: The conformity of the dimensions of the product to anthropometric and technical requirements.

A design proposition of a new modular type of headgear is developed. Several aspects of this proposal are tested and evaluated in the following sections. This will lead to recommendations for further research and development of the headgear proposal. A prototype is made that can be used in different stages of the evaluation. The simplifications of the prototype are discussed, together with insights that arose during the production of this prototype (5.2). The three sections thereafter focus on the three main themes of this project.

In section 5.3 a discussion is presented on the functionality of the product. This is approached in a three step evaluation of the available technologies (5.3.2) the target sites (5.3.3) and the headgear configurations (5.3.4). Its shortcomings are brought to light and improvements are suggested. This section is based on a digital model of the product and the prototype does not play a role during this evaluation.

The prototype is used to evaluate the ergonomic and technical fit of the design in practice in section 5.4. A test is set up in which the prototype is placed on the heads of ten participants. Its features are adapted for the specific head shape and size of the subject. The data about the accuracy and repeatability are collected and presented and other complications that come forward will be discussed.

The test subjects from the fit evaluation are given a questionnaire to assess their perceived experience of the product. This is discussed in section 5.5. The assessment divides the user experience in six factors. The main areas of improvement are identified and suggestions are done for further research and development.

The evaluation is finalized with a brief stakeholder discussion (section 5.6) before wrapping it up with a set of final conclusions and recommendations (5.7).
5.2. Prototyping

5.2.1. INTRODUCTION
A prototype is built to test aspects of the product usability. It will be used later to evaluate the fit and experience of the design with test subjects. It also gives additional insights in aspects such as aesthetics and assembly. The prototype design (5.2.2) and its functionality (5.2.3) are discussed here.

5.2.2. BUILDING THE PROTOTYPE
It is possible to build a prototype with only limited deviation from the actual design. Many of the 3D files of the parts are already created during the detailed design phase. Those parts can easily be prototyped with additive manufacturing (3D printing). A few simplifications were still made in the prototype.

• The material quality of none of the components has to match the actual intended material quality. This means that the spring strip can be replaced with regular steel and the plastic parts do not have the actual intended stiffness (any plastic will do).
• Components with a small thickness in the original 3D design can be thickened for the prototype purposes, compensating for lower material and production quality.
• The strap can be replaced with a simple piece of elastic without any further connection points for the electrodes. An OEM press-stud satisfies as connection to the main unit.
• The foam padding can be replaced with any flexible material at hand. Three materials have been tested and neoprene cell rubber was used in the final prototype.
• The slider function does not have to be incorporated in the prototype, as its behaviour can not represent actual deformations.

Table 11 lists the different prototype components and their material and production details. The prototype was assembled and found successful for the planned evaluation studies. Figure 67 show a series of photos taken from the prototype with different configurations.

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Production</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holder (left+right)</td>
<td>PLA</td>
<td>3D printing (Ultimaker 2+)</td>
<td>A smaller nozzle is used for the cassette discs. The arm end has been thickened for the prototype.</td>
</tr>
<tr>
<td>Front cover</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back cover</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arc plastic part</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arm plastic part</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cassette discs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arm metal part</td>
<td>Steel (0.8mm)</td>
<td>Cutting, Bending, Drilling</td>
<td></td>
</tr>
<tr>
<td>Arc legs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guides</td>
<td>Iron wire (0.5 mm)</td>
<td>Cutting, Bending</td>
<td></td>
</tr>
<tr>
<td>Strap</td>
<td>Knitted elastic, polyester (6mm</td>
<td>Cutting</td>
<td>Marked with dots for target sites. Snap buttons glued at the ends.</td>
</tr>
<tr>
<td></td>
<td>wide)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cushion 1</td>
<td>Neoprene cell rubber (sheet, 3mm</td>
<td>Cutting</td>
<td>Thick cushion (1) from stacked layers</td>
</tr>
<tr>
<td>Cushion 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Screws</td>
<td>Stainless steel</td>
<td></td>
<td>DIN965-M1,6, DIN965-M2,5</td>
</tr>
</tbody>
</table>

Table 11: Parts of the final prototype with the choice of material and means of production.
5.2.3. INSIGHTS ABOUT THE PROTOTYPE FUNCTIONALITY
The production and assembly of the prototype led to a number of insights for further design improvements. These are listed below.

- **Assembly ridge:** It would be easier in assembly if the edges of the front and back cover have a positive and negative offset that fall into each other, so they stay in place better when screwing them together.

- **Cable guiding:** The cable guides under the arm and arc can be useful, but a more simplified version could also suffice (just 2 opposing points every interval). In practice this could be more convenient. Furthermore it should be considered if cable guide functionality should also still be added on the main unit and holder to guide away the cable behind the ear.

- **Curved arc:** The arc currently has a straight shape (in side view). It should be studied if this could bend a little more upward (‘pringle shape’). It is believed that in this way it could be more successful in targeting the relevant sites.

- **Cassette snap fingers:** The discs of the cassette currently have 2 snap fingers to connect to each other and to the main embodiment. It would be good to increase this number to at least 3 for a more balanced connection and force distribution. The snap fingers that connect the top cap of the cassette to the middle disc seem not very successful. Actually during assembly they have been chipped off and the top cap still stays in place due to the form fit. This is also interesting for the final design.

- **Elastic:** With this prototype it seems that only the two guide elements in the middle of the arc are sufficient. Extra guides at the ends are not necessary. The knitted elastic strap in the prototype seemed to work well. However, with silicon or PU rubber straps the friction between the strap and the guide element can be an issue. This should be studied and a redesign might have to be made (different strap material selection or adapted guide element design).

- **Side slots:** The legs of the arc do not have enough guidance when inserted in the side slot (making it hard to come out the other end). Adaptations on the inside of the back cover are needed.

- **Thickness of probes:** Since some of the probes that would be placed under the arm can have quite some thickness (>10mm), it should be studied whether or not the design of the arm needs to be adjusted to accommodate this better. With the tES sponges at hand this seemed troublesome.
5.3. Functionality evaluation

5.3.1. INTRODUCTION
In this section the headgear’s functionality is evaluated. This evaluation does not relate to the prototype, but to the envisioned full product proposal as presented in the detail design chapter.

At the start of the project it was set as goal to make the product suitable for a wide variety of applications. Three key scenarios were selected in the Analysis phase, which all come with a set of potential product configurations. The intermediary program of requirements that is composed at the end of the Analysis phase lists such intended product functionality, as well as possible functionality beyond that. This section will evaluate the final design in relation to that in three steps; first the different technological possibilities are discussed (5.3.2), thereafter the potential target sites are analysed (5.3.3) and lastly it is discussed to what extend the design allows for configurations of the anticipated application scenarios (5.3.4).

5.3.2. TECHNOLOGICAL FUNCTIONALITY OF THE DESIGN
The program of requirements contains the following statements on technical product functionality:
•  The product should be able to adaptively incorporate EEG, (CW)fNIRS and tES technology.
•  The product needs to be adaptable for different quality demands (e.g usage of both wet and dry EEG electrodes should be possible).
•  Heart rate and respiration monitoring can be considered for implementation.
•  Integration of headphones or other audiovisual support can be considered for implementation.

The product proposal could meet all these requirements. It doesn’t do so in its current stage, but it holds the potential to do so. Future developments focussed on new extension designs (for fNIRS and for combinations of technologies) and new holder designs (with audio, heart rate monitoring) can deliver the specific desired functionality. The current development only focussed on the basic version.

5.3.3. THE REACHABILITY OF TARGET SITES
The program of requirements contains the following statements regarding the target sites of the headgear:
•  All 10-20 sites should be targetable with the headgear.
•  Popular 10-10 sites should be included, mostly from frontal and central regions such a FC4, FC6, CP4, CP6, AF4, AF8 and their mirrored counterparts.
•  The earlobes, mastoids and shoulders should be included in the target sites for the headgear channels.

Figure 68 shows the expected coverage of target sites. All sites that are marked green are definitely targetable. All yellow marked sites is not yet ensured. The image is included in large in Appendix XVIII, including a description per site of why it is marked yellow or green.

T3/4 are the only 10-20 site which reachability is not fully ensured. It is located behind the main unit of the product and it should still be studied if the space that is provided there is sufficient for placing electrodes. The other foreseen troubles occur with 10-10 sites that are close to the main unit, including FC6, C6 and CP6 that were listed in the requirements. Depending on ones head size and shape, these might not be reachable with the arms (since those cannot be inserted far enough in the main unit) and it could be troublesome with the arc (too little room between the scalp and arc to place probes, depending on the thickness of the probe). This is a point of further research.

Figure 68: Reachability of target sites. Green marked sites are believed to be definitely reachable. Yellow sites are foreseen to have complications that are yet to be resolved (also see Appendix XVIII).
The inclusion of target sites besides those on the scalp (shoulder, earlobe (A2) and mastoid (TP9)) has fallen outside the scope of this project after the Concept phase. Though it is suggested how these sites could be included (see section 3.3.3 and 3.3.6), there is no further elaboration, detailing and testing. This should be subject of future developments.

5.3.4. POSSIBLE HEADGEAR CONFIGURATIONS

The program of requirements contains the following statements regarding the desired configurations:

- The product should have an expandable channel count of at least 2-8, positionable at different sites.
- Common setups that need to be anticipated in the design are: (1) all 10-20 single site + neutral site setups, (2) Any two concurrent sites from the 10-20 system (including symmetry setups) (3) Ring setups (1 central channel + 4 surrounding).
- The headgear should be compatible with the existing popular protocols of key scenarios, targeting especially (1) motor and speech recovery, (2) anxiety, stress, depression and attention training and (3) improving learning, memory and insight, as presented in Figure 24, Figure 26 and Figure 28.

The suitability of the headgear to facilitate these configurations is analyzed and is captured in Table 12. Limitations that result from the currently missing inclusion of target sites on the shoulder or earlobe (as discussed in the previous section) are ignored for now.

It can be seen that the majority of listed configurations are possible. Next to these setups, the headgear allows for a wide range of other unique setups, including those that combine different technologies. This is a strong feature of the proposal.

The product seems to be optimal for setups up to 4-6 sites (though you can always place more electrodes under the arc). The main limitation that was found is that it is currently not possible to target more than two sites in the middle of the head (Pz, Fz, Cz). There are only two connection points available for the arcs in such positions. This same limitation plays up in other configurations (e.g. Fz Pz C3 C4).

There are three suggestions for improvement, either one of which could resolve this problem. These are:

- Include 3 rotating cassette discs or make the cassette expandable;
- Develop longer arms that reach to the midline (in other words, develop a half arc);
- Include a connection point in the middle of the arc to which extensions or arms can be connected.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Suitability</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single 10-20 sites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symmetry setups</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any two concurrent sites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring setups</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor rehabilitation setups</td>
<td></td>
<td>Development of the necessary arm-extension is still required.</td>
</tr>
<tr>
<td>Visual rehabilitation setups</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aphasia rehabilitation</td>
<td></td>
<td>Protocols use closer 10-10 sites (FC5, C5) of Figure 68.</td>
</tr>
<tr>
<td>Dysphagia rehabilitation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mindfulness centred setups</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mini full brain analysis</td>
<td></td>
<td>Extra connection points are needed to reach multiple midline sites.</td>
</tr>
<tr>
<td>Double symmetry setups</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enhanced cognition</td>
<td></td>
<td>The shoulder is often a target site, so the proposal of 3.3.6 is needed</td>
</tr>
<tr>
<td>Reduced pain, depression</td>
<td></td>
<td>The shoulder is often a target site, so the proposal of 3.3.6 is needed</td>
</tr>
<tr>
<td>Advanced &amp; personalized</td>
<td></td>
<td>Extra connection points are needed to reach multiple midline sites.</td>
</tr>
</tbody>
</table>

Table 12: The suitability of the headgear design for different configurations that can occur in practice.
5.3.5. CONCLUSIONS

In terms of functionality we can see that the design is suitable for a large number of applications, but that in its current state of development it has not yet reached the envisioned potential. With the right developments the functionality could expand significantly. Some of these developments were already formulated in the concept phase and additional improvement are suggested here. This results in the following list of recommendations:

- Focus on extension and holder development to widen the technological functionality.
  - New extensions can be developed that further allow the combination of different technologies;
  - New holders can be developed that also target sites that are relevant for the application, such as the earlobes, mastoids or sites out of the 10-10 system that are located close to the ear;
  - New holders can be developed that include other technology such as heart rate monitoring or audio support.
- The targetability of ‘closer’ 10-10 sites should be studied further. An alternative design of the arm and/or arc to better include those sites might be needed for some applications or headshapes.
- Expand the product proposal so as to also include target sites away from the scalp, such as the shoulder.
- Adapt the design of the cassette so that it can be expanded to 3 (or more) rotating discs when needed.
- Consider to develop longer arms that can reach to the midline.
- Consider a connection point in the middle of the arc to which extensions or arms can be connected.

Many of the basic setups target only 2 sites. The headgear can facilitate this in various ways. The shown configurations target the same sites, C4 and Fp2, which are used in motor rehabilitation.

For simple 1 channel or symmetry setups, there are also different ways to set it up. The user can always decide to hide away the arc (needed for its clamping force) from sight at the back of the head and use 1 or 2 arms to target the sites of interest. Of course, you can also use the arc to directly target the desired sites.

More elaborate setups require the placement of multiple arms and arcs in various orientations.

Figure 69: Different configurations of the headgear using multiple arms, arcs and different positions.
5.4. Product fit evaluation

5.4.1. INTRODUCTION
A test is set up to evaluate the accuracy of the product (prototype) when targeting 10-20 sites and to identify any complications that arise while placing, wearing or adjusting the product. The protocol of this test is included in Appendix XIX. It will be briefly explained below.

Ten participants are included in the test. They were approached on campus based on their availability at the time of testing. Anthropometric data of their head was recorded (see 5.4.2). A spandex hair net was thereafter placed over their heads, on which the 10-20 sites were marked. This was done so because it is very time efficient and the resulting deviation from the exact sites is believed to have little influence on the insights that this test can deliver.

The prototype is placed on their head. First it is assessed through visual inspection and measurement if the main unit can be placed correctly at the ear (5.4.3). The arms are then inserted and adjusted so to reach target sites F3, C3 and P3 subsequently. The accuracy and the arm position (extension, orientation) are recorded. The prototype is then removed and and put back on by the user. The deviations from the original sites are recorded. Insights from this are presented in section 5.4.4. Lastly, the accuracy of the strap and the fit of the arc in front, centre and back position are studied (5.4.5). This leads to a list of recommendations for further research and development (5.4.7). All test data are included in Appendix XX.

5.4.2. ANTHROPOMETRIC DATA OF THE SAMPLE
From all participants, the head circumference, sagittal arc length and bitragion arc length are recorded. This was done according to ISO standards rather than 10 20 standards in order to be able to compare the sample group with the selected design range. Since the prototype is very flexible, it is not suitable to assess its suitability for different head breadths.

Figure 70 displays the distributions of the metrics as recorded in the ISO7250 Standard ‘world’ range (ISO, 2015). The sample group data are plotted on the x-axis and the coverage is highlighted.

It can be seen that for head circumference and (especially) sagittal arc length, the extremities are not covered by the sample. These should be included in further studies. For bitragion arc length there is a better coverage of the spectrum, though most subjects fall within a much smaller range.

The bottom illustration shows the ratio between the sagittal arc and bitragion arc. It shows that the smallest values come from one test subject. This person (Subject 1) actually also had the smallest head circumference. The maximum values all come from different test subjects.

Further data was obtained from the ear, complementing the earlier test from during the detail design. This data suggests the average tragus-subaurale distance is 25.7mm; two millimetre more than in the earlier study.

Figure 70: Anthropometric data of the test subjects (units in mm). The top three figures display the ISO7250 World distribution of the recorded metrics (ISO, 2015). The dots on the x-axis display the recorded measurements of the subjects. The extremities are highlighted with red dots. The dashed lines represent the design range that is established in the Analysis phase and that is based on separate data from different ethnicities. The bottom figure displays the bivariate distribution from the sagittal (y) and bitragion (x) arc length of the test subjects.
5.4.3. FIT OF THE MAIN UNIT AT THE EAR

The placement of the main unit at the ear is assessed through measurements and visual inspection. The shape was found to successfully follow the curvature of the scalp for all participants. At the back of the ear there was for two subjects very little space between the ear and the product (Figure 71). No discomfort was reported during the test, but this could well be an issue after longer application. Further studies should clarify if the current shape is indeed satisfactory or if it is in fact a bit too tight for some users.

The measurement furthermore shows that the main unit is placed higher than anticipated in relation to the ear (6 mm on average). A first reason of this is in the quality of the prototype. The foam padding was thicker than it should be (Figure 72) resulting in higher placement. Secondly, the product thickness is based on the largest ear protrusion (Detailed Design section 4.3) and it could be tapered to better fall behind the ear at the root.

When users placed the product themselves (no specific further instructions were given), it ended up on different relative locations (see Figure 73). It should be studied if more cues can be provided to place the product correctly.

5.4.4. TECHNICAL FIT OF THE ARMS

All measurements regarding target sites were done on the left side of the head. For all ten participants, the arms could accurately reach sites F3 and P3. For two participants the arm was fully extended (Figure 74). This was the case for subjects 7 and 8, who have a large sagittal arc length. Since even larger arc lengths are included in the design range, it is necessary to have longer arms to ensure reachability and maintain stability for all users.

For four of the participants it was noted that the arm end was under a strong angle when targeted to F3 (see Figure 75). This is inherent to the shape of the frontal region of the scalp, but was stronger than expected. No actual angles were recorded during the test. This should be studied and it needs to be re-evaluated if the ball-join (section 4.6) is a successful solution for this. Otherwise the design of the arm might need to be changed.

In five cases it was not possible to target site C3. The arm was unable to be inserted far enough into the cassette. A first reason is that the main unit at the ear was placed a few millimeters higher than anticipated (see previous section). Secondly, the arm was placed in the bottom disc of the cassette. When inserted, there comes a point where the ribs under the arm bump into the main embodiment, loosing 7.5mm of adaptability. This was overlooked during the embodiment design. An update should be made to alleviate this limitation. This problem does not occur when the arm is placed in the second cassette disc.

Since the prototype arm does not have an actual spring system and the clamping force of the arc is much lower than what it should be, the prototype gets pushed away from the scalp when the arm targets C3 (see Figure 75, left). Some deviations in the test can be a result of such behaviour.

In the test the product was removed and reapplied by the user (blindly). The deviation of the location of the arm-end was recorded afterwards. The program of requirements lists a target repeatability under 12.5 millimeters. From the test it is believed that the design can meet this requirement. The deviation of the arm in the bottom disc of the cassette was on average just below 5 mm, never exceeding 12.5mm. For the arm in the second disc the deviations are larger; 16...
mm on average. Most of that can be attributed to undesirable rotation of this disc. Alternative cassette designs should be considered if further testing with higher quality prototypes keeps showing such behaviour.

5.4.5. (TECHNICAL) FIT OF THE ARC

The design of the arc is believed to be somewhat oversized. In most cases the arc would be fully inserted into the slots, yet still it’d have quite a strong offset from the scalp. A result of this is that the elastic strap is not always able to make full contact with the scalp (see Figure 76). For the larger heads the arc was often only halfway extended. The dimensions should hence be adapted. One of the reasons for this design flaw is that the width of the main unit was overlooked during the dimensioning of the arc.

In all cases the target sites did fall nicely under the slots in the arc (see Figure 77, Figure 78). The distance was recorded between marked sites on the elastic strap and the sites on the head cap. Though overall this was quite accurate, the inaccuracy increases for sites further from the midline. Where Fz, Fp1, Cz, Oz and O1 all show accuracy within just a few mm (not higher than 7); the average deviation of F7, C3 and P3 is higher than that. It averages at about 9 mm, with a maximum-recorded deviation of 17. It is already mentioned that C3 is in practice closer to the main unit than initially anticipated. It shows that the distribution of the target sites on the elastic strap should be optimized based on data from practice.

The current accuracy still falls very well within the set requirements (that sets an average within 25 mm and per site not more than 50). In this test however, the product is not placed blindly but it is adjusted to match the pinpointed target sites best. This means that the current deviations are ideal situations and a blind-placement study should be performed in the future.

5.4.6. ADDITIONAL FINDINGS

Next to the data that was purposefully harvested in the test, the test has also provided additional insights regarding other complications that can occur.

• The ‘claw’ design of the arm end makes that it easily gets entangled in long hair. It should be considered to close the circle so to minimize this.
• Curly hair gets in between rotating parts, especially when adjustments to the configuration are done with the product placed on the scalp. The effects of this and possible improvements need to be studied further.
• One user commented that he could feel the ‘bump’ in the shape of the holder pushing to the back of his ear. Though he did not find this disturbing, this bump could be evened out to prevent discomfort.
• For one user the metal leg of the arm pushed against the pinna of the ear when targeting C3 (Figure 79). Again, the user found this not disturbing. It needs to be ensured that the edges of the metal strip are smooth enough so that it cannot cut, hurt or irritate the ear. Other possible adjustments are seen for now as a point further on the timeline, after an initial batch size.
• The design seems to be suitable to be worn concurrently with glasses (Figure 80). Depending on the frame of the glasses and the ear of the subject, this can have minor implications on the product placement. The holder could be adjusted to anticipate on such situations by making some notches in the edge where the glasses could run through.
5.4.7. CONCLUSIONS

The purpose of this evaluation was to assess the success of the product in correctly targeting the relevant sites on the scalp. The test data suggest that with the right improvements, the product is likely to perform equal to or potentially better than current alternatives. Of course in this test a number of simplifications were made compared to real life events. Most importantly in the test the 10-20 sites were marked on the subject's scalp, which will not be the case during regular use.

It is envisioned that for regular usage there will be an indication on the body of the product that suggests the average angle to reaching specific sites. This is a major point for future research and development, since it can have a strong impact on both the user experience as well as the technical fit.

The test suggests furthermore that the product can indeed be suitable for a wide variety of head shapes, but some finetuning of the dimensions is needed. It can be wise to assess the value of a sizing system for at least some of the components (offering two sizes of arms and arcs). This is fairly easy since it only requires the metal parts to be elongated.

The following is a list of further research fields, development steps or design improvements that is composed based on the findings of this fit test.

• A study should be setup to define the average angular orientations of the elements when reaching specific sites. This should then be communicated to the user.
• In the prototype the cushion affected the product placement. It needs to be evaluated how the actual intended cushion would affect this. The protrusion and thickness might have to be reduced at the region just above the ear.
• The design should be a bit thinner (tapered) in order to fit better behind the ear.
• The contour of the holder can be ‘loosened up’ more to prevent discomfort for some ear shapes.
• It should be studied in what ways the user can be assisted in correctly aligning the product at the ear. The shape of the front ‘bubble’ of the holder (that falls on the temple) can for example be adapted.
• Following current insights, the arm needs to be at least 10 mm longer. This might be subject to change when the product is placed more accurately on the ear and when larger heads are included in the study.
• Especially for site F3 there can occur quite a strong angular offset of the arm end. It should be studied if this can be compensated for with the balljoint module, or if more flexibility in the arm itself is desirable.
• The current design cannot always successfully target site C3 and adjustments need to be made to either the cassette (raising the bottom disc opening 1-2 mm off of the front cover), the arm (removing the ribs from the first ca. 10 mm under the arm) or the front cover (a stronger slope towards the midline so as to accommodate the ribs of the arm).
• It should be evaluated using a high quality prototype of the cassette how susceptible it is to movement during application and during the take-off.
• The repeatability in ideal circumstances (no rotational movement of the arms possible) should be researched, and also the repeatability of setups that use other sites and configurations.
• The dimensions of the arc need to be adjusted (reduced) to better fit different head sizes.
• The length of the guide elements in the arc can be increased to better follow head shapes (this will depend on the adjustments that will be made to the arc).
• The distribution of connection points on the elastic strap needs to be optimized based on data from practice.
• The arm-end needs to be redesigned in order to be more suitable for users with long or curly hair.
• Tolerances and clearances should be optimized to prevent hair from getting stuck between parts.
• The shape of the holder can be adjusted in two ways: First, the angled transition should be smoothened out so it doesn’t poke into back of the ear. Second, some notches could be included in the sides to anticipate the concurrent placement of glasses.
5.5. User experience evaluation

5.5.1. INTRODUCTION
All ten participants of the product fit test were asked to fill out the User Experience Questionnaire (UEQ) developed by Laugwitz, Schrepp & Held (2008). The UEQ is build up of 26 sets of bipolar qualities. Participants are asked to mark which one of those represents their experience best (see Figure 81). The qualities are clustered in six main factors that comprise the product experience (Schrepp, 2015):

- **Attractiveness** Do users like or dislike the product?
- **Perspicuity** Is it easy to get familiar with the product?
- **Efficiency** Can users solve their tasks without unnecessary effort?
- **Dependability** Does the user feel in control of the interaction?
- **Stimulation** Is it exciting and motivating to use the product?
- **Novelty** Does the product catch the interest of users?

This test builds on the theoretical conception in which user experience is build up of ergonomical (practical) value, hedonic value and perceived attractiveness. There are a few limitations to the test and method that need to be mentioned.

- The users had limited interaction with the prototype. There was not a specific task that they had to perform besides putting the product on their heads. All of the test participants were told they could further inspect the prototype during evaluation, but only some subjects did so.
- The test did not represent real life interaction, as there were no electronics involved.
- None of the participants had any experience with other types of neurotech headgear. It was difficult for them to fill out some of the elements of the questionnaire for the lack of comparison.
- The UEQ is a ready-made tool that can be used to assess physical and digital products. This means that some interesting physical attributes are not explicitly included (comfort, rigidity) since they are not relevant for digital products.

As a result of these limitations, some of the data should be interpreted more carefully, especially regarding the ergonomical values. This is discussed in section 5.5.2. It could be an interesting next step to take the same questionnaire for other neurotech headgear in order to compare the results. In this study, the data can be compared to the benchmark that is provided so as to identify the main areas of improvement (5.5.3). These areas will then be discussed on the basis of the questionnaire and further discussions with test participants. The section is concluded with a list of recommendations (5.5.4).
5.5.2. DATA PROCESSING

GENERAL RESULTS
The UEQ data tool is used to analyze the data (UEQ, 2016). It processes the answers of the users so as to list the positive, neutral and negative associations. The mean scores of the six different usability factors are illustrated in Figure 82. It is assumed that values between -0.8 and +0.8 represent a neutral evaluation, higher values are positive and lower values are negative. It shows that Perspicuity and Dependability score worst: respectively 0.65 and 0.95. The other scales score higher, with novelty as best (1.5). The error bars show the 95% confidence interval. Appendix XXI includes all data of the evaluation.

STATISTICAL SIGNIFICANCE OF THE DATA
With such a small sample size (10 participants) it is hard to get trustworthy data. Still, for 5 of the user experience factors a confidence interval under 0.5 can be noted; i.e. it can be said with 95% certainty that the score from the whole population lies within 0.5 points of the recorded sample. For the factor Perspicuity the confidence interval is larger (0.75), which indicates that people’s judgements are rather inconsistent here compared to the other factors.

The analysis furthermore shows that the factor Dependability is statistically inconsistent, meaning there is no correlation between the individual items that compose this factor. It means that the participants interpret some of the aspects that form this factor in an unexpected way. This can be a result of the simplifications in the test setup. The test and/or the user group would need to be adapted to get a more representative measure for Dependability. The other five factors do show correlation (see Appendix XXI).

Following these reflections, the factors Perspicuity and Dependability (and their individual sub components) should be interpreted with extra care. They are still included in further discussions.

5.5.3. IDENTIFYING AREAS FOR IMPROVEMENT
At this point it is not possible to compare the data with scores of other neurotech headgear. However the group behind the UEQ provides a benchmark data set that is composed of other studies (Schrepp et al, 2013). This benchmark evaluation is also depicted in Figure 82 (right).

The scales Efficiency, Stimulation and Novelty all score high, with the latter even reaching within the range of the 10% best results. Attractiveness scores almost average, but actually a little below. So although people assess this factor positively, extra efforts would need to be made to make it outstanding.

Dependability and Perspicuity both score below average, the latter even almost qualifying as ‘bad’. Despite their higher statistical unreliability, it is still a relevant point of discussion. The following sections will be used to discuss Attractiveness, Perspicuity and Dependability in order to identify points of improvement.

Figure 82: (Left) General mean scores and confidence intervals of the six user experience factors. (Right) The mean scores plotted on the benchmark dataset from the UEQ data evaluation tool.
**ATTRACTIVENESS**

The Attractiveness score is built up of six individual items. The mean scores are depicted in Figure 83. It seems that improvements should be made that increase its friendly, pleasing and attractive attributes. The attributes are not explicitly connected to product features. However, with this evaluation in mind, some of the remarks that users made during the test and evaluation can be discussed.

The clearest remark comes from test subject 5, stating “The arc is actually the least attractive part of the product. It also seems fragile.. also due to the openings in it. Is this necessary? I think I would like it better if it’s closed. It would be okay if it looks more chic…”.

Subjects 1 and 4 also commented on this, stating things such as “I wouldn’t wear it in public just like this.” and “It looks like those outboard braces..”. It is true that the arc has a strong visual presence in the product composition. It is recommended to generate an alternative design for the arc that can increase the perceived friendliness and attractiveness of the product.

Mixed comments were made on the materialization, with test subjects stating they really like or don’t really like the combination of white plastic and metal elements. A more detailed material and colour study can help to increase the attractiveness.

Another possible area for improvement is to create more uniformity in the product. Elements can be added that visually combine the different components more. In the concept design phase of the arc it was already mentioned that it would be preferred to have more uniformity in the design of the arm and arc elements (3.3.5). This should be reinvestigated.

**DEPENDABILITY**

The Dependability score is built up of four items, as shown in Figure X. As discussed, there is no statistical consistency between them. The total score can not be interpreted as the actual Dependability. Still, test subjects have given assessments on qualities of the product and despite of the inconsistency it is interesting to see which of those qualities they have assessed worst. In this discussion should then be borne in mind that the interpretation of these qualities can be unexpected.

The data shows (Appendix XXI) that the variance and standard deviation of the items ‘not secure – secure’ and ‘unpredictable – predictable’ are largest, suggesting that those could be the ones that are misinterpreted (though this does not have to be the case). These are also the lowest scoring attributes (see Figure 84).

The low assessment on ‘secure-not secure’ can relate to the perceived sturdiness of the product. Three of the test subjects commented on this, stating that they would wish the design to be more robust. A reason for the inconsistency could be the evaluation of either the prototype or the anticipated end product. The prototype that was used during these tests lacked the envisioned material quality (stiffness, tolerances) of the final product.
Evaluation - User experience evaluation

There is a lot of functionality in there, and I think that needs to be explained better to the user.” - Subject 8

“So... if I do this [push the arc upward] it will move to the centre?” - Subject 6 (Actually, the arc was in the side slot where it cannot rotate.)

“Does it look like something that you would need to fine tune every time you use it?” - Subject 1

“Is the user or the producer the one who is in charge of the setup? [...] It seems difficult to setup at home.”

- Subject 10

80  Evaluation - User experience evaluation
5.5.4. CONCLUSIONS / RECOMMENDATIONS

This test has provided insights on the User Experience of the headgear design. The goal of the test was to probe the users reactions after introduction to the product and through this identify points for improvement. Despite the limitations of the method (as discussed in 5.5.1), different valuable insights have come forward. Though the evaluation cannot be simplified to one single metric of user experience quality, the overall impression is that the user experience is positive. The hedonic qualities of the product score very well (Novelty, Stimulation), the attractiveness is satisfactory (especially considering the fact that elaborate material, shape and colour studies have not been executed); and the pragmatic qualities are not too bad (Perspicuity, Dependability, Efficiency), yet they should be tested in a more realistic setting in order to assess their true value.

The following list of conclusions and recommendations is composed based on this study:

- The product is perceived as very innovative and creative. It is able to catch the interest of users.
- Users find it exciting and motivating to use the product.
- The product is perceived as efficient. Tasks can be achieved without unnecessary effort.
- The overall impression of the product is positive, but improvements can be made.
  - It is recommended to generate an alternative design for the arc that can increase the perceived friendliness and attractiveness of the product.
  - A more elaborate material and colour study should be executed.
  - More uniformity can be introduced between the products components.
- Test subjects are inconclusive whether or not the product is clear and easy to get familiar with.
  - More use cues should be introduced to the project to clarify the functionality and possibilities of the different components
  - It should be evaluated what elements that currently are experienced as complicated can potentially be left out or simplified.
  - The level of (perceived) adaptability can be subject of changes, resulting in a more static main product composition.
- The context and protocol of the test were found unsuitable for assessing the Dependability or 'feeling of control over the interaction' of the user.
- A high fidelity prototype should be used to test the (perceived) product stability. Changes to the product can be made to increase the stiffness and stability.
- A study with a more representative user group and test protocol would need to be set up in order to better assess the pragmatic qualities of the design.
- Another study should be set up to evaluate more neurotech specific aspects of the product experience, including comfort.
5.6. Stakeholder evaluation

5.6.1. MAIN CONCERNS OF EXPERTS
The dialogue with industry experts needs to be started to evaluate the product proposition better. The input of experts is necessary for the optimization or adaptation of the headgear. An attempt has been made to collect the first reactions of such people on the design. This was done by approaching several experts by e-mail and by setting up a forum discussion. Though only little input was collected, some recommendations can be formulated based on input from one of the organizers of HacktheBrain:

• There are concerns on the sturdiness of the design, especially regarding the armd-end where the electrode connects to. Improvements might be needed to ensure stable contact and prevent failure.
• The mechanism for maintaining pressure is critical and it should be ensured that all sites are equally well covered.
• The risk of the electrode wires getting pinched (e.g. when moving the arms) should be studied.

All three are practical points relating to the signal acquisition and the compatibility of the design with the actual electronics that will be used. The different electronics were not all available in this project. Any future developments should be done hand in hand with the actual electronics components.

Furthermore this expert commented that the overall concept is ‘very nice’ and that the flexibility in position can be great. These are valuable comments for the business case, but more expert evaluations should be set up to review the current assumptions on the key scenarios and market sizes.

5.6.2. CONSIDERATION OF THE END USER
The headgear has at this point not been tested with actual end users that were identified in the Analysis. This was not possible within the available timeframe. However, some conclusions can be drawn through empathic reasoning. The program of requirements mentions that the need for small motoric movements during the product operation should be avoided (taking into account impaired users). Furthermore it emphasizes the point that elderly and children should be able to understand and use the headgear.

It seems that these requirements were lost from sight during the later phases of this project and might not have been met. Actual user studies should clarify this. It could be studied which adjustments could make it more feasible for such target groups to operate the product. A more holistic question that can in retrospect be asked is how realistic it is that such, delicate, user groups will be served with a general rather than a specific product solution. This again is a dialogue that should be started with the industry. If the focus remains unchanged, it is very important that actual user groups will be more actively involved in the future development of the product proposal.
5.7. Conclusions

Though this evaluation shows that the product proposition is not yet perfect, the concept remains intact. The evaluation is not complete in the sense that all doubts have been addressed, but the main functionality is considered to be effectively put to test. The important features of the product have proven to be feasible and the practical potential of the proposal is affirmed. The efforts can be interpreted as a proof of concept: an indication that this proposal can be successful.

- Most of the parts have been found suitable for manufacturing and assembly, or at least within the prototyping context.
- The product is found suitable for a wide number of applications,
  - In its current stage it can cover about 75% of setups from the key scenarios,
  - There are clear recommendations to increase the functionality.
- The product can be adapted for a wide variety of head shapes.
  - The accuracy and repeatability can potentially outperform current commercially available alternatives.
- The overall user experience of the product can be interpreted as positive.
  - The hedonic qualities are high; the product is perceived as highly innovative and creative. It is able to catch the interest of users and users find it exciting and motivating to use the product.
  - The pragmatic qualities of the product score more average; the product is perceived as efficient and clear but users may find it hard to familiarize with it
  - The overall impression of the product is good; users like the product and find it moderately attractive.

The different sections have brought forward suggestions for further research and development. These suggestions have been clustered and are included on the following pages.

Research

High quality prototype

1. It should be evaluated using a high quality prototype of the cassette how susceptible it is to movement during application and take-off.
2. The repeatability of other sites should be researched (currently only F3 and P3).
3. The accuracy of the product should be studied in a blind placement test (following actions from point 16 and 28 further in this list).
4. It should be studied with a high quality prototype if and in which ways a users hair might get entangled or stuck in between (rotating) parts, and if changes to the design can be made to prevent this.
5. A high fidelity prototype should clarify if the (perceived) stability/sturdiness of the product is sufficient.
6. The product performance in different situations such as during movement of the subject should be tested (signal stability).

Test protocol

7. A study with a more representative user group and test protocol should be set up in order to better assess the pragmatic qualities of the design, especially the Dependability.
8. Another study should be set up to evaluate more domain specific aspects of the product experience, such as comfort and (perceived) set up time.

Full product

Holistic level

9. The level of (perceived) adaptability can be subject of changes, resulting in a more static main product composition.
10. It should be evaluated what elements that currently are experienced as complicated can potentially be left out or simplified.
11. Delicate user groups should be involved more prominently in all future developments and evaluations.
12. Industry experts should be involved prominently in all future developments and evaluations.
13. The compatibility of electronics should be studied and all future developments should be done with the relevant electronics as ones disposal.

Product level
14. More use cues should be introduced to the project to clarify the functionality and possibilities of the different components.
15. More uniformity can be introduced between the products components.
16. A study should be setup to define the average angular orientations of the arms/arc when reaching specific sites. This should then be communicated to the user.
17. The assembly process needs to be studied and relevant optimizations to the product embodiment should be made.
18. Product and material behaviour under different forces/tension and misuse scenarios should be studied further (which connections will let go and which materials will deform).
19. A more elaborate material and colour study should be executed to increase the attractiveness.
20. Research possibilities to deal better with hair, including the integration of a ‘move-hair-aside’ function that can help in fNIRS research.

Portfolio level
21. Focus on the development of relevant arm-extensions (in collaboration with the industry), including a ring-setup and a ball-joint module.
22. Focus on the development of different holder designs that offer different functionality & fit.
23. Consider to offer ‘shorter arms’ for reaching closer 10-10 sites, and ‘longer arms’ for reaching sites on the midline.
24. Expand the product proposal so as to also include target sites away from the scalp, (such as the shoulder) firstly through the development of an arm band.

Individual components
Main embodiment
25. Adding small ridges on the edges of the covers will benefit the assembly process.
26. It should be assessed if a cable guiding functionality should be added on the main unit to guide away the cable behind the ear and prevent them from getting pinched in between other parts or getting in the way of users.
27. The legs of the arc need more guidance on the inside of the main unit when inserted in the side slots, requiring some extra features in the back cover.
28. Visual & mechanical cues for positioning of arms need to be implemented, based on insights from point 16.
29. The presence and functionality of the side slots can be better explained to the users, for example by ‘highlighting’ them with the colour of the cassette.

Cassette
30. Adapt the design of the cassette so that it can be expanded to 3 rotating discs (1 for frontal, 1 for central and 1 for parietal).
31. The discs of the cassette currently have 2 snap fingers to connect to each other and the main embodiment. It would be better to increase this number (at least 3) for a more balanced connection and force distribution.
32. The snap fingers that connect the top cap of the cassette to the middle disc seem not very successful. Other options such as a form fit would be preferred.
33. The bottom opening in the cassette should be raised 1-2 mm off of the front cover.
34. It should directly be clear where the openings in the cassette are to insert the arms and arcs. This can be done by changing its shape or providing other use cues.

Holder
35. The design could be a bit thinner over the first 5 mm above the ear in order to fit better behind the ear (tapered). The cushion protrusion and thickness might have to be reduced.
36. The curvature of the rear part of the holder (that wraps around the ear) can be ‘loosened up’ to prevent discomfort for some ear shapes.

37. It should be researched in what ways the user can be assisted in correctly aligning the product at the ear. The shape of the front ‘bubble’ of the holder (that is placed in front of the ear on the temple) can play a role in this.

38. The angled transition between the rear part and top part should be smoothened out so it doesn’t poke into back of the ear.

39. Notches could be included in the sides to anticipate the concurrent placement of glasses.

40. Cable guiding functionality could be added to make it easy to run the cables downward behind the ear (and keep them from getting pinched or getting in the way of users).

Arms

41. It should be studied whether or not the design of the arm needs to be adjusted to accommodate probes with larger thickness.

42. A more simplified version of the cable guide under the arm would suffice. Two opposing notches every interval could in practice be more convenient. This should be studied.

43. If the ribs stay in place, they could be removed from the first (ca.) 10 mm under the arm so it can better slide in the cassette and doesn’t bump into the front cover.

44. Following current insights, the arm needs to be at least 10 mm longer to include larger head shapes.

45. It should be studied if the angular offset of the arm-end on the scalp (especially at F3/4) can be accounted for with the balljoint module, or that more flexibility in the arm itself is desirable.

46. The arm end needs to be redesigned in order to be more suitable for users with long or curly hair. It is suggested to ‘close the claw’.

Arc

47. Include a connection point in the middle of the arc so that Fz and Pz could be targeted from Cz with an extension module or an arm.

48. It is recommended to generate an alternative design for the arc that can increase the perceived friendliness and attractiveness of the product, starting with the consideration to close the slots.

49. Changes to the arc design can be made to increase the stiffness and stability.

50. The arc currently has a straight shape (in side view). It should be studied if a pringle shape would be more successful in targeting the relevant sites. It could improve the accuracy in angular orientations (such as when targeting F3, Fz and F4 concurrently).

51. The cable guides do fulfil their function but a more simplified version could suffice. In practice it seems to be more convenient to just have two opposing points every interval.

52. The dimensions of the arc need to be adjusted to better fit different head sizes. The width of the main unit needs to be taken into account in this new dimensioning.

53. The two strap guides at the end of the leg can be left out, only the two middle guides are needed.

54. With silicon or PU rubber straps, the friction between the strap and the guide element can be an issue. This should be studied and a redesign might have to be made (different strap material selection or adapted guide element design).

55. The distribution of connection points on the elastic strap needs to be optimized based on data from practice.
6. Conclusion
6.1. Results

PRODUCT PROPOSITION
The result of this project is the design of a new modular headgear design for neurotechnological applications. This design goes by the name Nerva headgear.

The concept is an adaptable frame that can be used to place various technical tools on different locations on the scalp. As such it can facilitate interactions with the human brain, such as the analysis, monitoring or modification of activity in different regions of interest.

The frame consists of multiple elements that can be configured in different ways. The electronics can be connected to the structure. In this way the product can be adapted for different applications, users and user contexts. It can be build up to target only relevant areas and using only necessary technological tools, minimizing discomfort from larger and obtrusive alternatives.

Possible applications domains include, but are not limited to, rehabilitation scenarios, therapeutic use or personal quantification or enhancement. The dimensions of the frame are based on anthropometric data. By simply extending or pivoting some of the key components of the headgear, the product can be adapted for users with many different head shapes and sizes. Furthermore, it is possible to regulate the pressure that these elements exert on the scalp. This allows to optimize the comfort and the signal stability during usage. The design is in this way believed to be able to deliver accuracy, repeatability and stability that can outperform other commercial systems.

The Nerva headgear can be seen as a platform solution, where different versions of its elements can coexist in an expanding portfolio of possibilities. As the field of neurotechnology moves forward, so can this product. It is a future proof concept that can play a role for the many of us that will sooner or later be embedded by the advancements of this field.

ROADMAP
The figure below depicts the roadmap that is envisioned to bring the product succesfully to market. Most important first is to start the dialogue with the industry and stakeholders. At the horizon of the timeline we see the development of tailored electronics, specific for this product and after that the launch of a neurotech app store, where people can share and find new neurotech protocols. The headgear so becomes an important hub in the implementation of neurotech in daily life.

![Figure 86: Roadmap for future activities](image)
6.2. Reflections

THE END RESULTS OF THE ASSIGNMENT

The goal of this project, as formulated in the original graduation assignment, was to “design an novel, modular, type of headgear that addresses the current compromises in functionality, anthropometry and experience of neurotech devices. […] the expected outcome is the design of a new modular headgear platform. One specific application hereof will be worked out into a detailed product proposal with a prototype that is able to show its most important features. The outlines of the complete platform will be described.”

The design proposition that is made in this project is believed to indeed score high on functionality, fit and experience. Surely there are improvements to be made (regarding all three aspects). Some of these improvements would be necessary on short term, whilst others can be seen as points further on the timeline. It can eventually be said that the project outcomes are very well in line with the set goals and expectations. The end result is complete in that it addresses the full complexity of the original problem. The solution appears to be feasible and viable; with desirability being a subject for future evaluations with experts and users.

GENERALIZING THE RESULTS

At the start of the project the assumption was made that modularity could be an interesting strategy to find a balance between (1) broad functionality, (2) product fit and (3) user experience of neurotech headgear. It can now be stated that the attempt to use modularity in order to find that better balance has in this case been successful, and that there is still room for some improvement. This is just a one project example. Though, if one would generalize the findings from this one project, what it could then mean for the domains of IDE or neurotech/headgear is that:

It is found possible to introduce a high modularity and adaptability in product designs, whilst still providing an moderately good experience. As such one can develop product propositions that perform better on relevant properties (in this case functionality and (technical) fit) than competition. However, one cannot expect outstanding performance on all such aspects. The designer will always have to incorporate a number of simplifications in order to benefit the attractive and pragmatic qualities of the product.

It could be recommended for any designer that deals with different usage contexts of a product, to consider to implement (higher) degrees of modularity and adaptability. This could be done by asking the question “(On what aspects) is the performance important for this product?” and then “(How) can higher degrees of modularity and/or adaptability contribute to this performance?” One might find interesting ideas.

THE PROJECT IN THE CONTEXT OF GRADUATION

This project is executed as graduation assignment and the primary objective of it is actually to learn and display academic qualities, proving worthiness of the degree Master of Science. As IPD student one specializes in balancing different interests (from users, business, society) into coherent designs. This project seems to have had all the right components to make this challenge exciting.

What made this project unique was that it required the generation of a basic understanding of neurotechnology and its implications on product design. A point that could be raised is that the complexity of the project was such that in a ‘real life’ situation it is unlikely that this would be the task of only one designer/researcher. The assignment could have been defined more delimited at the start, but on the other hand that would have ruled out any truly integrated solutions and taken away some of the fun.

Processing the challenges and complexity of neurotechnology in the project has proven to be an excellent
opportunity to demonstrate and learn different skills and theories. Many methods were adapted in order to best serve the design process (or designer). For example, TRIZ methodology was explored to deal with the inherent contradictions and it was implemented in the generation of a morphological chart. Other frameworks such as the VPD and Fishtrap model were also adapted to serve the project best.

Many other aspects of IPD were also incorporated in the project and it seems to be a good display of the curriculum. All in all this has been a valuable personal and academic learning trajectory, resulting in a realistic proposal and, hopefully, interesting concepts and insights for anyone working on similar challenges.

**THE PROCESS OF THE PROJECT**

The amount of time that is attributed to the project is 23 weeks of full time work (33 ECTS). The project has suffered from delays in several stages, resulting in a total project duration of about 31 weeks. Especially the Analysis phase has taken up too much time. As a matter of fact, most of the delay can be attributed to this part.

There is a number of reasons why this has been the case, starting with the project complexity. The field of neurotechnology is a big one and it can be hard to navigate through. The abundance of information was at times difficult to process into concrete project leads. The level of detail of the different parts of the Analysis was difficult to balance and it was also not always clear what information was exactly needed. Additionally, it was difficult to report the information in a way that was in line with the expectations of the supervisory team. As a result, a lot of time was spent with further expanding, clarifying or reframing the content.

The project planning included little time for the Analysis phase; only the first 3-4 weeks were dedicated to this. The idea was to generate some first leads and quickly start designing, acquiring other knowledge along the way. It can be said that it was unrealistic to execute the Analysis in such a short time frame. Secondly it would have benefitted this phase to have an expert partner involved that was more familiar with the content. Thirdly, more initiative could have been shown by the student to follow a path closer to what was envisioned, convincing the supervisory team that it would indeed benefit the project to start the designing and leave the analysis be as it is.

In these phases thereafter it was attempted to take more control. It is believed that these later phases of the project are actually characterized by an effective and result oriented work ethos. Time management was especially crucial towards the end of the project in order to get the all the work done. The abstention of work obligations that at earlier at times withheld full dedication to the project was also very important.

When looking at the results it is found that a high amount of work has been done within the project. In all honesty it is believed that it had not been possible to deliver results of the same quality within the original time frame of 23 weeks. The conclusion of this reflection is that the process did have its ups and downs; that there are moments in the process where more control and effectiveness would have been useful but that the overall process and the development therein can be looked upon with contentment.
**Glossary**

**10-20 System**  
Standardized method to locate sites on the scalp for neurotechnological research (see Figure).

**BCI System**  
Brain Computer Interface, a communication device between the brain and another system.

**Bitragion Arc**  
A measurement over the scalp, running roughly from left to right ear.

**Cephalic Index (CI)**  
The ratio of the head breadth in relation to the head depth.

**Cerebral Cortex**  
The outer layer of the brain.

**EEG**  
Electro Encephalography, a test that detects electrical brain activity using electrodes on the scalp.

**Electrode**  
A piece of hardware through which electricity can flow in and out of a system, or an object or substance.

**fNIRS**  
functional Near Infrared Spectoscopy, a brain imaging method that uses light to detect changes in bloodflow.

**Impedance**  
The resistivity of something to the flow of electric current.

**Inion**  
Prominent bump (bone) at the back of the head.

**Mastoid**  
The bone or prominent bump behind the ear.

**Nasion**  
The recessed area between the eyes.

**Neurofeedback**  
A type of research in which brain activity is made directly visible to the subject.

**Neurorehabilitation**  
A process with the aim to recover from injury to the brain or nervous system.

**Sagittal Arc**  
A measurement over the skull from front to back.

**tES**  
transcranial Electrical Stimulation, a procedure that uses small electrical currents to modify neural activity.

**Tragion**  
The notch just above the tragus of the ear.

**Tragus**  
The small pointy bump (cartilage) in front of the opening of the ear.
References

- Artinis, (n.d.), Portable NIRS device - PortaLita [Digital Image], Retrieved December 2, 2016, from https://static1.squarespace.com/static/54ddd9b0e4b0e11f3685f546f56c6afafd210b895cad930f56c6af0442628f126256da02146475836721/PortaLita+two+sensors.jpg
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# Appendix I. Products list

A list is made of currently available EEG, fNIRS and tES systems <1000$. This was done through an elaborate online study. The list might not be fully comprehensive, but it list all major an most minor players.

A table is included below that lists all systems and some basic characteristics. The next pages give visual impressions of these systems. The images are accompanied by letters that correspond to the respective systems in the table.

## EEG

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Appendices
Appendices
Appendix II. 10-20 sites on digital head model

The digital head models are edited so that they include the 10-20 sites. This process is described here.

The models are imported into SolidWorks. First the Nasion and Inion have been identified on the model. If the inion was not directly apparent from the 3D headform, an overlay was used as illustrated in the Figure below, and its location was approximated.

The intersection curve between the sagittal plane (that divides the head in left and right) and the head model was creates (Insert>Intersection Curve). This curve was cut off at the identified Nasion and Inion, so that the resulting curve is the sagittal arc length of the 10-20 system. A spline was fit to the curve so as to make it 1 line rather than numerous segments (Insert > Spline > Fit Spline). On this arc length the relevant 10-20 points can be plotted proportionally through Insert > Reference Geometry > Point, and selecting ‘Multiple points’ option.

The bitragion arc is created by identifying the locations of the tragion and creating a plane through these two locations and the middle point on the sagittal arc (Cz). This is done through Insert>Reference Geometry>Plane>3-point Plane.

The arc length is then again created through inserting the intersection curve and trimming this at the two identified fiducial points. A Spline is fitted again on this curve so that the 10-20 sites can be added proportionally through reference geometry function.

The circumference is drawn through the points Fpz, Oz, T3 and T4 that are now identified. This is done through Insert>Spline>Spline On Surface. This spline is cutted in 4 quarters between the points. The 10-20 sites are distributed proportionally on these quarter segments.

The remaining points can be created in a similar fashion by drawing Splines on the surface through the relevant points, and adding the on there proportionally.
<table>
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<th><strong>Appendix III. Context evaluation</strong></th>
<th>Epilepsy monitoring</th>
<th>Sleep monitoring</th>
<th>Environmental Control</th>
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<th>Neurofeedback</th>
<th>Neuromarketing</th>
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<td>Shorter set-up can lead to significant gains</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>The product can appear in a commercial market</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Usage in daily life and social context occur</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Delicate user groups or contexts are involved</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>There is prolonged use by a user</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><strong>total score</strong></td>
<td>26</td>
<td>26</td>
<td>27</td>
<td>16</td>
<td>29</td>
<td>19</td>
<td>30</td>
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<td>26</td>
<td>34</td>
<td>25</td>
<td>28</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td><strong>total score in</strong></td>
<td>51</td>
<td>50</td>
<td>51</td>
<td>31</td>
<td>55</td>
<td>36</td>
<td>57</td>
<td>48</td>
<td>49</td>
<td>64</td>
<td>68</td>
<td>54</td>
<td>48</td>
<td></td>
</tr>
</tbody>
</table>
Appendix IV. Common setups

The following list was composed to get an overview of what the setups are that are reported in scientific literature. This list is not comprehensive (and the sources are not well documented), but that was also not the purpose at the point of compilation. It has merely served as tool to formulate some of the initial requirements that become apparent when looking at the global setups that occur.

<table>
<thead>
<tr>
<th>Neurorehab</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cz Fz Pz C3 C4</td>
<td>Caparetti Halo shaped</td>
</tr>
<tr>
<td>C4 F4/Fp1</td>
<td>Clancy et al</td>
</tr>
<tr>
<td>C4 F3/Fp1</td>
<td>Clancy et al</td>
</tr>
<tr>
<td>C3 Fp2</td>
<td>Boggio et al 2006</td>
</tr>
<tr>
<td>C5 Fp2</td>
<td>Sohn et al 2012</td>
</tr>
<tr>
<td>C4 Fp1</td>
<td>Vines et al. 2008</td>
</tr>
<tr>
<td>C6 Fp1</td>
<td>Hummel et al 2010</td>
</tr>
<tr>
<td>C3 AF8</td>
<td>Tanaka et al 2009</td>
</tr>
<tr>
<td>C5 AF8</td>
<td>Galea et al 2009</td>
</tr>
<tr>
<td>C4 AF7</td>
<td>Rosenkrantz et al 2000</td>
</tr>
<tr>
<td>C6 AF7</td>
<td>Wach et al 2012</td>
</tr>
<tr>
<td>C3 C4</td>
<td>Vines et al 2008</td>
</tr>
<tr>
<td>C5 C6</td>
<td>Kang &amp; Paik 2011</td>
</tr>
<tr>
<td>C3 arm</td>
<td>Tecchio et al 2010</td>
</tr>
<tr>
<td>C4 arm</td>
<td>Schamba et al 2011</td>
</tr>
<tr>
<td>O2/Oz rchik</td>
<td>Galea et al 2011</td>
</tr>
<tr>
<td>Iz rchik</td>
<td>Jayaram et al 2012</td>
</tr>
<tr>
<td>P3 Fp2</td>
<td>Orban de Kiey et al 2011</td>
</tr>
<tr>
<td>P4 Fp1</td>
<td></td>
</tr>
<tr>
<td>P5 Cz</td>
<td></td>
</tr>
<tr>
<td>C1 Fpz</td>
<td>Vollmann et al 2012</td>
</tr>
<tr>
<td>visual</td>
<td>Source</td>
</tr>
<tr>
<td>O2 Cz</td>
<td>Antal et al. 2001</td>
</tr>
<tr>
<td>O1 O2</td>
<td>Antal 2003</td>
</tr>
<tr>
<td>O3 Cz</td>
<td>Krull 2010</td>
</tr>
<tr>
<td>O2 Cz</td>
<td>Chialvo 2008</td>
</tr>
<tr>
<td>O2 Fpz</td>
<td>Terhune 2011</td>
</tr>
<tr>
<td>POCFpz</td>
<td>Mancini 2012</td>
</tr>
<tr>
<td>CCPFpz</td>
<td></td>
</tr>
<tr>
<td>aphasia</td>
<td>Source</td>
</tr>
<tr>
<td>F5 rarm</td>
<td>Monti 2008</td>
</tr>
<tr>
<td>F5 Fp2</td>
<td>Lee, Cheon et al 2013</td>
</tr>
<tr>
<td>CPS Fpz</td>
<td>Devidio Santos et al</td>
</tr>
<tr>
<td>F7 Ibcc</td>
<td>Vestito 2014</td>
</tr>
<tr>
<td>F8 rbbcc</td>
<td>Fiori et al 2013</td>
</tr>
<tr>
<td>FC5 Fp2</td>
<td></td>
</tr>
<tr>
<td>dysphagia</td>
<td>Source</td>
</tr>
<tr>
<td>C5 C6</td>
<td>Kumar Yang</td>
</tr>
<tr>
<td>P3 P4</td>
<td></td>
</tr>
<tr>
<td>T3 T4 shoulder</td>
<td></td>
</tr>
<tr>
<td>Neurofeedback</td>
<td>Source</td>
</tr>
<tr>
<td>C4 right ear</td>
<td>Clark, Coffman, Falcone, Darpa</td>
</tr>
<tr>
<td>Cz right ear</td>
<td>Fregni</td>
</tr>
<tr>
<td>C3 left ear</td>
<td>Fregni 2005</td>
</tr>
<tr>
<td>C3 C4</td>
<td>Antal 2001</td>
</tr>
<tr>
<td>F3 F4</td>
<td>Nitsche et al 2003, Vines et al, Reis et al</td>
</tr>
<tr>
<td>P4</td>
<td>Fregni, Kimchi</td>
</tr>
<tr>
<td>C3 Cz C4 P4 Oz (one at a time)</td>
<td>Verhagen, Hammer, Robel, Fregni, Andrews</td>
</tr>
<tr>
<td>O1 O2</td>
<td>Marshall</td>
</tr>
<tr>
<td>P3 P4</td>
<td>Bolognini</td>
</tr>
<tr>
<td>F3 F4</td>
<td>M6</td>
</tr>
<tr>
<td>F10 O1 O2 R oxLR cerebells</td>
<td>Zaelke</td>
</tr>
<tr>
<td>F3 F4</td>
<td></td>
</tr>
<tr>
<td>Fpz F7 F3 F7 P3 T3 T7 T8</td>
<td>Bolognini</td>
</tr>
<tr>
<td>Fp1 Fp2</td>
<td></td>
</tr>
<tr>
<td>Fp2 Fpz left right ear</td>
<td>Chin</td>
</tr>
<tr>
<td>F2 Cz</td>
<td></td>
</tr>
<tr>
<td>F3 F4</td>
<td></td>
</tr>
<tr>
<td>C3 C4</td>
<td></td>
</tr>
<tr>
<td>P3 P4</td>
<td></td>
</tr>
<tr>
<td>T3 T4</td>
<td></td>
</tr>
<tr>
<td>O1 O2</td>
<td></td>
</tr>
</tbody>
</table>
The following lists shows the rough data of the analysis on the properties of the different applications. This list has not been edited. It continues on the next page.

### Thematic Overview

<table>
<thead>
<tr>
<th>Theme</th>
<th>Neurofeedback Attention Problems</th>
<th>Neurorehab Motorstroke</th>
<th>Neuroenhancement Learning &amp; Memory</th>
<th>Opportunities of modularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wearable technologies that are used</td>
<td>EEG and fNIRS are used, not simultaneously. Insights from a 9-channel qEEG and/or a questionnaire.</td>
<td>(H)D/Cs is used. EEG can be used for evaluation or monitoring. Insights from MRI and more advanced brain imaging data. Central region (C3/C4) combined with frontal (Fp1,Fp2). Other sites include F3/F4. HDDCS applications can use a larger variety of the 10-10 system in a ring montage (1 in the middle, 4 surrounding). Sometimes MRI data is used to determine the exact location of e.g. the motor (M1), visual (V1) or sensory (S1) cortex. This can differ slightly from 10-10 or 10-5 system positions.</td>
<td>TDCS and TACS are used for enhancement. EEG for training. No specific driver other than user desire.</td>
<td>Adaptable setup that allows for 2 concurrent technologies (EEG+fNIRS, EEG+HDCS, TDCS+EEG/fNIRS) Manual setup or automatic setup based on input data from advances imaging.</td>
</tr>
<tr>
<td>Driver of protocol setup</td>
<td>The Central region is most important (C3/C2/C4). Temporal and parietal sites (P4, T4, TP10, CP2, Pz) and to a lesser extent centrofrontal sites (FCz, Fz) are included.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical target sites</td>
<td>2 to 4 High for clinical use but moderate for home use. Price is not as much an issue as for neuroenhancement. Different software (BrainBay, BioExplorer, Matlab, etc), Audiospatial devices, control panels (PC, mobile).</td>
<td>2 to 8 or sometimes more.</td>
<td>2 Channel minimum and expandable</td>
<td></td>
</tr>
<tr>
<td>Typical number of channels</td>
<td>High for clinical use but moderate for home use. Price is not as much an issue as for neuroenhancement. Different software (BrainBay, BioExplorer, Matlab, etc), Audiospatial devices, control panels (PC, mobile).</td>
<td>High. Extensive filtering and signal stabilization desired. Different software (BrainBay, BioExplorer, Matlab, etc), control panels (PC, mobile).</td>
<td>Low. Price can be a main driver provided that a certain success rate is still accomplished. Different software (BrainBay, BioExplorer, Matlab, etc), control panels (PC, mobile).</td>
<td>Proving a price and a quality driven version.</td>
</tr>
<tr>
<td>Quality demands and efforts</td>
<td>Extensive maintenance possible by professionals. Same setup is typically used for longer periods of time. It is possible (but not common) to use different setups in 1 training. Reports have been found on 3x10 minute sessions with different targets, or where at the end of any session a short protocol targeting C3 was followed to bring patients back in an active mood. Both a clinician or an enduser can be the purchaser. NF is mostly offered as service.</td>
<td>Currently longer periods of the same setup are used in order to help build scientific knowledge. When colouring between the lines this will stay the case, but it is not ruled out that patients can stimulate different areas (e.g. train motor activity first and speech later)</td>
<td>Very likely, 1-4 different ones, though not per se on a single day.</td>
<td></td>
</tr>
<tr>
<td>Ability to communicate with ...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance and cleaning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Different setups</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchaser</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current market pricepoint</td>
<td>1500$-5000$ for clinicians &lt;500$ for end consumers, depending on setup</td>
<td>1500$-5000$ for medical grade systems</td>
<td>The end user is also the purchaser</td>
<td>B2B and B2C</td>
</tr>
<tr>
<td>Target Pricepoint</td>
<td>&lt;1500$ for HQ commercial system</td>
<td></td>
<td></td>
<td>Different quality and price levels</td>
</tr>
<tr>
<td>Typical user</td>
<td>children (12+), m/f; adults m/f</td>
<td>Adults (50+), m/f</td>
<td>Version(s) for age 12-60. Possibly using a children and adult version.</td>
<td></td>
</tr>
<tr>
<td>Number of users per device</td>
<td>Only one when the end consumer buys it, but many if the product is provided as service</td>
<td>One user</td>
<td>A personal or general fit</td>
<td></td>
</tr>
</tbody>
</table>
A travel and home version of the device can be useful. In the context of a portable, travel-friendly version, it is important to consider the flexibility and usage within different environments. The device must be suitable for use in various settings, including mobility and portability.

Desirable usage in different cases can range from short, a few minutes, to long durations. Below 5 minutes is suitable for individuals in caregiving circles (e.g., parents) who aim to train their brain, whereas others may find it unaffordable or impractical.

Users must be cautious of burns and irritations due to misuse. Users should implement safety precautions from shocks, ensuring their safety.

Autodidactic learning by the user is desirable for individuals aged 12 years or older. Children from 12 years should be able to use the device, with some requiring parental supervision or guidance.

The importance of hygiene is emphasized, with no special attention needed for simplicity. IP5 or IP6 protection is beneficial for users.

Users will experience a feeling of independence, feeling at ease with the device. However, some may have lower expectations of applications, requiring a different approach.

Expected usage intensity can range from 6 hours a day, particularly in the early stages, to 1 hour per day, with somecases requiring daily usage.

A product and service-based proposition (integrated modules) can be beneficial, offering pay-per-use, module-based and different battery life options.

Risk of impact (and its protection) is desirable, with a few cases requiring risk assessments for optimal usage. Users should consider risk factors, such as head position, which can lead to falls. Protection can be implemented to ensure usage is safe and effective.

Movement and vibrations during use are important considerations. Fixation to the scalp for passive and active use can enhance the effectiveness of the device.

Different software options (BrainBay, etc.) can be available, offering a variety of setup options. Different quality and price levels can be expected, with prices ranging from $150 to $500 for commercial systems and end consumers, depending on setup.

The end user is also the purchaser, with both clinicians and end-users being able to access the device. Different set-ups can be followed to bring patients back in for training. Reports have been found on the effectiveness of the device, with patients able to stimulate different areas of the brain.

The same setup is typically used for longer training periods, with extensive maintenance possible by professionals. Training with BioExplorer, Matlab, etc., can provide insights from MRI and more advanced imaging techniques, enhancing the effectiveness of the device.

Reported areas of enhancement include attention, memory, neuroenhancement, attention problems, neurorehabilitation, Motor stroke, Neurofeedback, Strokes, Motorstroke, and Learning, among others. Insights from a 19-channel qEEG can provide valuable data from advanced imaging techniques.

Manual setup or automatic setup based on input can be used, with some users preferring a customized experience. Different sets of equipment and software can be utilized to enhance the effectiveness of the device.

The usage of the device should be monitored and adjusted as needed, with different positions in the 10-20 system allowing for varying needs. Fz and T regions are popular (F10, F3, T3, T5, etc.), while surrounding regions can also be considered.

The device can be used to improve memory, attention, and other cognitive functions, with users reporting improvements in their abilities.

Frequent feedback and training are essential for maximum benefit, with different setups and training regimes. The device can be personalized to meet the needs of each user, with usage monitored and adjusted accordingly.

The device can be used as an end-user, with B2B and B2C purchasing. Different quality and price levels can be expected, with prices ranging from $150 to $500 for commercial systems and end consumers, depending on setup.

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## Appendix VI. Benefits and deficits of sub-solutions

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Benefits</th>
<th>Deficits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic product architecture</td>
<td>It is very easy to adapt for head shapes or different forms of headgear</td>
<td>It is not as plug-and-play as many other systems.</td>
</tr>
<tr>
<td>Configuring the setup</td>
<td>We can choose the optimal shape and size for each user</td>
<td>The complexity of the setup configuration is high</td>
</tr>
<tr>
<td>Adapting for different headshapes</td>
<td>The product can be easily adapted for different head shapes and sizes</td>
<td>It can be difficult to achieve the right fit and positioning for all users</td>
</tr>
</tbody>
</table>

### Table

<table>
<thead>
<tr>
<th>Probe connection to base</th>
<th>Architecture</th>
<th>Benefits</th>
<th>Deficits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible materials or foam</td>
<td>Easy to use and durable</td>
<td>Difficult to maintain and replace</td>
<td></td>
</tr>
<tr>
<td>Fixed arm (e.g. sliding)</td>
<td>High degree of comfort and stability</td>
<td>Less stable, maybe time consuming</td>
<td></td>
</tr>
</tbody>
</table>

### Figure

- **High ease of setup**
  - Can be easily adapted for different users
  - High degree of stability and comfort

- **Efficient usage context**
  - Can be used for all scenarios
  - High degree of accuracy

- **High ease of use**
  - Easy to use and maintain
  - High degree of comfort and stability

- **High ease of setup**
  - Easy to adapt for different users
  - High degree of flexibility

### Summary

- **Benefits**
  - Easy to adapt for different users
  - High degree of stability and comfort

- **Deficits**
  - Difficult to maintain and replace
  - Less stable, maybe time consuming
## Evaluation of sub solutions

<table>
<thead>
<tr>
<th>Subsolution</th>
<th>behind ears/neck</th>
<th>over top of head</th>
<th>circumferential</th>
<th>tiara</th>
<th>frame</th>
<th>satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesthetical potential</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Social acceptance</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Easy correct placement</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>High repeatability</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
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<tr>
<td>Approximating other sites</td>
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<td>1</td>
<td>2</td>
<td>0</td>
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<td>2</td>
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<td>Technology specific</td>
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<td>2</td>
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<td>1</td>
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<td>Dimensioning</td>
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<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Ease of setup</td>
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<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Room for modularity</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Stability, pressure, comfort</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Different heads</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Uniqueness</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
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<td>14</td>
<td>20</td>
<td>14</td>
<td>14</td>
<td>13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subsolution</th>
<th>segmentation</th>
<th>changing orientation</th>
<th>flexible movement</th>
<th>mechanical movement</th>
<th>rewiring</th>
<th>modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesthetical potential</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Easy correct placement</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>High repeatability</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
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<td>2</td>
</tr>
<tr>
<td>Approximating other sites</td>
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<td>1</td>
<td>2</td>
<td>2</td>
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<td>2</td>
</tr>
<tr>
<td>Technology specific, incorp.</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Dimensioning</td>
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<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Ease of setup</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Room for modularity</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Stability, pressure, comfort</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Different heads</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>19</td>
<td>10</td>
<td>16</td>
<td>15</td>
<td>14</td>
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<table>
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<tr>
<th>Subsolution</th>
<th>flexible materials</th>
<th>flexible rigid parts</th>
<th>state change</th>
<th>mechanical expansion</th>
<th>local quality</th>
<th>intermediaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesthetics</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Easy correct placement</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>High repeatability</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Ease of setup</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Different heads/users</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>11</td>
<td>9</td>
<td>7</td>
<td>10</td>
<td>10</td>
<td>10</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Subsolution</th>
<th>fully integrated</th>
<th>repositionable arms</th>
<th>flexible arm/probe</th>
<th>sticking</th>
<th>chucking</th>
<th>extending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesthetics</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
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<tr>
<td>placement correct</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Room for modularity</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Ease of setup</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Stability, pressure, comfort</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>8</td>
<td>9</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>
Appendix VIII. Moodboard
Appendix IX. Extended cassette proposal

It has deliberately been chosen not to integrate a ‘lock’ feature in the design. Ideally the arms stay in place much like the microphone arm of air traffic controller headsets does. During use the tension in the arms will likely prevent any rotational movement. This can be more difficult during placement on the head. An alternative proposal has been developed to aid in a more stable setup and more pleasant user interaction.

A fourth part can be placed on the bottom of this assembly and clamped between this cassette and the surrounding embodiment with a spring disc. It can push on the ring (g) of the second disc through the holes left by (b). Furthermore it pushes onto the back of the first disc (d). The tension that this introduces in the system would help to limit the ease of rotation. This solution should however be seen as a suggestion for if this situation cannot be achieved simply through adequate tolerances. If both do not suffice, a design proposition that includes a lock-unlock feature should be developed.
Appendix X. Curvature of the head surface

What is shown in image 1 (top right) is the top view of 9 different head shapes. There are 3 different head breadths and 3 different CI values (breadth-depth ratio). They capture the minimum, mean and maximum values of the design envelope. Highlighted are different values for the largest head breadth. The breadth is set at 172 mm (image displays half the breadth = 86). Based on the different CI values of 76, 81 and 86 the depths are set. Then on the left a vertical line is drawn and the distance between this line and the ellipse at a length of 20 mm is noted (representing the product width. This has been done for all 9 head shapes.

Image 2 (bottom left) shows a cross section of the head in front view. Again, three different head breadths have been included. It is assumed that the arc between T3 and T4 forms a half circle contour. A vertical line has been drawn at the location of T3. The distance between this line and the arc has been noted at a length of 20 mm for the 3 different contours. All values are included in the table below. A surface has been modeled based on the average values (figure 3). The minimum and maximum values have been noted in order to understand the variance. In order to take account for additional shape variations, deviating from the circular and elliptical simplifications that are made, the ‘range’ has been multiplied by a factor 2. As such it was found that a padding of at least 2.0 mm should be added to the back of the product to absorb shape variations. At this location. Future testing should evaluate if this is sufficient.

The final 2 images display a cross-section of the back plate of the product on a digital head model (#4 is top view, #5 is side view). The head model that was used here is the NIOSH large head model. It is believed that the modeled surface and actual surface appear to be similar enough to assume that the desired surface for now is adequately described.

<table>
<thead>
<tr>
<th>Breadth (mm)</th>
<th>CI</th>
<th>img 1 (mm)</th>
<th>img 2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>134</td>
<td>75</td>
<td>1.7</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>81</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>87</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>152</td>
<td>75</td>
<td>1.5</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>81</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>87</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>172</td>
<td>75</td>
<td>1.3</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>81</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>87</td>
<td>1.8</td>
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<td>1.76</td>
<td>2.73</td>
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<td>range</td>
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<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Design</td>
<td></td>
<td>2.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>

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Appendix XI. Calculations for the cassette angle

For this calculation, it is assumed that the bitragion arc is an exact half circle. Though not correct, this should provide first good insights.

The location of C3 is located at 25% of this arc length. We are looking for the value of x for both the smallest and largest heads. The ISO 7250:4.3.11 data shows that smallest P5 and largest P95 for head breath (b) are 136 and 171 mm respectively. Following goniometric principles, the distance x can be defined as 0.5b – (b*sqrt(2)/4). The calculations show that x1 is 44 mm and x2 is 55.5 mm. This is a 11.5 mm translation.

The arms are expected to be extendable over ca. 40 mm (based on first measurements of head models). To achieve the 11.5 mm translation, this means that an angle of 16 deg would be needed.

Now in order to place the cassette under a ca. 16 deg angle from the midsagittal plane, it will be placed under ca. 10 degrees from the rest of the embodiment. The reason is that the rest of the embodiment itself will already be placed under an angle in relation to the mid plane (also included in image). The tangent at the location T3 is estimated to be about 5 degrees. This estimation was done on basis of NIOSH head models.

Of course this calculation does not at all cover the complete range of sites. In reality the distances that need to be covered are definitely larger. This is the result of the various different head shapes and the different target site locations. What can be achieved with this suggested angle is merely a slight helping hand for an adaptation that can be done further by using the pressure-regulation feature of the arms.
Appendix XII. Ear study

The necessary data is the distance between T3 (from the 10-20 system) and the attachment of the ear. This data is needed to understand the space that is ‘available’ for the embodiment of the product. In order to get a first rough impression of this data, a small study was set up using 4 participants. This study indicates that the distance between T3 and the top of the ear is 12 mm on average. The data are shown below. From the subjects, first the bitragion arc was measured over the top of the head using a measuring tape. Next the distance from their Tragus to the top attachment of the ear was measured using a ruler. This was done on the right side of the subject. As a result the relevant metric can be calculated as 10% of bitragion – tragus-top distance. The average is 12.7 mm

<table>
<thead>
<tr>
<th>Subject Demographics</th>
<th>Bitragion arc</th>
<th>Tragus-top</th>
<th>T3 top (10% bitragion - tragus-top)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 M, Caucasian, 26</td>
<td>385 mm</td>
<td>22 mm</td>
<td>16 mm</td>
</tr>
<tr>
<td>2 M, Caucasian, 25</td>
<td>352</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>3 M, Hispanic, 24</td>
<td>368</td>
<td>27</td>
<td>10</td>
</tr>
<tr>
<td>4 F, Caucasian, 25</td>
<td>337</td>
<td>24</td>
<td>10</td>
</tr>
<tr>
<td>average</td>
<td>361 mm</td>
<td>23,8 mm</td>
<td>12,7 mm</td>
</tr>
</tbody>
</table>

The target group is of course not representative for the whole audience. A second estimation was done using the data of 100 westerners (M/F) that was made available by CADANS. The database does not mention the metric, but it can be approximated by making a few assumptions.

The assumption is that the ear attachment spans 80% of the total ear projection, and that this projection is equal on both ends (10% at top and bottom of the attachment) furthermore it is assumed that the tragus is situated exactly at the middle of the ear. The calculation that can then be made based on their available data is:

\[ X = 0.1 \times \text{bitragion}_\text{arc} - 0.4 \times \text{projected}_\text{ear}_\text{length} \]

Surprisingly this averages at 12.73 mm, almost identical to the test that was performed, despite of the numerous assumptions in this calculation. The standard deviation is 2.1 mm. The minimum and maximum in the database are 7.6 mm and 19.8 mm.
Appendix XIII. Ear holder shape modelling

Process:

1. The surface of the large head model from the NIOSH 3D headmodels is used. For this part of the product it is better too big than too small.

2. The main embodiment was placed in the digital environment and the surface of the head model was copied.

3. The contour from Lee et al. (2016) is placed over the surface and scaled and rotated to approximate the rough contour from the copied surface best. The surface is cut with this contour.

4. The resulting surface is placed over the curved surface that was previously generated in order to assess if they are similar. The cross section with 2 surfaces is shown. It was concluded that the smooth, averaged surface can be used. It describes the contour from the head model quite well. The fact that it curves a bit more inward than the model is considered to be acceptable. The cushion can adapt for some of the variation and after all it is better if its curvature is too strong rather than too weak.

5. The shape of the holder is modeled on the surface.

Now this would represent the averaged shape. As discussed, it is envisioned that different versions of this part would exist. Herefor a more elaborate study on the ear anthropometry, its relation to the 10-20 system and across the whole target range would need to be executed. The design in the current state is ought to be.
Appendix XIV. Arc dimensioning

Looking at the left side of the head, the underlying positions are: (distance in relation to midline):

<table>
<thead>
<tr>
<th></th>
<th>Cz</th>
<th>(On mid line)</th>
<th>Fpz</th>
<th>(On mid line)</th>
<th>Oz</th>
<th>(On mid line)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3 (20% of bitrag. arc)</td>
<td></td>
<td></td>
<td>Fp1 (10% of front arc)</td>
<td></td>
<td>O1 (10% of back arc)</td>
<td></td>
</tr>
<tr>
<td>T3 (40% of bitrag. arc)</td>
<td></td>
<td></td>
<td>F7  (30% of front arc)</td>
<td></td>
<td>P7  (30% of back arc)</td>
<td></td>
</tr>
<tr>
<td>T3 (50% of front arc)</td>
<td></td>
<td></td>
<td>T3  (50% of back arc)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The data on the bitragion arc and circumference are included in the Analysis phase. What is missing is the data of the front half of the circumference in relation to the back half. This has been analyzed using the five NIOSH 3D head models. These values are shown in the table below:

<table>
<thead>
<tr>
<th>Headmodel:</th>
<th>large</th>
<th>small</th>
<th>shortwide</th>
<th>longnarrow</th>
<th>Medium</th>
</tr>
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<tbody>
<tr>
<td>Circumference</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front arc</td>
<td>579</td>
<td>527</td>
<td>548</td>
<td>553</td>
<td>549</td>
</tr>
<tr>
<td>back arc</td>
<td>293</td>
<td>271</td>
<td>276</td>
<td>270</td>
<td>267</td>
</tr>
<tr>
<td>front ratio*</td>
<td>0.494</td>
<td>0.486</td>
<td>0.496</td>
<td>0.512</td>
<td>0.514</td>
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<tr>
<td>discrepancy</td>
<td>0.6%</td>
<td>1.4%</td>
<td>0.4%</td>
<td>-1.2%</td>
<td>-1.4%</td>
</tr>
</tbody>
</table>

*defined as front/(front+back)

The data suggest that the front and back halves are very similar, even across different head shapes. Within the available models there is only a maximum of 1.4% discrepancy between the front and back halves. Surely in reality there can be larger differences. The head models are namely statistical averages. Therefore a safety factor 3 is applied. Ideally this would be expressed as a percentile, but with the limited data (5 subjects) this is not possible. The safety factor 3 on top of the largest current deviation should be high enough to include many if not almost all head shapes. This means in practice that it is assumed, for circumferential measurements, that the smallest head is even 4.5% smaller, and the largest head is 4.5% larger. In this way we can still treat the front and back halves as one single arc, without ruling out uneven extremities.

Now with this we can define the distances of the target sites in their minimum and maximum dimensions. The minimum and maximum bitragion arc are taken from the envelope described in the Analysis phase (based on ISO7250), and the minimum and maximum front/back arcs can now be calculated.

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>523</td>
<td>610</td>
</tr>
<tr>
<td>Half arc</td>
<td>261.5</td>
<td>305</td>
</tr>
<tr>
<td>4.5% safety</td>
<td>249.7</td>
<td>318.7</td>
</tr>
<tr>
<td>Bitragion arc</td>
<td>322</td>
<td>402</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cz  (On mid line)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C3 (20% of bit arc)</td>
<td>64</td>
<td>80</td>
</tr>
<tr>
<td>T3 (40% of bit arc)</td>
<td>128</td>
<td>161</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fpz/Oz (On mid line)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fp1/O1 (10% of half arc)</td>
<td>25</td>
<td>32</td>
</tr>
<tr>
<td>F7/P7 (30% of half arc)</td>
<td>75</td>
<td>96</td>
</tr>
<tr>
<td>T3 (50% of half arc)</td>
<td>125</td>
<td>160</td>
</tr>
</tbody>
</table>

* Fig: NIOSH ‘large’ head model with 10-20 sites modeled, displaying the frontal and occipital circumference arc lengths between T3 and T4. This was done for all 6 acquired head models.
Appendix XV. Coordinates of sites C3, F3 and P3 in relation to T3 on digital head models

The five NIOSH head models were used to analyze the locations of C3, F3 and P3 in relation to T3 (at the ear). The vertical and horizontal distances between the sites were noted (see Table below). These are the distances on the plane on which the shortest curvature over the surface can be made towards the target site. These planes are pictures in the image for the short+wide head model. The table also lists the angle between these planes and the bitragion plane on which the C sites are located. (So these angles would be the angles of the arms in order to reach the sites F3 and P3).

<table>
<thead>
<tr>
<th></th>
<th>C3 x</th>
<th>F3 x</th>
<th>P3 x</th>
<th>Plane deg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>CF</td>
</tr>
<tr>
<td>medium</td>
<td>15,9</td>
<td>31,1</td>
<td>26,5</td>
<td>51,3</td>
</tr>
<tr>
<td>small</td>
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<td>28,4</td>
<td>26,5</td>
<td>51,6</td>
</tr>
<tr>
<td>wide</td>
<td>16,2</td>
<td>31,3</td>
<td>33,3</td>
<td>54,1</td>
</tr>
<tr>
<td>narrow</td>
<td>14</td>
<td>30,4</td>
<td>36</td>
<td>60,1</td>
</tr>
<tr>
<td>large</td>
<td>19,1</td>
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<td>31,9</td>
<td>51,9</td>
</tr>
<tr>
<td></td>
<td>64,5</td>
<td>79,6</td>
<td>80,8</td>
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<tr>
<td></td>
<td>63,4</td>
<td>76,8</td>
<td>85</td>
<td>48,1</td>
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<td>66,7</td>
<td>81,5</td>
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</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Target site locations**

- C3 sites cluster
- F3 and P3 sites cluster

*Series 1*
Appendix XVI. SolidWorks simulation tests and results for the optimalization of the Arm

The three tests that are performed are:

- Is it possible to create contact pressure on the head surface (using the slider) of at least 100gr/cm², starting from a floating position?
- Is it possible to create a -10mm horizontal translation using ‘pre-pressure’ within 0-150gr/cm²?
- Is it possible to create a 10mm translation in horizontal direction using the slider?

For this a number of simplifications are made in the model. It has been cut in half over its symmetry plane, and all parts are modelled as a surface. A thickness is assigned to these 2D surfaces. This makes the simulation process much more rapid than working with solids.

The slider has been removed from the assembly and has been replaced by an equal force on opposing segments of the two strips.

Through a series of iterations, the dimensions have been optimized. The adaptations were mostly done on the following features: (1) thickness of the plastic strip, (2) thickness of the rib underneath this strip, (3) height of the rib under the plastic strip and (4) attachment of the rib to the shape transformation at the end of the probe. Furthermore the metal strips thickness and shape have been subject to small adjustments, and different material grades have been used in the simulations.

The design has been brought to a stage where it seems to pass all three tests. The figures on the next pages are captures of the simulations and exemplify this. It has to be noted that the translation that is shown is the resultant displacement (depth and height combined). Since the displacement happens at about 45 deg., the displacement in horizontal direction is hence ca. 10mm (slider movement) and 8mm (pre-pressure, 100gr).

As shown the pressure on the scalp in this case can rise to about 190gr/cm². This is well in line with what is minimally desired (ca 100gr/cm²). This means that not only can it be increased from 0 to 100, it can also be increased further when larger probes or multiple probe-heads (on one arm) are in play.

The final dimensions include a metal strip thickness of 1mm, made from AISO1095 temperature hardened at 205deg. The thickness of this strip can be varied with changing grades of the spring metal.

The plastic strip has a thickness of 1.25mm, with the ribs being 1mm thick and protruding 1 mm from the bottom surface. The ribs gradually fade from 1mm to 0 over the shape transition towards the arm end. The material is PA6 with 35% glass fibre reinforcement.

Further research would be needed to evaluate the effect of the exact contour of the two elements on the resultant forces and displacement. By doing so one could strive to attain the lower internal forces and larger displacement/pressure in the system. This could be subject for future studies. The design in its current state shows that the envisioned properties are at least theoretically possible.

Further simulations should also determine how various misuse scenarios would affect the materials and how this can be accounted for in the design.
Figure: 100gr/cm² pre-pressure applied to the final design results in 11mm translation.

Figure: Maximum deformation using the slider (replaced with a force) results in 14mm displacement of the tip of the arm (no underlying surface).
Figure: the average contact pressure on the selected faces of the arm tip is 18970 N/m2 (190gr/cm2).

Figures: model simplification using surfaces, cut in half (image 1 and 2), model with fixed geometry and symmetry constraints, and a force representing the slider (image 3).
Appendix XVII. Elaboration on cost price estimations

A injection molding tooling cost estimator was used for determining the expected mold prices. The calculations from CustomPartNet use data based on typical industry averages. A mold-making labor of 40$/h was used, representing expected European production. If tooling would be done overseas (China/India) all molds could probably be half the price that is stated below.

For all injection molded parts we assume a cost distribution as follows: 50% mold, 30% processing, 15% material, 5% tryouts/defects/other. This ratio is based on stated typical costs distributions of industry players (e.g. ACOmold).

Front cover + back cover

The envelope of both parts is about 40x40x3mm. The part complexity is simple: a flat parting surface, no cores/lifers/slides and a limited feature count. The needed tolerances are moderate and the surface roughness too (normal polish). A double cavity mold is estimated to be ca. $10.000 using rapid tooling.

The estimated batch size is 6000pcs, but for various setups one would need a unit of this at either side. Therefor a quantity of 10.000pcs is assumed for these parts, resulting in a $1 investment per set. Following the average cost distribution, this results in $2 in total including materials, processing, tryouts and other costs ($1 a piece).

Cushion 1

This part will be stamped out of EVA sheet material. The highest price noted by CES for this raw material is 2,30$/kg. With the low density of the material and low volume of the design this is almost neglectable, though sheets with an adhesive back side (which are envisioned to be used) could be a little more expensive. A rough estimate is set for now at $0.1 a piece.

Cassette

The three discs of the cassette have an average envelope of about 17x17x5mm. High precision is needed, but complexity is very simple and no special surface polish is needed. The mold costs are expected to be about $8000 in total for the 3 discs. With a quantity of 10.000 pcs this results in 0.66 cents per complete cassette for the mold investment, and 1.32 in total.

Holder

The holder part will be injection molded. It has a moderate complexity and needs 1 side core. The envelope is about 45x90x15mm, and the projected area is quite low. With moderate precision, normal polish, rapid tooling and 2 cavities (for a left and right sided holder), the estimation is set at $10.000 in total. With a batch size of 6000 pcs this results in a $0.83 per piece, and a total of $1,66 including other costs.

Cushion 2

The cushion can be produced with injection molding. In comparison to the holder it has a lot less critical tolerances and surface finishing. The estimated mold costs are $5.500, which includes a left and right cavity. This results in $0.46 per unit ($0.92 including other costs).

Alternatively the cushion can be produced using die cutting out of sheet material. Though in this way it will not have the exact desired 3D shape, it could still be fitted in the holder and is expected to cost maybe only about a $0.20 per piece.

Spring strip

The spring strip will be die cut and press-formed into the desired shape. Spring steel sheet of 1mm thickness costs about 20$ per sheet of ca. 1600 cm2 (source: Amazon). The strip used in the product has a surface of about 5.5 cm2. This means 284 strips could theoretically be produced from a sheet. Taking into account a loss coefficient of ca. 10% would result in 250 strips a 0.08$ per piece for the material. The further processing is very simple: it only needs to bent in the right shape. A factor 2 is added to the material cost, resulting in an estimated part price of 0.16$.

Plastic strip

The plastic strip has envelope of about 75x15x15 mm. A higher quality mold would be needed to deal with the reinforced plastic. The highest quality (Class 101) if for now assumed in the estimation. With a double cavity the
mold costs are expected to be 12.500$. This results in $1.05 per part, and 2,10 including other costs.

Slider and guides

These parts are considered to be similar. The mold costs for such small parts are expected to be about $4000 a piece for double cavity molds using rapid tooling. This results in 0.33$ per piece (batch size is 12.000pcs), and 0.66 including other costs. As discussed earlier, the guide can be replaced by a bent wire that would probably cost only a couple of cents, ca. 0.05$.

Middle arc

This part has many insecurities regarding its actual detailed production method at this point. Still a rough estimation can be made. The product envelope is quite large, but the projected area is only a small percentage of that. An estimation using a 2-step parting surface and a Class 102 mold results in an estimated mold price of ca. $20.000 ($3.33 per part). Adding 2 side cores and a higher mold Class (101) to the estimation makes a mold cost of ca $30.000 ($5 per part). For now an estimation is set in the middle at $4.17 per part. This is quite high, but that is mainly because of the low initial batch size (6000pcs). The molds are likely still well suited for a higher production volume, especially with Class 101 molds. A class 104 mold using rapid tooling (that could go up to about 10.000 runs) is much more affordable (about $15.000) but its suitability for highly reinforced plastics should be discussed with experts.

The cost distribution is assumed to not hold up in this case. The tooling costs likely hold a larger share. Assuming their share is not 50% but 75% makes the total part costs $5.56.

Arc legs

These are considered to be similar in production to the metal strip elements and are henceforth estimated to be $0.16.

Strap

These will be cut out of sheet material. The PU and silicon elastomers are a bit more expensive than the other die cut components' materials (steel, EVA). A guesstimate is set at a price of $0.30 a piece for the strap. The plastic rings that are placed in the strap are OEM products from electrode cap manufacturers. Including all such attachment the price is set for now at $0.5.

Validity of these estimates

All of these estimated can only be viewed as first guide. Costs may vary greatly based on a number of different properties. The mold costs of injection molded parts can all turn out to be lower than stated if production would be moved to low-wage countries such as China, India or Cambodia. This could potentially half all the tooling costs. Furthermore the distribution of costs (50% tooling, 30% processing, 15% materials, 5% defects) is of course a simplification that can not last long in practice. Actually, since the production volumes are rather low, the share of the tooling costs in the total equation can be larger than what is stated here. This could go as far up to well over 75%. All in all this means that in the most beneficial scenario, all injection molded parts could cost below 37,5% of the currently stated costs. Keeping the costs of other parts equal this could reduce the cost price from $23 to $10. Together these are believed to represent a best case and worst case scenarios.

Also it has to be noted that with the current estimations the tooling costs are spread out only over the first batch size, but the tools could likely be used for another batch.
Appendix XVIII. Reachability of target sites

This discussion only focuses on the left side target sites, since the targetability is symmetric over the two hemispheres. All sites that are marked green can be targeted with the arc. The dimensions of the arc are chosen such that this is (theoretically) possible. It can be placed in different angular orientations, and the elastic strap can be adapted to include all intermediary sites. Additionally, some of the sites that are marked green can be targeted with the arm. The actual sites that can be targeted in this way depend on the head size of the individual. For those with smaller heads it could be possible that some further sites such as C1 or AF7 can also be targeted with the arm. For those with larger heads this is not possible, and it is retrained to C3, F3, P3.

Now for the yellow sites.

**T3:** This is located behind the main product embodiment. In the design of the product there is room for an electrode at the back of it. However, this is not tested in practice. It can also affect the signal stability if the main embodiment is susceptible to movement. In the current design it would not be possible to execute fNIRS research here. tES would be possible but only with a small electrode size or by replacing the cushion of the product for a sponge.

**TP7, CP5, C5, FC5, FT7:** These are located quite close to the main embodiment. In practice this means that the arms are too long to reach them (for most of the head shapes). With the arcs it might be possible, but it depends on the head shape and the thickness of the probe. There might be too little room left between the leg of the arc and the scalp. For all these sites it would be best if the arc is placed in the cassette rather than the side slots, since in that way its offset from the scalp is larger and no big problems are foreseen for regular probe thicknesses.

**TP9, T9, FT9:** These sites are (approximately) underneath the main embodiment. They are in the current state of developments not yet included, but they can be targeted by changing the design of the main product embodiment. This could be integrated with electronics and target these sites.

**F9:** This is on the temple, next to the eye. You could set up the arc to this orientation but it would run in front of your eyes. It is likely too close to be targeted with the arm. Also, this region is very sensitive for pressure. It is currently not underneath the main product embodiment, and it is not desirable to extend this main embodiment as far inward to include this site. It can be said that F9/10 is the only site that is currently truly troublesome. It is a site that does occur in set ups for cognitive enhancement and accelerated learning, so it should be included in future developments.

**A1:** This is the earlobe. The same applies as for TP9 and T9. Actually most EEG systems come with a little clip that can already be used, since the earlobe is not obstructed.
Appendix XIX. Test protocol of fit evaluation

1. An explanation will be given about the product context, design and the test to a test subject. Subjects will be approached on campus during the testing days. No specific criteria for participation are maintained, but during scouting it should be at least attempted to include various head types.

   All participants are asked to sign an informed consent form in they choose to participate.

2. Global head measurements will be taken (circumference, bitragion arc, sagittal arc).

3. An elastic hairnet that is prepared with the 10-20 site indication will be placed on the users head.

4. The headgear model will be put into place by the test executor. It will be noted if the holders fit around the ear through visual inspection. The distance between the tragus and the cassette centre, and the distance between the holder and the ear root at the back of the head are then recorded. This will be done on the left side of the head.

5. The arms will be inserted and they will be rotated and exerted so as to best approximate the target site locations F3, C3 and P3 (in that order). It will be noted if the arm head can end up precisely on the target site, or what the distance between the two is.

   The extension and angular orientation in relation to the main product embodiment will be documented.

6. With one arm in place for F3 and one for P3, the headgear will be taken fully off of the scalp and put back on by the user. It will be noted what the distance between the arm end and the sticker is after re-application.

7. The arms will be removed and the arc will be placed in the cassette. It will be noted towards what extend the slots line up with the target sites. When the arc is in middle position (cassette), front or back (slots).

8. The user can then have time to freely interact with the product.

9. The user will be asked to fill in the User Experience Questionnaire.

10. The research will be concluded.

» Data form from the test (blank)
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Note: After five tests, the tolerances were affected so that due to gravity, the arms would directly rotate downward and repeatability couldn't be tested.
### Appendix XXI. Data from the UEQ

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Scale consistency (alpha coefficient)

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<p>| Dependability | Stimulation | Novelty | | | | | | | |</p>
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