Evaluation of cognitive workload using EEG

Investigation of how sensory feedback improves function of osseo-neuromuscular upper limb prostheses

Linn Berntsson
Master of Science Thesis in Electrical Engineering

**Evaluation of cognitive workload using EEG**

: Investigation of how sensory feedback improves function of osseo-neuromuscular upper limb prostheses

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Abstract

The e-OPRA Implant System (Integrum AB, Sweden) is a system which employs permanently accessible implantable neuromuscular electrodes in combination with osseointegrated attachment of the prosthesis to the skeleton, in order to create a more natural control of advanced robotic upper-limb prostheses. The system enables the possibility of sensory feedback, via a cuff electrode to the ulnar nerve which allows for direct neurostimulation of the nerve.

This work proposes a method using electroencephalography (EEG) to quantitatively evaluate the cognitive workload of a person controlling a prosthesis, and how said workload changes when sensory feedback is enabled. Based on previous studies on EEG and cognitive workload, the proposed methods include collecting EEG data from subjects who are performing a grasping task while listening to a selection of sounds and counting the number of times a specific tone is presented. The data is analysed using both event related potentials (ERPs) as well as spectral analysis.

The method was used in a trial run consisting of two healthy subjects, and one transhumeral amputee implanted with the e-OPRA system. Although the subject group was not large enough to draw any statistical conclusions, the trial run and the results from it suggest that the methods could be used in a larger study to evaluate the cognitive workload of amputees implanted with the e-OPRA system.
Contents

Notation ix

1 Introduction 1
  1.1 Motivation .................................................. 1
  1.2 Problem formulation ........................................ 2
  1.3 Limitation ................................................... 3

2 Theory and Related Work 5
  2.1 Electroencephalogram ........................................ 5
    2.1.1 Event related potentials ................................ 6
    2.1.2 Spectral analysis ........................................ 7
  2.2 EEG signal processing ....................................... 9
    2.2.1 Low-pass, high-pass and notch filtering ............... 9
    2.2.2 Re-referencing .......................................... 10
    2.2.3 Independent Component Analysis (ICA) ................ 10
    2.2.4 Epoching ................................................ 12
    2.2.5 Baseline correction ..................................... 12
    2.2.6 Artefact rejection ....................................... 12
  2.3 Cognitive workload and EEG ................................. 14
    2.3.1 Single- and dual-task paradigms ....................... 14
    2.3.2 Attentional reserve .................................... 15
    2.3.3 ERP paradigms ......................................... 16
  2.4 Summary of related work .................................... 17
    2.4.1 A novel approach to the physiological measurement of mental workload .................................................. 18
    2.4.2 Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking .................................................. 18
    2.4.3 Combined assessment of attentional reserve and cognitive-motor effort under various levels of challenge with a dry EEG system .................................................. 19
<table>
<thead>
<tr>
<th>Contents</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A    Experiment protocol</td>
<td>51</td>
</tr>
<tr>
<td>B    Self-report questionnaire - NASA TLX</td>
<td>55</td>
</tr>
<tr>
<td>Bibliography</td>
<td>57</td>
</tr>
<tr>
<td>Index</td>
<td>62</td>
</tr>
</tbody>
</table>
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEG</td>
<td>Electroencephalography</td>
</tr>
<tr>
<td>ERP</td>
<td>Event Related Potential</td>
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<tr>
<td>ICA</td>
<td>Independent Component Analysis</td>
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<tr>
<td>EOG</td>
<td>Electrooculography</td>
</tr>
<tr>
<td>FIR</td>
<td>Finite Impulse Response</td>
</tr>
<tr>
<td>IIR</td>
<td>Infinite Impulse Response</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyography</td>
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1 Introduction

1.1 Motivation

The Biomechatronics and Neurorehabilitation Laboratory (BNL) is a part of the Biomedical Signals and Systems research group at Chalmers University of Technology. One of their major research projects is called *Natural Control of Artificial Limb Through an Osseointegrated Implant*. The project is a collaboration between BNL, Centre for Advanced Reconstruction of Extremities in Sahlgrenska University Hospital, and Integrum AB. The main aim of this project is a more natural control of advanced robotic prosthesis, using implantable neuromuscular electrodes which are permanently accessible through osseointegration - the e-OPRA Implant System (Integrum AB, Sweden). The project includes research on the e-OPRA; electronics (e.g. biopotential amplifiers, filters, microcontrollers); bioelectric signal processing, pattern recognition, control algorithms; and the clinical implementation of this technology.

The e-OPRA is based on a system called Osseointegrated Prostheses for the Rehabilitation of Amputees (OPRA) which has been in use since 1990. OPRA consists of a fixture which is attached to the bone at the stump of an amputee, and an abutment which is used to anchor the prosthesis to the fixture. The fixture and the abutment are connected by an abutment screw. The e-OPRA system, which is currently used for upper-limb amputees, uses the abutment screw by embedding connectors which are used for bidirectional electrical communication. The system is presented in figure 1.1. The connectors allows the prosthesis to be controlled through epimysial electrodes, with pattern recognition control. Furthermore, a spiral cuff electrode connected to the ulnar nerve allows direct neurostimulation of the nerve, i.e. sensory feedback. This enables the possibility of distally referred tactile perception, i.e. tactile feeling in the phantom limb. [1].
Which type of movements that can be performed and how the sensory feedback is perceived differs between users. Previous work on the function of this specific prosthetic control has been focused on opening and closing of the prosthetic hand.[2] Nonetheless, other movements are also possible, and there is continuous work to enable more detailed movements.

![Figure 1.1: The e-OPRA Implant System [1]. The abutment and the fixture are used to attach and secure the prosthetic limb. (1) is a connector that is embedded in the screw, interfacing the prosthetic limb. It is linked to connector (4) in the soft tissue, via connectors (2) and (3). The neuromuscular electrodes ("e.") are connected to (4). The cuff electrode is used for sensory feedback.](image)

It is intuitive to imagine that sensory feedback would lessen the cognitive workload with a person who is performing a grasping task - e.g. cracking an egg, pouring a glass of milk or making the bed. Without sensory feedback, one would have to rely heavily on visual feedback instead. If and how the cognitive workload is in fact lessened can be evaluated qualitatively, for example using self-report questionnaires.

Electroencephalogram (EEG) has often been used to evaluate cognitive workload quantitatively. Furthermore, there are examples of EEG being used to evaluate the workload in motor tasks (e.g. [3] and [4]), including a few examples of motor tasks which include prosthetic usage ([5], [6]). On the basis of this, the aim of this thesis is to employ EEG to investigate how to quantitatively evaluate the cognitive workload induced by controlling a prosthesis. Specifically, the aim is to examine how sensory feedback affects this workload.

### 1.2 Problem formulation

The following questions will be investigated in the thesis:
1.3 Limitation

- Which methods can be used to evaluate cognitive workload with EEG?
- How can these methods be applied to evaluate the cognitive workload with a person controlling a prosthesis?
- Can these methods be used to show a difference in cognitive workload when a person is performing a task with and without sensory feedback?

At the time of this thesis project, only a handful amputees had received the e-OPRA Implant System. Therefore, the number of possible subjects for the experiment was very limited. To facilitate testing of the methods, two intact-limb subjects took part in the experiment. In addition, the experiment was run with one transhumeral amputee implanted with the e-OPRA, for a final test of the methods. Owing to this, the results from the experiment cannot be used to draw any statistical conclusions, but merely to give an indication of the outcome of the methods.
2.1 Electroencephalogram

The electrical activity of the brain can be measured using electrodes attached to the scalp. The electrodes detect the voltage potential across the scalp, and these detections are amplified and recorded. This measurement is called an electroencephalogram (EEG), and can be used to analyse the brain function in a variety of ways. The electrical activity origins from the cerebral cortex which is the outer layer of the cerebrum. The cerebral cortex is divided into two hemispheres, left and right, and each hemisphere is in turn divided into four lobes, which are named frontal, temporal, parietal and occipital. Because different areas are in control of different actions, the electrical activity will not be uniform across the brain. Therefore, the EEG data will differ depending on where on the scalp the activity is being measured. Consequently, it is necessary to place the electrodes in such a way that the analysis can be done correctly. [7]

The standardised way of placing the electrodes is called the 10-20 system, and is based on measurements of the skull, see figure 2.1. The measurements emanate from two baselines: one from nasion to inion, and one between the preauricular points. The electrodes are placed on 10% and 20% points along these lines and in between them. The original 10-20 system employs only 19 electrodes (plus two reference electrodes placed on the earlobes). [8]. Therefore, additions to the original 10-20 system are usually made in order to include a larger number of electrodes. Furthermore, the electrodes are commonly placed on the skull using a cap or a headband with pre-placed electrodes.

In accordance of the 10-20 system, the electrode sites are labelled based on their location. Electrodes are labelled with numbers together with letters according
to the placement on the skull, e.g. Fp (fronto polar), F (frontal), C (central), P (parietal) or O (occipital). Sites along the line from the nasion to the inion are labelled 'z', e.g. Pz, see figure 2.1.

![Diagram of EEG electrodes](image)

**Figure 2.1:** The 10-20 system. [8] Nasion and inion marked as 'Nz' and 'Iz', respectively. Preauricular points are located right in front of the ears, close to 'A1' and 'A2'.

There exist multiple ways to analyse EEG data. For this thesis, two methods are used: analysis of event related potentials, and a simple analysis of frequency power.

### 2.1.1 Event related potentials

Event related potentials (ERPs) are based on the idea that specific brain activity is triggered by certain stimuli. When employing an ERP paradigm, EEG is recorded continuously. Short stimuli that trigger certain brain process are presented repeatedly and time-locked to the EEG data, see figure 2.2. The triggers can be e.g. auditory, visual, or somatosensory. When processing the data, short segments of the EEG data are extracted, e.g. from 100 ms before each stimulus, to 900 ms after. The segments are then averaged together. Because EEG activity that is not triggered by the stimuli will be unrelated between each segment, the stimuli related activity will be enhanced and the unrelated activity will be dampened. When using a large enough number of triggers, the resulting averaged segment will show only the stimuli related activity - the ERP. [7]
An ERP has a typical waveform, and the components of the waveform can be analysed in regards to latency and amplitude. Components of interest will vary between studies. The components are typically named from a naming convention based on the latency in regards to the trigger, or based on the position in the waveform (e.g. the P3 component is the third positive peak). Both the names, and more importantly, the latency ranges and how they are selected vary between studies. Some studies (e.g. [9], [6]) use a method reported in Handy et al. [10], where the grand average of all ERPs in the study is calculated, and narrow time windows are centred around the maximum of each component. In contrast, Luck ([11], Ch. 9) advises against using the grand average to draw conclusions about the components’ latencies, stating that choosing the measurements based on the basis of the data could cause the results to be misinterpreted.

Commonly, only a few components are mentioned in ERP studies on cognitive workload and only these will be mentioned in this thesis for simplicity. Furthermore, because the naming convention differs between studies, this thesis will follow the same convention used in a study by Miller et al. [9]. See table 2.1 and figure 2.3 for the components and their respective latencies (as used in the study by Miller et al.).

### 2.1.2 Spectral analysis

Analysis of the power spectrum of the EEG data is quite commonly employed in studies on cognitive workload. On occasion, this is performed in conjunction with an ERP analysis, see e.g. [4], [12], and [5]. In these studies, the analysis is done by estimating the power spectrum of the EEG signal using Fourier transform, and subsequently calculating the power across different frequency bands. The absolute powers of the frequency bands are then compared across conditions. Which frequencies that dominate the signal will depend on the subject (age etc.),
Table 2.1: The different components of an ERP. Names and component latencies of the components are presented, following the same convention used in [9].

<table>
<thead>
<tr>
<th>Component</th>
<th>Component latency [ms]</th>
</tr>
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<tbody>
<tr>
<td>N1</td>
<td>140-160</td>
</tr>
<tr>
<td>P2</td>
<td>225-255</td>
</tr>
<tr>
<td>P3</td>
<td>290-320</td>
</tr>
<tr>
<td>LPP</td>
<td>570-610</td>
</tr>
</tbody>
</table>

![ERP components](image)

**Figure 2.3:** ERP components

as well as the mental state of the subject. [7]

The frequency bands are presented in table 2.2. As with peak latencies in ERPs (see 2.1.1), the specifications differs between studies. This thesis will follow the bandwidths specified by Sörnmo et al. [7], but dividing the alpha rythm into low-alpha and high-alpha, as in [5].

Table 2.2: Bandwidths of EEG signals, as specified in [7] and [5]. In bold are the bandwidths used in this thesis. In parenthesis, abbreviations for the names are presented, which are used in other tables in this thesis.

<table>
<thead>
<tr>
<th>Name</th>
<th>Bandwidth [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta (D)</td>
<td>&lt; 4</td>
</tr>
<tr>
<td><strong>Theta (T)</strong></td>
<td>4 – 7</td>
</tr>
<tr>
<td>Low-alpha (lA)</td>
<td>8 – 10</td>
</tr>
<tr>
<td><strong>High-alpha (hA)</strong></td>
<td>11 – 13</td>
</tr>
<tr>
<td>Beta (B)</td>
<td>14 – 30</td>
</tr>
<tr>
<td>Gamma (G)</td>
<td>&gt; 30</td>
</tr>
</tbody>
</table>
2.2 EEG signal processing

Recording and analysing EEG can be troublesome on account of the many sources of disturbances. Firstly, there is power line noise from any electrical equipment in the vicinity of the EEG recording equipment. In Sweden, the power line frequency is 50 Hz. [13] EEG signals are usually measured in $\mu V$, meaning that there is a great risk of EEG signals being overpowered by power line noise.

Secondly, there are biological disturbances to the EEG signals in form of e.g. eye blinks and eye movements, electromyography activity (EMG, i.e. muscle signals) such as jaw movements etc., and cardiac activity. These types of contaminations are more difficult to remove, since they are not predictable and uniform in the same way as power line noise.

Thirdly, artefacts can be caused by the equipment, e.g. by bad electrodes, electrodes moving on the scalp on account of the subject moving, sub optimal contact between the skin and the electrodes, etc. [7]

On account of the previously mentioned issues, it is necessary to process the EEG data prior to analysis. This section aims to describe some commonly used processing methods for EEG data.

2.2.1 Low-pass, high-pass and notch filtering

Power line noise

As mentioned in 2.2, the power line frequency can cause disturbances in the EEG. If frequencies above the power line frequency are of interest in a study, a notch filter is required to filter out the power line noise. However, if only frequencies below the power line frequency are of interest a low-pass filter will suffice. This is often the case in studies concerning cognitive workload (e.g. [3], [14]).
Slow voltage shifts

According to Luck ([11], Ch. 1), slow voltage shifts in the EEG often arise from the electrodes and the skin. To suppress these slow drifts, one usually applies a high-pass filter of e.g. 0.1 Hz to the EEG signal. A higher cutoff-frequency is not suitable, as it would risk distorting valuable traits of the signal. [11], Ch. 7

2.2.2 Re-referencing

When the EEG is recorded, the electrical potentials between the electrode sites and a common ground electrode are measured. Depending on the EEG recording system, a reference electrode might also be used online (i.e. during the recording).

The purpose of the reference is based on the fact that the ground electrode is by necessity connected to a ground circuit in the amplifier, which creates electrical noise. Let \( A \) be the absolute voltage at a specific electrode, and \( G \) the absolute voltage at the ground electrode. Then the potential between \( A \) and \( G \) will be \( A - G \), and because \( G \) contains electrical noise, so will \( A - G \). By including a reference \( R \) (online or offline), the noise from the ground electrode can be eliminated. The potential is instead measured as the difference in potential between \( A - G \) and \( R - G \), i.e. \( (A - G) - (R - G) = A - R \). Consequently, the ground, which is required for the amplifier to record the signal, is removed in the actual output signal.

The referencing can be done online in the recording, or offline when processing the data. If a reference is used online, it can still be re-referenced offline, if another reference is desirable. Common reference sites include earlobe(s), mastoid(s) (bone located behind the ear), tip of the nose, or an average of all electrodes. Which reference site(s) that is used depends on the application. ([11], Ch. 5)

2.2.3 Independent Component Analysis (ICA)

In order to describe Independent Component Analysis (ICA), it should, as already has been mentioned, be noted that recorded EEG data consist of not only cortical activity, but also of recorded activity from other sources, such as muscle movement (scalp, jaw, etc.), eye blinks and eye movements, cardiac activity, and non-biological noise from electrodes and environment. Furthermore, the cortical activity measured from one electrode site on the scalp will be a mixture of electrical potentials across the scalp - different EEG sources. The purpose of ICA is to divide the recorded EEG signals into independent sources, thus making it possible to remove unwanted activity such as eye blinks from the signal.

For a simplified example, let there be two different independent EEG sources, and one additional source from eye movement, i.e. in total three sources. When recording the EEG from three electrode sites in between the sources, the recorded signal will be a compound of these sources. Depending on where the electrodes are placed, the weighting of how much of each source is recorded will differ. ([15]) The example can be expressed mathematically as in (2.1).
Here, $x_i$ are the recorded signals, $s_j$ are the independent sources (let e.g. $s_3$ be the eye movement source), and $a_{ij}$ are the weights. Because the interesting part of the recorded signal is the part that stems from the EEG sources, it is desirable to be able to remove $s_3$, the source from the eye movement. However, the matrix (2.1) contains twelve unknown variables, and only two known, meaning that it is not possible to solve the equations exactly. Instead, ICA aims to approximate the weights and the sources, by estimating the so called unmixing matrix $W$, according to (2.2)

$$x = As \Rightarrow s = Wx$$

where $W = A^{-1}$. [16]

ICA estimates the unmixing matrix, e.g. by taking the recorded signals $x$ as input to a neural network which uses a learning algorithm. The estimation is done under the assumption that the sources are statistically independent and non-gaussian, and the estimation of the unmixing matrix is performed by maximising the independence of the components in the matrix. ([11], Ch. 6)

ICA components are visually inspected, and components that corresponds to e.g. eyeblinks (and not cortical activity) are removed from the EEG signal.

In general, the visual inspection of the ICA components is quite subjective. Although there exists software designed for automatic detection of components with artefacts (e.g. ADJUST [17]), manual inspection is still required to choose which components to reject. The following example follows the recommendations of a lecture by Cohen [18], and is used to describe the process of manual inspection of the ICA components.

**Visual inspection of ICA components**

Figure 2.5 shows an image of a few channels of recorded EEG data, along with a few of the ICA components calculated from the data, and the time activations of said components. Looking at component 3 in figure 2.5c, it is obvious that the distribution of weights is mostly anterior, i.e. it corresponds to activity in the front of the skull. Looking at the EEG channels in 2.5a, eye blinks are clearly visible at around time stamps 126, 127, 128, and 129.5 s, which corresponds to the ICA time course in component 3. In addition, component 3 does not seem to contain any additional activity. Therefore, component 3 can be safely removed.

Similarly, the EEG channels appear to contain an horizontal eye movement slightly before time stamp 128 s, judging by the sudden and square motion in the signal.
This corresponds to component 6 in the ICA components, which does not seem to contain much else information beside the eye movement. Like component 3, component 6 has a primarily anterior weight distribution. Based on this, component 6 can also be removed.

EMG artefacts can also be removed using ICA. However, according to Luck ([11], Ch. 6), there is controversy concerning the suitability of using this method. In addition, judging from the result from the literature review for this thesis, it appears that it is more common to use ICA only for eye movement artefacts, and rely on other methods for rejection and correction of EMG artefacts (see e.g. [19], [20], [3]).

2.2.4 Epoching

If conducting an ERP study, it is necessary to epoch the data, i.e. to segment the data in regards to the time-locked stimuli (ERP is described briefly in section 2.1.1). This is a simple procedure, where segments, or epochs, of a specific time interval are extracted from the data. When performing an ERP study, the epochs are extracted in regards to the stimuli, which are time-locked to the EEG signal during the recording. The length of the epochs differs between studies, but a common length is around 1 s, e.g. starting 200 ms before the stimulus and ending 800 ms after. ([11], Ch. 8)

On occasion, epoching is used in non-ERP studies as well, e.g. in [12]. This is to be able to apply baseline correction to the epochs (see 2.2.5), and for an easier artefact rejection procedure (see 2.2.6).

2.2.5 Baseline correction

To remove slow drifts from the epochs, a baseline correction is usually performed after the epoching. The correction can be performed in different ways, but a common way is to take the mean of the pre-stimulus voltage and subtract the result from each point in the epoch. The slow drifts are the same that are mentioned in 2.2.1, where high-pass filters are used to remove slow drifts. Luck ([11], Ch. 8) promotes using an explicit baseline correction in addition to a high-pass filter, arguing that filtering alone can cause differences across conditions.

2.2.6 Artefact rejection

Artefact detection and rejection are necessary parts of an EEG study. As has already been mentioned, artefacts in the EEG can be caused by either biological disturbances, or by equipment and environment. It has already been discussed in 2.2.3 that ICA can be used to correct the EEG data for e.g. eye blinks.

In addition to this, the data can be visually inspected, and artefacts can be manually removed. This can be done either on the continuous data, or on the epoched data. Periods of data in the EEG signal which are dominated by e.g. muscle signals are simply removed. If performing the artefact rejection on epoched data, epochs which are contaminated by artefacts are rejected as a whole. Along with a
(a) Eye movement and blinks in EEG channels. Eye blinks are visible at all channels at time stamps ~ 126, 127, 128 and 129.5. A horizontal movement is visible right before 128.

(b) Eye movement and blinks in ICA components. Eye blinks are visible in component 3 at time stamps ~ 126, 127, 128 and 129.5. A horizontal movement is visible in component 6 right before 128.

(c) ICA components scalp map. Components 3 and 6 has primarily anterior weight distribution, which corresponds to activity in the front at the skull.

*Figure 2.5:* ICA components and how the components relate to the EEG data.
visual inspection, an automated artefact detection can be used. Luck ([11], Ch. 8) advocates using a moving window peak-to-peak amplitude method, where a window of e.g. 200 ms is moved across the epoch, and the peak-to-peak amplitude is calculated. If the peak-to-peak amplitude at any point in the epoch exceeds a set threshold, the epoch is marked for rejection. Luck argues that using this method in favour of e.g. measuring the absolute voltage of the epoch is preferable, as it will only mark sudden changes (such as eye movements) as artefacts, and not falsely mark e.g. slow drifts.

2.3 Cognitive workload and EEG

Cognitive workload is a complex subject. Kantowitz et al. [21] described it as a variable that varies depending on the environmental demands, i.e. task difficulty, and the cognitive ability of the person that is performing the task. That is, the level of cognitive workload is dependent not only on the difficulty of the task, but also on the cognitive capacity of the subject. A difficult task is likely to cause a greater cognitive workload than a more simple task, but how much greater it is differs from person to person. This is a notion to keep in mind, as it greatly impacts the way one can try to measure cognitive workload.

There has been a large number of EEG studies that aim to measure the cognitive workload with people performing a variety of tasks. When performing EEG measurements of cognitive workload, one usually sets up an experiment where the subject are asked to perform a certain task while the EEG is being measured. The task is to be designed in such a way that it imposes a certain cognitive load. The evaluation of the workload of the task(s) can be performed either by event-related potentials (ERP) (e.g. [9], [22], [19]), or by frequency-based analysis (e.g. [23], [24]). A combination of the two can also be applied, see e.g. [4] and [3].

This section aims to describe some general experiment paradigms, as well as previous work, mostly focused on ERP paradigms.

2.3.1 Single- and dual-task paradigms

The paradigms can be either single-task, for example playing a computer game (e.g. [25], [26], [4]), or dual-task. When using single-task paradigms, the level of difficulty is varied and the ERP components from each level are analysed. In dual-task paradigms, the subjects are required to carry out two tasks simultaneously. An example of this is dual-task walking experiments where the subjects carry out a primary, cognitive task of some sort (e.g. detecting visual stimuli) while walking or sitting. The tasks can be varied in regard to difficulty (in this case the difficulty of the visual task), or varied in conditions (in this case walking or sitting). Comparisons can be made both between the levels of difficulty and between the conditions. [3], [5]
2.3 Cognitive workload and EEG

![Diagram of attentional reserve](image)

**Figure 2.6:** The attentional reserve is divided between the task and the stimulus. When the difficulty of the task increases, the attention to the stimulus is decreased.

### 2.3.2 Attentional reserve

ERP studies have been used to evaluate mental workload for several decades (e.g. Wickens et al. in 1983 [27] and Israel et al. in 1980 [28]). The typical method for evaluating workload using ERP is letting the subjects carry out a task while probes (i.e. stimuli, e.g. visual or auditory), are presented randomly in order to elicit a response. This method is based on the idea that conclusions regarding the cognitive workload can be drawn from measurements of what is often referred to as attentional reserve (e.g. [3], [19]). This stems from the very intuitive notion that when a person is attending to a task, a certain amount of their cognitive resources is used for that particular task. Consequently, the amount of spare cognitive resources, or attentional reserve, that is left to perform other task is dependent on the difficulty of the first task, see figure 2.6. That is, a very simple task that is not cognitively demanding will leave much attentional reserve which can be used for other simultaneous tasks. [27], [9] For example, imagine a person doodling while listening to a lecture. Doodling is not a particularly demanding task, and the person can without any difficulties listen to the lecture at the same time. If the person instead of doodling was trying to solve a complicated mathematical equation, the cognitive resources left to spend on listening to the lecture would be significantly lessened. This concept is the basis of using ERP paradigms to evaluate cognitive workload.

The ERPs are created by probing the subjects while they are performing a task, and the cognitive resources that are spent on the stimuli would inversely reflect the resources that are spent on the task. That is, the amplitude of the ERP components would be dampened when the difficulty of the task increases.

The general ERP paradigm that is presented in the literature is the following: A subject is instructed to carry out one or more tasks which are considered to impose a cognitive strain. While the subject is performing the task(s), EEG is recorded and the subject is probed repeatedly with some sort of stimuli. The difficulty of the task(s) is varied, and ERPs from the EEG are extracted. If the difficulty variation causes a change in cognitive load, this is reflected in the ERPs. While this is the general method used in ERP studies on mental load, there exist several variations of the implementation.
**2.3.3 ERP paradigms**

When using an ERP paradigm, some sort of stimuli is required.

The probing of the stimuli varies. Some studies employ visual stimuli (e.g. [29], [30]), whereas other use somatosensory stimuli (e.g. [31]). It seems reasonable to assume that one concern regarding the use of visual stimuli is that there is a risk that the stimuli are undetected by the subject, and therefore does not trigger a brain activity response. Moreover, it could be speculated that adding visual stimuli to a visual task would cause changes to the task. Similarly, using somatosensory stimuli together with a task that involves some sort of touch could possibly change the task. With these speculations in mind, this thesis will henceforth focus on auditory stimuli. This is also due to the fact that auditory stimuli are commonly used in scientific studies on cognitive workload (e.g. [9], [22], [6]).

As mentioned previously (2.3.3), there are plenty of variation of ERP studies. Stimuli can either be presented as part in the task, or irrelevant to the task.

Firstly, when a single-task paradigm is employed, and the task involves stimuli inherently, using the first approach is natural. Brouwer et al. [29] performed a study using the n-back test, where letters are presented on a screen and the subject is required to indicate when the letter is the same as the one n letters before. In this case, the target letters are used as ERP stimuli, which are naturally included in the task. However, unless the single task is not designed in such a way that the stimuli are inherently present, this approach is not applicable.

Additionally, there is the approach to present stimuli that are irrelevant to one task, but involved in a second task where the subject are asked to address the stimuli. This approach has commonly been used in what is referred to as an oddball task. In an oddball task, non-frequent target and frequent non-target stimuli are presented to the subject which is asked to notify whenever a target, i.e. an oddball, appears. For example, Song et al. [30] used the oddball paradigm when studying mental workload related to flight tasks, where the pilots were required to carry out a complex flight simulation. In addition, visual stimuli in forms of red and green light signals where shown on the experiment interface. The subjects where required to ignore the green signals (non-targets) and to press a button whenever a red signal (target) was shown. Similarly, Ullsperger et al. [22] presented auditory stimuli of different sorts in a study were the subjects where asked to count the target stimuli.

Kramer et al. [32] claimed, based on the results of an EEG study on dual-task integrality, that the addition of a secondary task might change the recruitment of cognitive resources to the primary task. However, it was shown that this also depends on how the tasks are correlated. Given this, issues regarding dual-tasks arise from the fact that it is difficult to identify how a primary task is correlated to an oddball task, especially where complex primary tasks are employed. Nevertheless, dual-task paradigms are utilised frequently in the literature. One explanation to this could be that for cases where the primary task is very simple and/or repetitive, the subject might become bored or stop paying attention to the
task. In such experiments a secondary task would likely be more beneficial than disadvantageous.

Secondly, an approach where the stimuli are ignored can be used. Allison and Polich [26] presented a study where subjects viewing or playing a video game of varying difficulties were probed with pure tones (1000 Hz) and asked either to count them or to ignore them. Their findings suggested that the probes elicited ERPs even when ignored, and changes in the ERPs (P2, N2, P3) were detected between the view condition and the play condition. However, the ERPs changed little in regard to changes in difficulties in the game. Ullsperger et al. [22] conducted a study where the subjects were probed either with pure tones or with novel sounds (various computer edited sounds). Based on their results, Ullsperger et al. suggested that the novel sounds were more robust in eliciting ERPs (P3 component). In the study, the subjects performed different tasks but the levels of difficulty were not varied. Miller et al. [9] combined the two aforementioned studies and conducted a study where the subjects were playing Tetris® while being probed with novel, complex sounds (e.g. a dog barking or a person coughing). In their study, the N1, P2, P3 and late positive potential (LPP) component amplitudes were found to change in relation to the difficulty of the game. Dyke et al. [33] supported this in a similar study but with different types of task-irrelevant sounds (repeated simple sounds, novel simple sounds, repeated complex sounds and novel complex sounds). Their results suggested that novel complex sounds were most effective in indexing cognitive workload.

In contrast to these studies, Debener et al. ([20]) showed in an auditory oddball study that both task-irrelevant and task-relevant stimuli were successful in eliciting the P3 component. Subjects were probed with three types of stimuli: 80 % pure tones of either 350 or 650 Hz (standard), 10 % pure tones of either 350 or 650 Hz (deviant), and 10 % of the same novel, complex sounds that Miller et al. ([9]) employed. The 350 Hz tones and the 650 Hz tones were either used as standard stimuli or as deviant stimuli, and the assignment of them was counterbalanced across subjects. One subject group were required to count the deviant tones, and second group were asked to count the novel sounds. In addition, their results suggest that the novel, complex sounds were most robust in eliciting ERPs, similarly to Dyke et al. [33].

Several studies using the auditory probing technique presented by Miller et al. [9] have been done ([3], [5], [4], [6]). This technique is relatively simple and appears to be quite robust in indexing variations of cognitive workload. Combining this technique with the oddball approach of Debener et al. could be an appropriate way to take advantage of the benefits with the novel, complex stimuli while using a secondary task.

### 2.4 Summary of related work

In order to enable comparison, and to summarise results from related studies, this section will give a short summary of a few related studies that are of a par-
ticular relevance to this thesis. Electrode sites of interest, the employed stimuli, 
ERP components of interest, and bandwidths of interest are presented in a table 
for each study.

### 2.4.1 A novel approach to the physiological measurement of 
mental workload

As previously discussed in 2.3.3, Miller et al. [9] combined two previous studies 
in an Tetris®-experiment with three levels of difficulty (view, easy, and hard). 
Novel, complex sounds were used as stimuli. The results suggested that novel, 
complex sounds were effective in eliciting ERPs. This was later supported by a 
study by Dyke et al. [33]. Post hoc analyses showed that the amplitudes of the 
N1 component (Cz) and the P2 component (Fz, Cz, and Pz) were reduced for 
the hard condition compared to the view and easy conditions. It is particularly 
interesting that the results showed that the amplitudes of the ERP components P3 
and LPP were reduced gradually in regard to the difficulty (view > easy > hard), 
at electrode site Pz.

#### Table 2.3: Miller et al. [9] - Tetris®

<table>
<thead>
<tr>
<th>Electrode sites of interest (ERP)</th>
<th>Fz, Cz, Pz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimuli</td>
<td>Task-irrelevant novel auditory stimuli [34]</td>
</tr>
<tr>
<td>ERP components of interest</td>
<td>N1, P2, P3, LPP</td>
</tr>
<tr>
<td>Bandwidths of interest</td>
<td>-</td>
</tr>
</tbody>
</table>

### 2.4.2 Measurement of attentional reserve and mental effort for 
cognitive workload assessment under various task 
demands during dual-task walking

Shaw et al. [3] performed a dual-task study where a cognitive task of two different 
levels of difficulty was performed under two different conditions; walking and 
sitting.

P3 was reduced for all electrode sites for the harder level of the cognitive task. 
Post-hoc analyses showed that the N1 amplitude was reduced for walking compared to 
sitting (Fz and Cz), and P3 was reduced for walking compared to sitting (Cz and Pz).

Theta power increased, and high-alpha power decreased during walking. Post-
hoc analysis showed that high-alpha power decreased for the hard task compared 
to the easy task.
2.4 Summary of related work

### Table 2.4: Shaw et al. [3] - Sitting/walking

<table>
<thead>
<tr>
<th>Electrode sites of interest (ERP)</th>
<th>Fz, FCz, Cz, Pz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimuli</td>
<td>Task-irrelevant novel auditory stimuli [34]</td>
</tr>
<tr>
<td>ERP components of interest</td>
<td>N1, P2, P3</td>
</tr>
<tr>
<td>Bandwidths of interest</td>
<td>T, lA, hA, B (14–30 Hz) and G (36–44 Hz). Frontal theta/parietal alpha ratio power</td>
</tr>
<tr>
<td></td>
<td>Frontal theta/frontal alpha ratio</td>
</tr>
</tbody>
</table>

#### 2.4.3 Combined assessment of attentional reserve and cognitive-motor effort under various levels of challenge with a dry EEG system

Gentili et al. [4] conducted a study where subjects were asked to play a computer game (Tetris®), with varying levels of difficulty (easy, medium, hard).

Post-hoc analysis showed that the P3 amplitude (FCz electrode) decreased during the hard level compared to the easy and medium levels.

Theta power increased during the hard level compared to the easy and medium levels. Post-hoc analysis showed that high-alpha power decreased during hard level compared to the easy level (Fz), and progressively decreased when difficulty increased from easy to medium to hard level (Pz). Post-hoc analysis showed that the theta/alpha ratio increased during medium and hard level compared to the easy level (Fz, FCz, Cz), and progressively increased when difficulty increased from easy to medium to hard level (Pz).

### Table 2.5: Gentili et al. [4] - Tetris®

<table>
<thead>
<tr>
<th>Electrode sites of interest (ERP)</th>
<th>Fz, FCz, Cz, Pz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimuli</td>
<td>Task-irrelevant novel auditory stimuli [34]</td>
</tr>
<tr>
<td>ERP components of interest</td>
<td>P3</td>
</tr>
<tr>
<td>Bandwidths of interest</td>
<td>T, lA, hA, T/A ratio</td>
</tr>
</tbody>
</table>

#### 2.4.4 A simple ERP method for quantitative analysis of cognitive workload in myoelectric prosthesis control and human-machine interaction

EEG studies on cognitive workload during hand-motor tasks are few, and EEG studies on cognitive workload during prosthesis control task even fewer. Deeny et al. [6] conducted an ERP study comparing the cognitive workload with (able-bodied) subjects controlling a virtual upper-limb under different conditions. The virtual arm was controlled myoelectrically, and subjects were asked to perform
three different tasks; viewing the arm move (view), moving the arm in 1 DOF (easy), and moving the arm in 3 DOF (hard). The subjects performed the tasks under two different conditions of control; direct control, and pattern recognition control.

P2 (Fz, Cz, Pz), P3 (Pz), and LPP (Pz) showed significant difference between the different levels of difficulty (view, easy, and hard).

Only LPP (Pz) showed a significant difference between the two different control conditions, and only in the hard task (moving the arm in 3 DOF). It should also be noted that no correction for multiple comparisons was conducted.

**Table 2.6: Deeny et al. [6] - Virtual limb control**

<table>
<thead>
<tr>
<th>Electrode sites of interest (ERP)</th>
<th>Fz, Cz, Pz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimuli</td>
<td>Task-irrelevant novel auditory stimuli [34]</td>
</tr>
<tr>
<td>ERP components of interest</td>
<td>N1, P2, P3, LPP</td>
</tr>
<tr>
<td>Bandwidths of interest</td>
<td>-</td>
</tr>
</tbody>
</table>

**2.4.5 Psychophysiological support of increasing attentional reserve during the development of a motor skill**

Rietschel et al. [19] conducted a study comparing the attentional reserve with subjects performing a reaching task under two different visual conditions (visual distortion and no visual distortion).

The P3 component decreased when attentional demands were increased. Furthermore, the P3 component increased when learning progressed, showing that more attention was spared after a learning period.

**Table 2.7: Rietschel et al. [19] - Reaching task with visual distortion**

<table>
<thead>
<tr>
<th>Electrode sites of interest (ERP)</th>
<th>Fz, Cz, Pz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimuli</td>
<td>Task-irrelevant novel auditory stimuli [34]</td>
</tr>
<tr>
<td>ERP components of interest</td>
<td>N1, P2, P3</td>
</tr>
<tr>
<td>Bandwidths of interest</td>
<td>-</td>
</tr>
</tbody>
</table>

**2.4.6 What is novel in the novelty oddball paradigm? Functional significance of the novelty P3 event-related potential as revealed by independent component analysis**

As mentioned in 2.3.3, Debener et al. [20] employed a dual-task paradigm in a study comparing task-relevant and task-irrelevant stimuli, as well as novel com-
plex sounds and pure tones. Three different types of stimuli were played; 80% pure tones of 350 or 650 Hz (standard), 10% tones of 350 or 650 Hz (deviant), and 10% of the same novel, complex sounds that Miller et al. ([9]) employed. The frequency of the deviant sound (350 or 650 Hz) was counterbalanced across subjects. The subjects were divided into two groups, where one group was asked to silently count the novel complex sounds, and the other group was asked to count the pure tones. Comparisons were made between counting and ignoring, and between the novel sounds and the pure tones.

The results showed that the amplitudes of P3 components elicited by the task-relevant stimuli (novel sounds) were larger than those elicited by task-irrelevant (novel sounds). In addition, it was found that the novel sounds were more robust in eliciting the ERP than the pure tones.

*Table 2.8: Debener et al. [20] - Task relevance vs. irrelevance + novel sounds vs. pure tones.*

<table>
<thead>
<tr>
<th>Electrode sites of interest (ERP)</th>
<th>- (10-20 system was not used)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimuli</td>
<td>Task-irrelevant novel auditory stimuli [34] or pure tones of either 350 or 650 Hz.</td>
</tr>
<tr>
<td>ERP components of interest</td>
<td>N1, P1, P2, P3</td>
</tr>
<tr>
<td>Bandwidths of interest</td>
<td>-</td>
</tr>
</tbody>
</table>
Experimental setup

The methodology can be divided into three phases; developing the experimental setup, running the finalised version of the experiment, and analysing the data. It should be noted that the focus of this thesis was the development of the methods; therefore, the methods include not only the finalised version of the experimental setup and analysis, but also previous iterations.

The subjects are referred to as either H (for “Healthy”) or A (for “Amputee”), together with a number. In total, the experiment was run six times with different subjects (referred to as H1, H2, H3, H4, H5, A1) to test the procedures, see table 3.1. Of these six tests, the EEG data from three subjects (A1, H4 and H5) were used in the data analysis. Subjects H4 and H5 (both intact-limb) were included primarily to test the experimental setup and the analysis methods. A1 (subject with an upper-limb transhumeral amputation, and an osseointegrated prosthesis) was the main focus of the analysis. See 3.1 for the final experimental setup. Changes in the experimental setup were made between H1, H2, H3, and the finalised version, see 3.2. The finalised version was used for A1, H4, and H5.

The finalised version of the experimental setup will be described first (3.1), and thereafter the iterations of previous versions will be presented (3.2).

3.1 Final experimental setup

The finalised version of the experimental setup was used for the last three subjects. The protocol for the experiment is presented in appendix A.
### 3.1 Experimental setup

#### Table 3.1: The subjects and the iterations of the experiments.

<table>
<thead>
<tr>
<th>Subject no.</th>
<th>Type</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>Intact-limb</td>
<td>Test run of a first version of the experiment.</td>
</tr>
<tr>
<td>H2</td>
<td>Intact-limb</td>
<td>Test run with a revised version of the auditory stimuli. No grasping task.</td>
</tr>
<tr>
<td>H3</td>
<td>Intact-limb</td>
<td>Test run with the second version of the experiment.</td>
</tr>
<tr>
<td>A1</td>
<td>Upper-limb transhumeral amputation</td>
<td>Test run with the finalised version of the experiment.</td>
</tr>
<tr>
<td>H4</td>
<td>Intact-limb</td>
<td>Test run with the finalised version of the experiment.</td>
</tr>
<tr>
<td>H5</td>
<td>Intact-limb</td>
<td>Test run with the finalised version of the experiment.</td>
</tr>
</tbody>
</table>

#### 3.1.1 Equipment

- Biosignal amplifier (g.HIamp Research Edition, g.tec Medical Engineering GmbH, Austria)
- EEG cap with active electrodes (g.GAMMAcap + g.SCARABEO active electrodes, g.tec Medical Engineering GmbH, Austria)
- Trigger pulse box, used to time-lock the stimuli (g.TRIGbox, g.tec Medical Engineering GmbH, Austria)
- Magnetic force cube, see 3.1.4 and figure 3.2
- Magnetic boards, see 3.1.4 and figure 3.3
- Laptop for the audio
- Digitizing scanner, used for electrode digitization (Polaris® Krios System, NDI, Canada)

The experiment was divided into two trials for the intact-limb subjects H4 and H5 (no grasping task + grasping task), and three trials for subject A1 (no grasping task + grasping task with sensory feedback + without sensory feedback). Each trial was in turn divided into three blocks of 4 min, with breaks in between to let the subject rest. The breaks lasted for at least 1 minute, but the subjects were asked to decide themselves when they felt ready to continue.

For each trial, the subjects were seated in a comfortable chair in front of a table. In order to minimise the effects of the surrounding, the room was quiet, and no other people than the subject and the experiment leaders were in the room.
3.1.2 Data acquisition

EEG data were recorded continuously during the experiment. Data were recorded from 124 sites (according to an extended 10-20 system, see figure 3.1), 4 EOG electrodes (left and right of both eyes + above and under left eye), and from both earlobes for offline re-referencing. Common ground was AFz, and all impedances were kept below 100 kΩ. Specifically, the impedances for electrodes Fz, FCz, Cz, and Pz (which were later used in the analysis) were kept below 30 kΩ. No online reference or online filters were used.

Auditory stimuli were time-locked to the EEG data using g.TRIGbox.

Localisation of the electrodes was performed using the NDI Polaris® Krios System. This was later used for the ICA analysis.

Figure 3.1: The placement of the electrodes in the extended 10-20 system (g.GAMMAcap, image received via e-mail from g.tec Medical Engineering GmbH, Austria).

3.1.3 Auditory stimuli and oddball task

A combined version of the stimuli used by Miller et al. [9] and the oddball task used by Debener et al. [20] was created. The occurrence frequencies of the frequent and rare tones were chosen based on a study by Ullsperger et al. [22].

During the task, three different types of auditory stimuli were presented:

- 80% Frequent: 1000 Hz tones, 400 ms
- 10% Rare: 2000 Hz tones, 400 ms
- 10% Novel: complex, novel tones, ~ 300-400 ms [34]

The novel sounds were randomly chosen from a selection of 95 audio clips. Each novel sound was only played once in each trial.
Interstimulus intervals were varied between 960 and 1360 ms (as in [20] and [14]) and the total number of stimuli for each trial was varied between 600 and 720, which ensured at least 60 novel stimuli per trial. The total number of stimuli was varied in between trials and subjects in order to be able to keep the ratio between the different types of stimuli (80/10/10 %) while still being able to have different amounts of the rare tones. The interval lengths, the number of stimuli, and the order of the stimuli were pseudorandomised for each trial using MATLAB. The stimuli were divided into three blocks, with each block containing the same total number of stimuli but with varied interstimulus intervals and different number of frequent, rare, and novel tones.

The subjects were asked to count the rare tones (2000 Hz), and report the number at the end of each block.

The novel sounds were used to elicit ERPs, whereas the frequent and rare tones were only used for the oddball task. This is discussed further in 3.2.

Each block started and ended with three short tones.

The speaker was placed in front of the subject, and the distance to the subject and the volume level were set the same for all subjects. Before beginning the experiment, the different types of audio clips were played for the subject.

### 3.1.4 Grasping task

The purpose of the experiment was to compare differences in the EEG data when a subject was performing a motor task under different conditions.

The grasping task involved moving a small, magnetic cube from one magnetic board to another. The cube is designed to light up in red if it is pressed too hard. Similar objects were used in a study by Clemente et al. [35] (and later in a similar study by Mastinu et al. [2]), where subjects were required to move plastic blocks with a magnetic latching mechanism between the walls. Pressing the blocks too hard, thus exceeding a set threshold of the magnetic fuse, caused the blocks to break.

The cube used for this thesis project was designed and built by a visiting researcher at BNL, and is meant to simulate a fragile object such as an egg or a grape. Early discussions about the grasping task involved picking grapes from a bunch, similarly to a study by Anderson et al. [36], where the functional performance of a subject implanted with a nerve cuff electrode was tested by letting the subject pull stems from cherries. The transferring of the magnetic cube is meant to simulate that type of grasping task. The force required to break the cube was measured to ~ 14 N, and the force required to lift the cube from the magnetic boards was measured to ~ 6 N.

The instructions for the grasping task differed for the intact-limb subjects and the amputee. This was because the force required to break the cube, as well as the magnetic force that attached the cube to the board, were the same for all subjects. These forces were adjusted based on the sensitivity of the sensory
3.1 Final experimental setup

Figure 3.2: The magnetic cube.

feedback of the prosthesis controlled by subject A1. The forces were adjusted such that it would be a challenge to move the cube without breaking it, when using a prosthesis. However, to move it with a biological limb the level of force was not challenging, and it was very easy to transfer the cube without breaking it. Nevertheless, the intact-limb subjects were asked to perform the grasping task with the same settings of the cube in order to collect data under the same conditions as for subject A1.

A1 was asked to transfer the cube as fast as possible between the boards without ”breaking” the cube, i.e. without the cube lighting up. A square was painted on each of the boards and the subject was asked to place the cube in the square. Between each transfer, the subject was asked to touch a mark between the boards. This was to ensure that the subject fully let go of the cube in between each transfer. The subject was instructed to release the cube and start over with the transfer if the cube lit up. See figure 3.3 for the experimental setup.

For A1, the number of transfers, as well as the number of times the cube was dropped or broken, were reported.

The intact-limb subjects (H4 and H5) were given similar instructions, but were not asked to transfer the cube as fast as possible. Instead, they were asked to transfer the cube in a calm, comfortable manner. As previously mentioned, it was extremely easy to move the cube with a biological limb. Thus, moving it as fast as possible would present only a physical challenge, which was not the intention with the experiment. More importantly, the quick motions would cause unnecessary movement of the EEG electrodes, contaminating the collected data.

3.1.5 Self-report questionnaire

After each trial, the subjects were asked to complete a self-report questionnaire used to estimate cognitive workload, see appendix B. The questions in the questionnaire were taken from the National Aeronautics and Space Administration
Experimental setup

Figure 3.3: The finalised version of the setup of the grasping task. N.B. The barriers in front of and between the boards were not used.

Task Load Index (NASA TLX), which is a self-report questionnaire specifically designed to assess workload. [37], [38] The NASA TLX is commonly used to assess self-perceived workload in studies. More specifically, there are several examples of studies employing the questionnaire in motor task studies, see e.g. [39], [40], [41]

The questionnaire contains six questions, where the subject is asked to rate their perceived level of mental, physical, and temporal task demands, as well as, effort, frustration, and self-perceived level of performance, on a scale from 1 to 21. It should be noted, that to properly employ the NASA TLX questionnaire, the subjects are required to complete a workload weighting sheet in addition to rating the demands. This was not used for the experiments in this thesis, and the scores on the self-questionnaires were only used as an indication of the self-perceived workload.

3.1.6 Trials

Two and three trials were run for the intact-limb subjects and the amputee, respectively. During each trial, the auditory stimuli were played in blocks of three. The subjects were asked to quietly count the number of rare tones and to report the number in the end of each block.

The entire experiment is presented in figure 3.4

Trial 1: No grasping task

The first trial was used as a control trial. The subjects were seated and asked to focus their gaze on a white plus sign showed on a black computer screen.

Trial 2: Grasping task with sensory feedback

For the second trial, the subjects were asked to perform the grasping task.
3.2 Test iterations

Before the finalised version was determined, the experiment was run three times with different subjects (H1, H2, and H3). The results from these test runs were not included in the analysis. The iterations are presented below.

3.2.1 Subject H1

Subject H1 (intact-limb) participated in a first version of the experiment. For this version, only one board, placed vertically rather than horizontally, was used. The subject was asked to remove the cube from the board, put it back and release it, and then repeat. A horizontal placement was found to be more suitable because vertical placement required walls to place the board, which might cause problems if the experiment would have to take place at another location. Furthermore, it was decided that two boards were preferable to only one board, as it is more natural to transfer an object rather than picking it up and placing it back. This was another reason to place the boards horizontally, as it would require a
very unnatural movement to move the cube from left to right if the boards were placed vertically.

The pressing force of the cube was significantly lower than the one used in the finalised version. Furthermore, the grasping task was performed in an additional trial, where the hands were obscured partially by a piece of frosted plexiglass in order to decrease the visual feedback. However, the plexiglass slightly obstructed the movement, and it was decided that it was not necessary to include it in the experiment.

Moreover, the auditory stimuli contained only the novel, complex tones, and the subject was instructed to ignore them. This was in line with the studies of e.g. Miller et al. [9] and Deeny et al. [6]. Although these kinds of single-task paradigms appear to work well, it was decided to add an oddball task in addition to the grasping task. The reason for this was that the grasping task was repetitive, which raised concerns that the subjects might become bored and lose focus. Luck ([42]) stresses the importance of keeping the subjects alert, saying "If they are unmotivated or become bored, they may not pay close attention to their performance, weakening your effects. Moreover, bored subjects tend to become tense and uncomfortable, leading to muscle noise and movement artifacts.". On account of this, in conjunction with the many examples of dual-task paradigms (e.g. [41] and [3]) and oddball tasks (e.g. [43] and [44]) in the literature, the auditory oddball task was added.

### 3.2.2 Subject H2

Subject H2 participated in a version of experiment used to try out the auditory oddball task, and to collect data for testing of the signal processing methods. The oddball task was the same as the one used in the finalised version.

### 3.2.3 Subject H3

The experiment in which subject H3 participated in employed the same setup and paradigms as the finalised version, but with the one difference that a barrier was placed in between the boards. This was to make the experiment as similar as possible between subjects, by ensuring that a subject could not rest their arm on the table. However, when later trying this setup with subject A1 it was found that the barrier made it uncomfortable to use the prosthesis. Therefore, the barrier was removed from the finalised version of the experimental setup.
All comparisons between results were made between trials, but within subjects, on account of the small group of subjects.

4.1 Pre-processing

All pre-processing of the data was made using EEGLAB Toolbox [45], which is a MATLAB [46] toolbox specifically designed for processing of EEG data.

Because the trials were divided into blocks of three, so was the EEG data. Therefore, it was necessary to merge the data before any pre-processing was performed. It should be noted that this should not cause any concerns since no epochs were extracted from the data until at least 5 seconds into each block (see 4.2), and the frequency analysis was made based on data from the middle of each block (see 4.3).

As stated in 3.1.2, data were acquired from a total of 128 channels (plus reference sites and ground). However, this was because data were simultaneously collected for another project, which uses 128 channels. Therefore, only the first 64 channels (including EOG channels) were selected and re-referenced to the average of the earlobes. This reference was chosen based on the recommendations from Luck ([11], Ch. 5) to chose a reference site that (1) is convenient and comfortable, (2) is not biased toward a hemisphere, (3) does not introduce too much noise to the data, and (4) is not nearby sites of specific interest in the study (in this case the mid-line of the scalp).

The data were baseline corrected by removing the channel means from the continuous data.
The steps of the pre-processing are presented in figure 4.1.

4.1.1 Filtering

The data were high-pass filtered at 0.1 Hz and low-pass filtered at 40 Hz. A Blackman windowed sinc FIR filter was used, of 66000 points for the high-pass filter and 1320 points for the low-pass filter, respectively.

The Blackman window was chosen in favour of EEGLABs default filter which uses a Hamming window. This decision was based on the results from a study by Diana et al. [47], where different types of windows were compared based on the outcome of EEG filtering. The Blackman window gave the best outcome based on stop-band attenuation, transition bandwidth, and cutoff frequency measurements, compared to a Hamming, a Hann, and a Rectangular window.

4.1.2 Artefact correction

ICA was run and the results were visually inspected. Any ICA components which were evaluated to be corresponding to non-cortical activity (such as eye blinks) were removed from the EEG signal, according to the process described in 2.2.3.

4.2 ERP analysis

The ERP analysis was made using ERPLAB Toolbox [48], which is an open source MATLAB [46] toolbox, tightly integrated with EEGLAB Toolbox [45], and specifically designed for analysis of ERP data. The steps of the ERP analysis are presented in figure 4.2.

Epochs were extracted in regards to the novel, complex sound stimuli, starting from -200 ms pre-stimulus to 700 ms post-stimulus. This range was chosen by considering the length of the interstimulus intervals (960-1360 ms), trying to avoid any overlap. The epochs were baseline corrected using the mean of the 200 ms pre-stimulus. A moving window peak-to-peak amplitude algorithm (as recommended by Luck [11], Ch. 6) was applied, using a 100 ms window, and a rejection amplitude of 100 µV. Any epochs marked for rejection by the algorithm were removed. To include the same number of epochs from each trial, the 55 first accepted epochs from each trial were selected and averaged together. It has been shown that the P3 amplitude stabilises after 20 epochs, and changes very little after 30 epochs. [49] Thus, 55 epochs were considered plenty to produce a stable ERP.

The mean amplitude for ERP components P3 and LPP at electrode site Pz were
4.3 Spectral analysis

Prior to the frequency analysis, 1 minute data from each block in each trial was extracted, starting at 1 minute from the first stimulus. The extracted data were merged, meaning that for each trial, a total of 3 minutes of data were used.

The power spectral density of the data was estimated for electrode sites Fz, FCz, Cz, and Pz, using Welch’s method (see e.g. [50]). The window size was set to 2400 points (based on the sampling rate), with no overlap between segments. 1 Hz resolution was achieved, and the power was summed across the frequency bands specified in table 2.2 (theta, low-alpha, and high-alpha). The power was summed over the four electrodes sites.

In addition, the frontal theta/parietal alpha ratio was calculated by dividing the theta power at Fz with the sum of the low- and high- alpha power at site Pz. This because the frontal theta/parietal ratio has been shown to be a robust index of cognitive workload. [4], [3], [12], [5], [51]

All bandpowers were natural log transformed prior to analysis. The steps of the spectral analysis are presented in figure 4.3.
4.4 Performance results

For all subjects (i.e. A1, H4, and H5), the performance on the oddball task was reported. For subject A1, the performance on the grasping task was also reported.

4.4.1 Oddball task performance

For each block in the trials, the absolute difference between the reported number and the correct number of oddballs was calculated. The differences were summed across each trial.

As an example, assume that a trial contained 700 stimuli (10% rare tones) in total, with the rare tones (the oddballs) divided as 23, 17, and 20. Assume that the subject reported 21, 18, and 20, at the end of block 1, 2, and 3, respectively. The absolute difference for each block would be 2, 1, and 0, and the final reported number would be 3 (2 + 1 + 0).

4.4.2 Grasping task performance

For subject A1, the number of transfers, as well as the number of times the cube was dropped or broken, were reported. The numbers were summed over the blocks.

Because the length of each trial differed slightly (see 3.1.3), the rate was calculated as transfers/minute, dropped/minute, and broken/minute.

4.5 Self-report questionnaire

The total score from the self-report questionnaire, described in 3.1.5, were summed for each trial. The possible score range was 6-126 (6x1 – 6x21).
In this chapter, the results from the experiments with subject A1, H4, and H5 are presented. The results from each trial and subject are presented.

For subject H4 and H5, the trials are divided into ‘No task’ (i.e. the trial with only the oddball task and not the grasping task) and ‘Task’ (i.e. the trial with the oddball task + the grasping task). Because subjects H4 and H5 performed the trials under the same conditions, the results from the trials with H4 and H5 are presented together in the same table. This to enable an easier comparison between these results. However, the results from the ERP analysis and the spectral analysis are plotted in separate figures.

For subject A1 the trials are divided into ‘No task’ (i.e. the trial with only the oddball task), ‘With sensory feedback’ (i.e. the trial with the oddball task + the grasping task, performed with sensory feedback), and ‘Without sensory feedback’ (i.e. the trial with the oddball task + the grasping task, performed without sensory feedback).

It should be noted that because the variation between subjects is very large, the scale of the bar graphs varies between subjects.

The ERP results as well as the spectral analysis results are presented both in tables and in plots. In addition, the ERP waveforms for each subject and condition are plotted. The tables include the following:

- **ERP**
  - P3 mean amplitude at electrode site Pz.
  - LPP mean amplitude at electrode site Pz.
• **Bandpower**
  
  – Theta power, natural log transformed (Fz + FCz + Cz + Pz).
  
  – Low-alpha power, natural log transformed (Fz + FCz + Cz + Pz)
  
  – High-alpha power, natural log transformed (Fz + FCz + Cz + Pz)
  
  – Frontal theta/parietal alpha ratio, natural log transformed (Theta Fz/(Low-alpha+high-alpha Pz))

• **Oddball task performance**, as described in 4.4.1.

• **Grasping task performance**, as described in 4.4.2. This result was only reported for subject A1.

• **Self-report score**, as described in 4.5.

### 5.1 Subject A1

In this section, the result from the experiment with subject A1 is presented.

*Table 5.1: Subject A1: Results. (Note: s.f. = sensory feedback.)*

<table>
<thead>
<tr>
<th></th>
<th>ERP</th>
<th>Bandpower</th>
<th>Performance oddball</th>
<th>Performance cube</th>
<th>Self-report</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P3 [µV]</td>
<td>No task</td>
<td>With s.f.</td>
<td>Without s.f.</td>
<td>No task</td>
</tr>
<tr>
<td></td>
<td>LPP [µV]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ERP</strong></td>
<td></td>
<td>1.9</td>
<td>1.5</td>
<td>0.18</td>
<td>0</td>
</tr>
<tr>
<td><strong>Bandpower</strong></td>
<td></td>
<td>0.71</td>
<td>1.1</td>
<td>0.64</td>
<td>0</td>
</tr>
<tr>
<td><strong>Theta</strong> [ln(µV^2)]</td>
<td></td>
<td>3.9</td>
<td>3.7</td>
<td>3.8</td>
<td>0</td>
</tr>
<tr>
<td><strong>Low-alpha</strong> [ln(µV^2)]</td>
<td></td>
<td>5.5</td>
<td>3.7</td>
<td>4.2</td>
<td>0</td>
</tr>
<tr>
<td><strong>High-alpha</strong> [ln(µV^2)]</td>
<td></td>
<td>4.4</td>
<td>3.5</td>
<td>3.3</td>
<td>0</td>
</tr>
<tr>
<td><strong>Theta/alpha</strong> [ln(µV^2)]</td>
<td></td>
<td>−1.9</td>
<td>−0.57</td>
<td>−0.72</td>
<td>0</td>
</tr>
<tr>
<td><strong>Performance oddball</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Diff.</strong> (reported-correct)</td>
<td></td>
<td>0</td>
<td>7</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td><strong>Performance cube</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Transfers/min</strong></td>
<td></td>
<td></td>
<td>3.9</td>
<td>1.8</td>
<td>0</td>
</tr>
<tr>
<td><strong>Broken/min</strong></td>
<td></td>
<td></td>
<td>3.8</td>
<td>6.4</td>
<td>0</td>
</tr>
<tr>
<td><strong>Dropped/min</strong></td>
<td></td>
<td></td>
<td>1.2</td>
<td>2.9</td>
<td>0</td>
</tr>
<tr>
<td><strong>Self-report</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NASA-TLX rating</strong></td>
<td></td>
<td>12</td>
<td>51</td>
<td>61</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 5.1: Subject A1: ERP amplitudes

Figure 5.2: Subject A1: Bandpowers
5.2 Subjects H4 and H5

Note that the results from the trials with H4 and H5 are presented in the same table, but in separate figures.

Table 5.2: Subjects H4 and H5: Results

<table>
<thead>
<tr>
<th>ERP</th>
<th>H4</th>
<th>H5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No task</td>
<td>Task</td>
</tr>
<tr>
<td>P3 [µV]</td>
<td>2.1</td>
<td>0.98</td>
</tr>
<tr>
<td>LPP [µV]</td>
<td>1.1</td>
<td>0.80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bandpower</th>
<th>H4</th>
<th>H5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No task</td>
<td>Task</td>
</tr>
<tr>
<td>Theta [ln(µV²)]</td>
<td>2.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Low-alpha [ln(µV²)]</td>
<td>2.6</td>
<td>1.9</td>
</tr>
<tr>
<td>High-alpha [ln(µV²)]</td>
<td>2.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Theta/alpha [ln(µV²)]</td>
<td>−0.29</td>
<td>0.42</td>
</tr>
</tbody>
</table>

| Performance oddball | H4                     | H5                     |
|                     | No task | Task | No task | Task |
| Diff. (reported-correct) | 0       | 2    | 0       | 2    |

<table>
<thead>
<tr>
<th>Self-report</th>
<th>H4</th>
<th>H5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No task</td>
<td>Task</td>
</tr>
<tr>
<td>NASA-TLX rating</td>
<td>32</td>
<td>36</td>
</tr>
</tbody>
</table>
5.2 Subjects H4 and H5

**Figure 5.4:** Subject H4: ERP amplitudes

**Figure 5.5:** Subject H4: Bandpowers
Figure 5.6: Subject H4: Waveforms of the averaged ERPs at Pz. The P3 and the LPP latencies are marked in grey (see table 2.1 for specific latencies). N.B., the ERP waveforms were low-pass filtered at 15 Hz prior to plotting.

Figure 5.7: Subject H5: ERP amplitudes
Figure 5.8: Subject H5: Bandpowers

Figure 5.9: Subject H5: Waveforms of the averaged ERPs at Pz. The P3 and the LPP latencies are marked in grey (see table 2.1 for specific latencies). N.B., the ERP waveforms were low-pass filtered at 15 Hz prior to plotting.
6.1 Experimental setup

In this section, the methods regarding the development and execution of the experimental setup will be discussed.

6.1.1 Grasping task

On the whole, the design of the grasping task was satisfactory. It was a difficult, yet not an impossible, task to perform for subject A1, and it could be considered to provide an adequate level of workload. However, it is possible that a simpler version of the task would have been sufficient. To simplify the set up of the task, the magnets could be removed and the level of force required to "break" the cube could be lowered. By lowering this level, the task would be challenging even without the magnetic boards. In this case, the grasping task would consist of transferring the block between two spots, perhaps over a barrier, as in previously mentioned studies by Clemente et al. [35] and Mastinu et al. [2]. Although this might have been a simpler setup, the similarity to grasping tasks such as picking grapes from a bunch, or cherries from their stems, would have been lost. For the intact-limb subjects, the grasping task was not challenging, and it was only used to add a second task in order to test the methods. For subject H3, a similar cube but with a lower threshold was used. This made the grasping task slightly more challenging for intact-limb subjects, and it is possible that it might have been better to use said cube also for subject H4 and H5.

6.1.2 Oddball task

The oddball task was added rather late in the development of the experiment. As discussed in 3.2.1, the oddball task was added (1) on account of concerns that the
subject would become bored and lose focus, due to the repetitive nature of the grasping task, and (2) in order to increase the overall imposed workload of the experiment.

However, when the decision to add the oddball task was made, the grasping task had only been tested using intact-limb volunteers. As previously stated, the grasping task was easy for intact-limb subjects to perform, even when using the cube with the lower threshold. The level of difficulty was much higher for subject A1, and it could be argued that the oddball task was unnecessary. Removing it would make experimental paradigm more simple.

Furthermore, it is difficult to assess if the oddball task affected the performance of the grasping task for subject A1. As mentioned 2.3.3, it has been shown that adding a secondary task changes the way the neural resources are distributed to the primary task (dual-task integrality). [32] Speculating, there is a possibility that when the combination of the double task becomes more difficult, the subject chooses, consciously or subconsciously, to focus more on one task than the other.

Regarding the experiment in this thesis project, it is conceivable that if a subject controlling a prosthesis becomes frustrated with the grasping task, they would focus more on the oddball task, which could affect the results. Although this could be a concern, it also has to be taken into account that only using the grasping task might not introduce a workload big enough to be able to impact the EEG results.

6.2 Analysis

6.2.1 ERP

As explained in 4.2, the ERP latencies were chosen based on a study by Miller et al. [9], which is briefly presented in 2.4.1. Miller et al. employed the same novel, complex stimuli which were used to create the averaged ERPs in this work. Although the choice to base the latencies on a previous similar study was made according to the recommendations of Luck ([11], Ch. 9), there are other approaches, and changing the latencies would of course change the mean amplitudes. For instance, several studies use an approach where the grand average of all ERPs is calculated, and a narrow time window is centred around the maximal amplitude of each component. In fact, this is the approach used by Miller et al. in the study which was used as basis for the latency selection in this thesis.

A visual inspection of the ERPs in the result section (5) shows that the P3 and the LPP amplitudes seem to coincide quite well with the used latencies (290-320 ms and 570-610 ms, respectively). For both subject H4 and subject H5, and both conditions, there are prominent positive peaks around 300 ms, which coincide with the specified latencies for the P3 components. Additionally, there are positive peaks at around 600 ms, especially for subject H5, which correspond to the latencies for the LPP components. As for subject A1, the peaks are not as prominent. However, for ‘With sensory feedback’ and ‘Without sensory feedback’, there appears to be positive increases around the specified latencies, albeit very small
increases.

In contrast, looking at e.g. the N1 component (140-160 ms), it appears to differ between subjects. Although this component was not studied in this thesis, it does raise concern that the choice of latencies perhaps was not well suited, and thought has been given as to whether or not it would have been more suitable to use the grand average to choose the latencies. Luck ([11], Ch. 9) advises against this approach, stating that "because we are choosing the measurement on the basis of the data, we are biased to find a significant difference even if there is no true difference...". The data from this thesis work are too limited for a statistical analysis, meaning that the reasoning of Luck is not directly applicable to the results. Nonetheless, the objective of the thesis work is to establish methods for a larger study, and hence the same concerns need to be taken into account.

In conclusion, there are pros and cons of each approach, and it is necessary to keep this in mind when choosing the latencies.

### 6.3 Results

It is necessary to emphasise that no statistical conclusions can be drawn from the results. Comparisons are only made within subjects, and the results can only be used to assess the methods.

In this section, the results from the intact-limb subjects (H4 and H5) will be discussed first. The performance result and the self-report score are indicators of whether or not there was an increase in cognitive workload when the grasping task was added to the oddball task.

Continuing, the results from subject A1 will be discussed.

#### 6.3.1 Subject H4 and H5 (intact-limb)

As discussed in 6.1.1, the approach to use the same settings on the cube for all subjects entailed that the grasping task was not challenging for the intact-limb subjects. Some issues with this approach were encountered, primarily the issue that the tasks were not equal between subjects H4 and H5. Subject H4 performed the grasping task in a calm manner, whereas subject H5 misunderstood the instructions to do so, and instead attempted to transfer the cube as fast as possible. This brought on two concerns. Firstly, the quick motions caused an excess of motion artefacts in the EEG, which might have influenced the results. Secondly, this meant that the increased level of difficulty which the introduction of the grasping task entailed, was greater for subject H5 than for H4. Due to this, H5 made several mistakes in the grasping task. It is likely that this also influenced the performance of the oddball task. Supporting this, the self-report score for ‘No Task’ differed very little between subject H4 and H5 (32 and 27, respectively), whereas subject H4 scored much lowered on ‘Task’ than H5 (36 and 68, respectively).

The self-report rating increased between ‘No task’ and ‘Task’ for both subject H4 and H5.
and H5, although the increase was minor for H4. The results indicate that it was perceived to be more difficult to perform the oddball task when simultaneously performing the grasping task. This is also supported by the results of the oddball task performance, which were better for both subjects in 'No task', compared to 'Task'. Together, this indicates that the cognitive workload was increased when introducing the grasping task.

Previous studies show that the amplitudes of the P3 and the LPP components decrease when the workload increases (see e.g. [9], [6], [3] which are all presented in 2.4). An indication of increased workload based on the self-report scores and the performance results should therefore be expected to be mirrored inversely in the amplitude of the ERP components. Both the P3 and the LPP amplitudes were lower for 'Task' than for 'No task', for both subjects (see figures 5.5 and 5.8). In conjunction with the self-report scores, as well as the oddball task performance results, this indicates that these components were successful in showing changes in attentional reserve.

For both subjects, the theta power differed very little in between 'No task' and 'Task'. Puma et al. [52] states in literature review on theta power variations that although there has been many studies using theta power as a marker for cognitive workload, it has often failed to be efficient in doing so. This is in line with some of the findings from the literature review of this thesis, where there are examples of theta power failing to assess changes in cognitive workload. [53], [14], [12]. However, there are also examples of studies which successfully show that theta power changes according to the level of difficulty. [4], [54], [5], [31]

For H4, both the low-alpha and the high-alpha power decreased for 'Task', compared to 'No task'. However, for H5 they increased. The literature shows that alpha power in general decreases when the workload increases. [52], [12], [54], [3], [5], [4], [31]

The theta/alpha ratio increased for 'Task', compared to 'No task', for both subjects. This is in line with the literature, where frontal theta/parietal alpha ratio often has been showed to be sensitive to changes in cognitive workload, see 4.3.

### 6.3.2 Subject A1 (amputee)

The self-report score for subject A1 showed an increasing level of perceived workload, from 'No task' to 'With sensory feedback' to 'Without sensory feedback'. The difference between 'No task' and 'With sensory feedback' was much larger than the difference between 'With sensory feedback' and 'Without sensory feedback'. Furthermore, the performance of the oddball task decreased between the trials. Looking at the performance of the grasping task, all three measurements (transfers, broken, and dropped) showed that the subject performed better in the trial with sensory feedback compared to the trial with sensory feedback. These results indicate that the sensory feedback reduced the workload for subject A1.

The ERP waveform for 'No task' for subject A1 5.3 is overpowered by a frequency of around 10 Hz - the alpha frequency. The alpha wave increases e.g. when a
subject is tired or have their eyes closed. It can also be very prominent in some people even when they are alert. ([11], Ch. 6) Because this only occurred during the 'No task'-trial, a likely explanation is that the subject was very relaxed during this trial. Because of the contamination of the alpha frequency, the results from the 'No task'-trial should be interpreted very cautiously.

The P3 amplitude was gradually lower between trials 'No task', 'With sensory feedback', and 'Without sensory feedback'. The LPP amplitude was lower for 'Without sensory feedback', than for 'With sensory feedback'. However, it was lower for 'No task' than for 'With sensory feedback'. The difference between 'With sensory feedback' and 'Without sensory feedback' is of most interest. The fact that both the P3 amplitude and the LPP amplitude were lower for 'Without sensory feedback' compared to 'With sensory feedback' indicates that the cognitive workload was higher during the trial with condition 'Without sensory feedback'.

Comparing these results to the results from H4 and H5, there are clear similarities. The P3 and the LPP amplitudes for H4 and H5 were lower for 'Task' compared to 'No task', indicating an increased level of workload, as did the performance results and the self-report scores. Similarly, the performance results and the self-report scores for A1 indicate an increased level of workload from 'With sensory feedback' to 'Without sensory feedback', while at the same time the P3 and LPP amplitudes were lower.

The theta power was almost the same for all three trial, similar to the results from subject H4 and H5. Both the low- and the high- alpha power were higher for 'No task' compared to the other trial, but differed very little in between 'With sensory feedback' and 'Without sensory feedback'. The theta/alpha ratio was higher for 'With sensory feedback' and 'Without sensory feedback' compared to 'No task', but differed very little in between. It is possible that the spectral analysis method is not sensitive enough to detect the change in the cognitive workload between the grasping task trials.

### 6.4 Conclusion and future work

The results from the experiments suggest that the combined methods could be used to compare the cognitive workload with prosthetic users in a larger trial. For a larger trial, the self-report questionnaire should be employed with the weighting sheet. Moreover, a more thorough investigation of the choice of ERP component latencies should be performed. It might also be beneficial to choose fewer measurements, e.g. the P3 and LPP ERP components (Pz), the frontal theta/parietal alpha ratio, the self-report score, and a summation of the performance result. Furthermore, there is a possibility that the workload is lessened when learning progresses, meaning that the workload might change not only due to the conditions but also due to if the subject has performed the task previously. In the study by Rietschel et al. [19], presented in 2.4.5, it was found not only that the P3 amplitude decreased when the attentional demand was increased,
but also that it increased when learning progressed. Therefore, the order of the conditions ('No task', 'With sensory feedback', and 'Without sensory feedback') should be counterbalanced between subjects.

In a larger trial with several subjects, the ERPs should be calculated for each subject and condition, as was done in this thesis. The ERPs for each condition should then be averaged across the entire subject group. That is, there would be one ERP per condition. Similarly, for the spectral analysis, the power should be calculated for each subject and condition, and then the average for each condition should be calculated.

The proposed methods in this thesis could also be applied to other aspects of prosthetic usage, e.g. different types of control systems.

Looking at the problem formulation presented in 1.2, it can be concluded that they have been answered, considering the limitations presented in 1.3. Several methods of evaluation of cognitive workload using EEG are presented in 2.3. Continuing, the methodology in this thesis work presents an application of these methods that, in combination with the motor task, can be used in an experiment that aims to evaluate cognitive workload with upper-limb prosthetic users.

The question if the proposed methodology can in fact be used to show a difference in cognitive workload when a person is performing a task with and without sensory feedback cannot be answered within the scope of this thesis work. However, although the subject group is very limited, the results do indicate that the methods could be used to show a difference.
Appendix
Experiment protocol
Experiment protocol

Before participant arrives

- Set up EEG equipment. Connect all cables.
- Plug in g.TRIGbox to g.HIamp and laptop.
- Connect the Krios
- Open audio script. Set search path. Run it to make sure it is working correctly. Set speaker levels.
- Set up whiteboards and eggs and barrier.
- Set up camera.
- Make sure there are enough copies of the self-report, and a pen.
- Prepare two copies of informed consent: one for the patient to keep and one with the signature to give to Maria
- Prepare Photo agreement to obtain permission to take picture from the patient.
- Open the picture of the cross on the laptop.
- Prep syringes.
- Take out shampoo and a clean towel.

Before trials

- Fill in demographics – name, date of birth, sex, handedness, amputation side, if they have any issues with motor function in the arm
- Inform the participant about the purpose of the study, possible risks etc.
- Make the participant sign the case report form.
- Ask participant to sign photo agreement.
- Fit the participant with cap.
  - Insert gel into electrodes 1-62 (61, 62, 34, and 26 excluded), plus 63 and 64 at ear lobes. Check impedances. Add eye electrodes, insert gel, and check impedances.
  - Take a screenshot of the impedance page.
  - Take pictures of the patient fitted with the cap from different angles. Channel numbers should be visible.
  - Check signal.
- Make sure electrode cables are not covering the electrodes. Do electrode digitization with Krios.
- Make sure the participant is sitting comfortably and can reach everything.
- Make sure the participant can hear the audio.
- Instruct the participant of the task
  - Explain the grasping task.
  - Emphasise that it is more important not to drop or break the eggs, than to do the task quickly.
  - Explain that the task is divided into 3 blocks, of ~5 minutes each. Explain that there will be a 1 minute break in between each block.
  - Inform the participant of the audio stimuli. Play one of each type of stimuli. Instruct the participant to count the high pitch tones.
Inform the participant that a sound will be played at the beginning and end of each block.

Inform the participant that they will be asked to fill out a self-assessment questionnaire after each trial.

Show the questionnaire and explain the questions and how it is to be filled out.

Explain that the first trial will be without the grasping task, and the second one will be with the grasping task (or the other way around).

**Without task**

- Place the laptop with the image of the cross in front of the patient.
- Ask the participant to begin task. At the same time, start audio script.
- At the end of each block, tell the participant that there will be a 1 minute break.
- When 1 minute has passed, tell the participant that the next block will start.
- Start audio script. Start the EEG recording: at the start correctly name the file with patient name and birthday. Avoid ÅÖÄ characters in the names.
- When all blocks are finished, stop the EEG recording.
- Ask the participant to fill out the questionnaire.

**With task**

*The same procedure is used for both conditions (with sensory feedback and without).*

- Start the camera.
- Start recording.
- Ask the participant to begin task. At the same time, start audio script.
- At the end of each block, tell the participant that there will be a 1 minute break.
- When 1 minute has passed, tell the participant that the next block will start.
- Start audio script.
- When all blocks are finished, stop the EEG recording and the camera.
- Ask the participant to fill out the questionnaire.

Take at least one picture during a fake trial asking the patient to pretend to do the task. It is important not to do it during the trial in order not to make weird noise that might generate ERP similar to the ones generated following the auditory probes.

**Total time:**  12 min/task = 24 minutes

break + questionnaire = 10 minutes.

Fitting of the EEG cap = 30 minutes

Explaining the task = 10 minutes

With buffer -> 2 hours.

(Setting up: 45 minutes. Cleaning: 30 minutes. Total time about 3 hours)
Self-report questionnaire - NASA TLX
How mentally demanding was the task?

Very low               Very high

How physically demanding was the task?

Very low               Very high

How hurried or rushed was the pace of the task?

Very low               Very high

How successful were you in accomplishing what you were asked to do?

Perfect               Failure

How hard did you have to work to accomplish your level of performance?

Very low               Very high

How insecure, discouraged, irritated, stressed and annoyed were you?

Very low               Very high


[31] S. Mun, M. Whang, S. Park, and M. C. Park, “Effects of mental workload on


Index

EEG
  abbreviation, ix
EMG
  abbreviation, ix
EOG
  abbreviation, ix
ERP
  abbreviation, ix
FIR
  abbreviation, ix
ICA
  abbreviation, ix
IIR
  abbreviation, ix