BEYOND THE STATE OF THE ART,TOWARDS INTUITIVE AND RELIABLE NON-VISUAL BRAIN-COMPUTER-INTERFACING

ENTWICKLUNG INTUITIVER UND ZUVERLÄSSIGER NICHT-VISUELLER GEHIRN-COMPUTER-SCHNITTSTELLEN

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Die Kraft der Gedanken ist unsichtbar
wie der Same, aus dem ein riesiger Baum erwächst;
sie ist aber der Ursprung für die sichtbaren
Veränderungen
im Leben des Menschen.

— Leo Tolstoi

Dedicated to our family

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ABSTRACT

For the present work three main goals were formulated:

GOAL 1 To design a tactile BCI used for mobility which is intuitive *(G1.1)*, reliable and fast while being usable by participants aged 50 years and above.

GOAL 2 To design an auditory BCI used for communication which is intuitive and reliable.

GOAL 3 To examine the effects of training on tactile and auditory BCI performance.

Three studies were performed to achieve these goals. In the first study nine participants aged above 50 years performed a five-session training after which eight participants were able to navigate a virtual wheelchair with mean accuracy above 95% and an ITR above 20 bits / min. In the second study 15 participants, four of them end-users with motor-impairment, were able to communicate meaningful with high accuracies using an auditory BCI. In the third study nine healthy and nine visually impaired participants (regarded as sensory experts for non-visual perception) performed tactile, auditory and visual (for healthy participants only) copy tasks. Participants with trained perception significantly outperformed control participants for tactile but not for auditory performance. Tactile performance of sensory experts was on equal levels as the visual performance of control participants.

We were able to demonstrate viability of intuitive gaze-independent tactile and auditory BCI. Our tactile BCI performed on levels similar to those of visual BCI, outperforming current tactile BCI protocols. Furthermore, we were able to demonstrate significant beneficial effect of training on tactile BCI performance. Our results demonstrate previously untapped potential for tactile BCI and avenues for future research in the field of gaze-independent BCI.

ZUSAMMENFASSUNG

Im Rahmen der vorliegenden Arbeit wurden folgende drei Hauptziele formuliert:

ZIEL 1 Entwicklung eines taktilen Mobilitäts-BCIs, das sowohl intuitiv, zuverlässig und schnell als auch von Personen älter als 50 Jahre verlässlich benutzt werden kann..

ZIEL 2 Entwicklung eines auditorischen Kommunikations-BCIs, das intuitiv und zuverlässig sein soll.

ZIEL 3 Untersuchung des Effekts von sensorischem Training auf die Leistung bei Verwendung eines BCIs.

Um die genannten Ziele zu erreichen, wurden drei Studien durchgeführt. In der ersten Studie absolvierten neun Teilnehmer älter als 50 Jahre ein BCI-Training, das fünf Sitzungen umfasste. Nach Abschluss des Trainings konnten acht Teilnehmer einen virtuellen Rollstuhl mit mittleren Genauigkeiten von über 95% und einer ITR über 20 bits / min steuern. In der zweiten Studie waren insgesamt 15 Teilnehmer, davon vier End-Nutzer mit motorischen Einschränkungen, in der Lage, bedeutungsvoll und mit hohen Genauigkeiten mittels unseres BCIs zu kommunizieren. An der dritten Studie nahmen neun sehende und neun blinde (sensorische Experten für nicht visuelle Wahrnehmung) Versuchspersonen teil und absolvierten taktile, auditorische und visuelle (nur für sehende Teilnehmer) Copy-Aufgaben. Verglichen mit den Sehenden waren die sensorische Experten signifikant besser in der taktilen,

jedoch nicht in der auditiven Modalität. Leistungen von Blinden in der taktilen Modalität waren gleich gut wie die von Sehenden in der visuellen Modalität.

Zusammenfassend konnte im Rahmen der Arbeit gezeigt werden, dass intuitive blickunabhängige taktile und auditorische BCI eine gültige Alternative zu bestehenden visuellen BCI darstellen. Mit dem vorgestellten taktilen BCI konnten Leistungen erbracht werden, die mit denen visueller BCIs vergleichbar sind. Zusätzlich wurde ein signifikant positiver Einfluss von Training auf die taktile Leistungsfähigkeit gezeigt. Zusammenfassend kann gesagt werden, dass die im Rahmen dieser Arbeit gewonnenen Erkenntnisse bisher ungenutzes Potenzial für taktile BCI aufzeigen und wertvolle Ansätze für zukünftige Forschung liefern.

PUBLICATIONS

- **The WIN-Speller: A new Intuitive Auditory Brain-Computer Interface Spelling Application** - *Sonja Kleih, Andreas Herweg, Tobias Kaufmann, Pit Staiger-Sälzer, Natascha Gerstner, Andrea Kübler* - Frontiers in Neuroscience - 2015

- **Successful wheelchair control in a virtual environment with a brain-computer interface (BCI) and tactile stimulation** - *Andreas Herweg, Julian Gutzeit, Sonja Kleih, Andrea Kübler* - in prep.

- **BCI performance of sensory experts** - *Andreas Herweg, Sonja Kleih, Andrea Kübler* - in prep.

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ACRONYMS

BCI	Brain-Computer-Interfaces
ITR	Information-transfer-rate
SMR	Sensory motor rhythm
BOLD	Blood oxygene level-dependent
EEG	Electroencephalogram
ERP	Event-related potential
LIS	Locked-in-syndrome
SCP	Slow cortical potentials
SSEP	Steady-state evoked potentials
SSVEP	Steady-state visual-evoked potentials
SSSEP	Steady-state somatosensory-evoked potentials
SSAEP	Steady-state auditory-evoked potentials
SWLDA	Stepwise linear discriminant analysis
ALS	Amyotrophic lateral sclerosis
SMA	Spinal muscular atrophy

Part I

THE LOCKED-IN-SYNDROME

Brain-Computer-Interfaces aim to provide a communication or control channel which is independent of motor control. One central focus is users suffering from the locked-in-syndrome, a rare condition in which patients are paralyzed while retaining their consciousness. The following chapter deals with the locked-in-syndrome and its causes.

1

THE LOCKED-IN-SYNDROME

The locked-in-syndrome (LIS) (Plum & Posner, 1966), is defined by a loss of motor function with preserved higher cortical functions, leading to a person with working consciousness inside a paralysed body (Bauer et al., 1979). It can be classified into three different subtypes (Bauer et al., 1979):

- Total locked-in-syndrome, no residual motor functions exist
- Classical locked-in-syndrome, only vertical eye movement is preserved
- Incomplete locked-in-syndrome, additional residual motorfunctions are preserved.

The locked-in-syndrome can be caused by neurodegenerative diseases such as amyotrophic lateral sclerosis (ALS) or spinal muscular atrophy (SMA), brainstem stroke or traumatic brain injury (for review see Bruno et al., 2009; Laureys et al., 2005).

1.1 AMYOTROPHIC LATERAL SCLEROSIS (ALS)

Amyotrophic lateral sclerosis (ALS) was first described by Charcot (1869) and causes degeneration of higher motor neurons along the motor cortex as well as of lower motor neurons along the brainstem and spinal cord (for review see Kiernan et al., 2011).

The incidence rate of ALS in Europe has been reported as 2.16 cases in 100.000 per year (Logroscino et al., 2010) and men are more often affected than women (Logroscino et al., 2010; Mitchell & Borasio, 2007). These incidence rates are similar to US estimates (McGuire et al., 1996). Prevalence for ALS in the USA is about 6 of 100.000 (Mitchell & Borasio, 2007). According to a meta-analysis by Byrne and colleagues (2011) only 5.1% can be related to genetical preposition, therefore most cases are diagnosed as sporadic disease onset (Kunst, 2004). Symptoms of sporadic and inherited cases are clinically indistinguishable (for review see Hand & Rouleau, 2002).

Mean age of disease onset was found to be 56 years of age (Hudson, 1981) and 50% of patients die within 30 to 36 months after first symptoms (for review see Mitchell & Borasio, 2007; Talbot, 2009). Nevertheless, for some cases symptoms have been reported as stable for 10 years and more (Bach, 1993).

Dependent on primary affected region four subtypes have been defined (for review see Mitchell & Borasio, 2007):

- Bulbar: dysarthria (impaired speech), dysphagia (impaired chewing and swallowing)
- Cervical: impairment in upper-limb extremities
- Lumbar: impairment in lower limb extremities
- Thoracic: impairment in respiration.

Cervical and lumbar subtypes account for 70% of all onset occurances, bulbar subtype accounts for 25% and thoracic for less than 5% of cases (Kiernan et al., 2011).

While symptoms and order of appearance differ depending on subtype, a number of symptoms are typical for all subtypes such as: muscular atrophy, muscle fasciculation, cramps or spasms, dysartria, dysphagia and dyspnea and malnutrition (for review see Borasio et al., 2001). Malnutrition which is often related to dysphagia and increased respiratory effort can be counteracted by artificial nutrition via percutaneous endoscopic gastrostomy (PEG).

Most patients die due to respiratory failure (Hardiman et al., 2011). Artificial non-invasive ventilation is commonly used with onset of respiratory problems, prolonging life and relieving symptoms (Radunovic et al., 2009). For later stages of disease progression only invasive mechanical ventilation is feasible (Hardiman et al., 2011). At this point patients need to decide if this life-sustaining treatment is desired. Due to tracheotomy communication abilities are severely restricted under mechanical ventilation (Dengler et al., 1999). Despite these factors depression is only diagnosed in a minority of cases (Kurt et al., 2007).

1.2 BRAINSTEM STROKE

Brainstem stroke is the most common cause for locked-in-syndrome. Interruption of blood flow in the vertebral arteries can result in a stroke in pons, medulla oblongata and mid-brain (Grehl & Reinhardt, 2008).

Bogousslavsky and colleagues (1988) reported 48% of all vertebrobasilar strokes to affect the brainstem, 27% the pons, 14% the medulla oblongata and 7% the midbrain. Caplan and colleagues (2004) reported embolism as the source for 40-54% and stenosis of an artery leading to ischemia as the source for 32-35% of all occurances. Outcomes of such a stroke were reported to be major disabilities for 18%, minor disabilities for 51% and no disabilities for 28% of all cases (Glass et al., 2002). A high disability stroke can reduce residual motor capabilities to vertical eye movement only, resulting in locked-in-syndrome (Bauer et al., 1979; Smith & Delargy, 2005; Voltz et al., 2004).

Part II

BRAIN-COMPUTER-INTERFACES

While treatment and assistive technology for locked-in patients improve, deteriorating communication still remains a major concern (Dollfus et al., 1990). Brain-Computer-Interfaces (BCI) provide a muscle-independent communication channel by translating brain signals into commands used for control of assistive technology. In the following chapter recording techniques, brain responses and stimulus modalities used in BCI are examined. Additionally, the effects of age and training on BCI performance and the need for an user-centered approach are discussed.

2

BRAIN-COMPUTER-INTERFACES

For Brain-Computer-Interface (BCI) control an adequate brain signal needs to be recordable, features need to be extracted, classified and translated into commands, see Figure 1. To evaluate such a system some key variables should be examined:

- Accuracy is the ratio of commands correctly identified by the BCI among all commands. High reliability can only be mediated if sufficient accuracy is achieved.
- Number of classes is the number of different targets that can be chosen with each step. While communication BCI benefit from a high number of classes, some BCI applications, e.g. navigation BCI, can be achieved with lower number of classes.
- Speed of the system is defined as the required time to send a desired command. Higher speeds is generally preferable as it decreases the total time spend to achieve a specific goal. Additionally, some application might require a certain level of responsiveness to be viable, e.g. BCI for outdoor navigation.

For most BCI a balance between accuracy and speed has to be found, as recording of additional data does increase classification accuracy but also increases the required time, therefore decreasing speed. To evaluate dif-

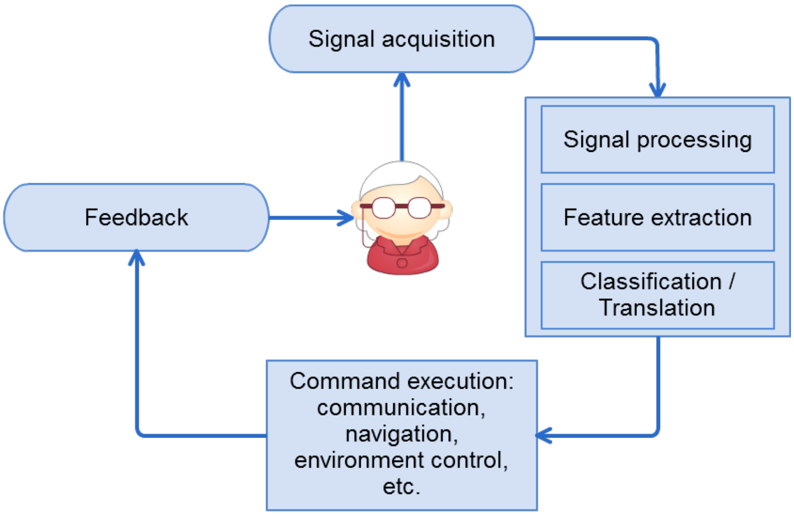


Figure 1: Overview of the closed feedback loop of BCI control.

ferent systems achieving different accuracies, speeds and number of classes, the information-transfer-rate (ITR) is calculated. Information per selection can be calculated as seen in formula 1 and can afterwards be divided by time per selection to achieve the ITR as used in this thesis.

$$B = log_2 N + P log_2 P + (1-P) log_2 (\frac{1-P}{N-1}) \tag{1}$$

While the ITR combines the most relevant information regarding BCI performance, it should not be the only evaluating factor. Kübler and colleagues (2001) found an accuracy of at least 70% to be required in order to allow meaningful communication. Therefore, a high ITR might ultimately be meaningless from an end-user point of view if no sufficient accuracy is achieved.

The following chapter examines recording methods, afterwards different signal features for BCI control are presented.

2.1 RECORDING METHODS

Usable signals for brain-computer-interfacing are commonly extracted from either hemodynamic or electrical responses.

2.1.1 *Hemodynamic recording*

Hemodynamic responses such as the blood oxygene level-dependent (BOLD) response can be used to detect neural activity. Increased neuronal activity results in increased oxygen consumption, inducing increased flow of oxygenated blood towards affected regions in the brain. Due to characteristic differences in light absorbtion and magnetism of ogygenated vs deoxygenated hemoglobin these changes in blood flow can be measured using functional near infrared spectroscopy (fNIRS) and functional magnet resonance imaging (fMRI), see Figure 2.

While BOLD responses offer good spatial resolution and reliably reflect neural activity they suffer from low temporal resolution (Ramsey, 2012). Hemodynamic responses have been used for successful BCI control, e.g. Naito and colleagues (2007) demonstrated a binary BCI achieving 80% accuracy. Furthermore, fNIRS can be utilized for hybrid BCI, i.e. systems that use more than one signal for control. Fazli and colleagues (2012) were able to increase classification accuracy from 90% - 93% by using both EEG and fNIRS data for classification. For a review on BCI using fNIRS see Sitaram et al. (2012).

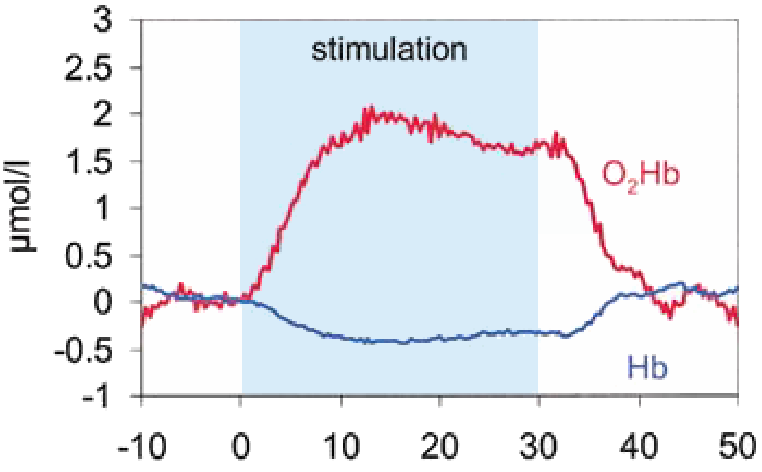


Figure 2: Mean changes of oxygenated and desoxygenated hemoglobin concentration in the visual cortex in response to repeated visual stimulation. (Modified from Wolf et al., 2002)

2.1.2 *Electrical recording*

Electrical responses, however, offer a direct representation of neural activity in real time. Using electrodes on top of the head referenced to a nearby electrode at mastoid or earlobe an electroencephalogram (EEG) can be recorded. The EEG signal represents the electrical activity of the brain along the scalp. It measures the ionic currents of groups of neurons within the brain. EEG signal quality is negatively affected by tissue between electrode and brain, but EEG can be measured using relatively cheap and easy-to-use equipment. It is the most commonly used technique for BCI research.

For an overview of hemodynamic and electrical brain recording techniques see Figure 3.

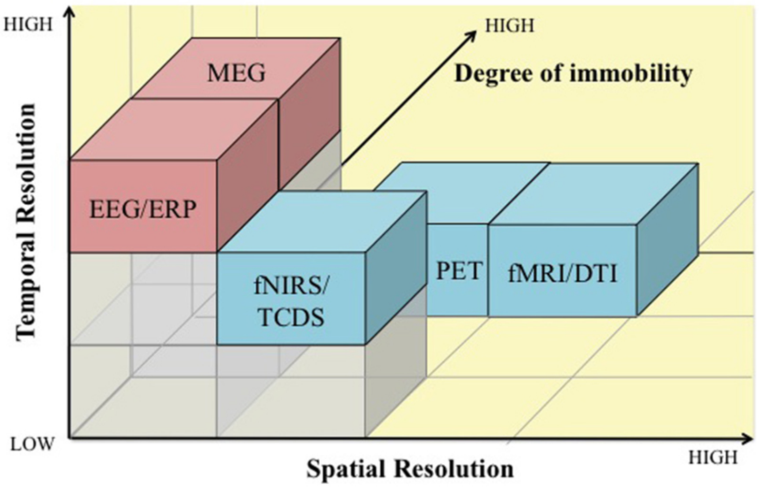


Figure 3: Overview of hemodynamic (blue) and electromagnetic (red) imaging techniques. Figure taken from Mehta & Parasuraman, (2013).

2.2 SIGNAL FEATURES

A multitude of brain-signals can be used for BCI applications. Features used for BCI control can be separated into two groups depending on how they are elicited:

Signals can be elicited without use of external stimulation, e.g. sensory motor rhythm (SMR) can be manipulated by motor imagination or slow cortical potentials (SCP) can be elicited by certain mental tasks. Reliable generation of such signals often requires training of the user.

Signals can be elicited using external stimulation. Frequently used features include steady-state evoked potentials (SSEP) as well as event-related potentials (ERPs). Most brain-Computer-Interfaces (BCI) using ERPs can be used without any prior training.

Different signal features are topic of the following chapter.

2.2.1 *Sensory motor rhythms (SMR)*

Sensory motor rhythm (SMR) describes a synchronized brain activity in the 9 to 12 Hz frequency range. These patterns can be detected above the motor cortex and are likely produced by large numbers of pyramidal neurons. SMR is most prominent when the body is at rest. Performing motor action or imagination results in a desynchronization, reducing the SMR power (Pfurtscheller & Silva, 1999, also see 4). SMR can also be suppressed by observing motor action and has, therefore, been suggested to be under influence of the mirror neuron system (Pineda, 2005). Development of the SMR during infancy and childhood has been a recent focus of research towards autism spectrum disorders which could be influenced by an altered mirror neuron system (Nyström et al., 2011; Oberman et al., 2005).

Users can learn to actively manipulate their SMR, which enables usage of SMR for BCI control. Control of the SMR does not require actual movement and can, therefore, be utilized by locked-in patients. Most trained users can use two control signals, in some cases even three (e.g. left hand, right hand, feet; McFarland et al., 2010). Most users suffer from insufficient control (Blankertz et al., 2010; Halder et al., 2011; Hammer et al., 2012). Guger and colleagues (2009) estimate the number of healthy users not able to control a SMR-BCI at all to be 30%. Only 19% are estimated to achieve high accuracy.

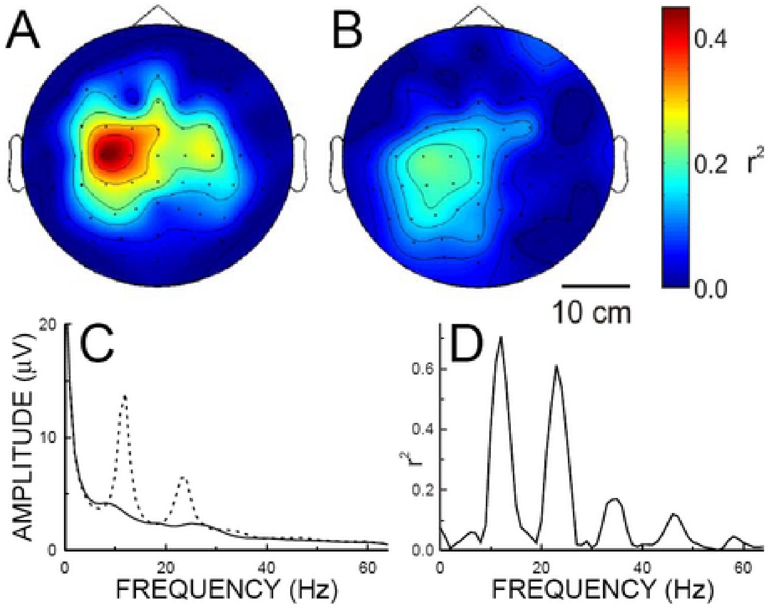


Figure 4: Movement execution (A) and movement imagination (B) of the right hand results in desynchronization within the left motorcortex. Desynchronization is stronger for actual movement than for movement imagination. Band power is high for μ (9 to 12 Hz) and β (20 to 30 Hz) rhythm (C, dashed line) for resting state and decreases with movement imagination (C, solid line). Differences between resting state and movement imagination can be classified (D). Figure taken from Schalk & Mellinger, (2010).

While required training times and low number of target classes are disadvantages of SMR-BCI, the independence of external stimuli allows for self-paced systems, enabling users to elicit control signal autonomously (Galán et al., 2008; Leeb et al., 2007). SMR-BCIs have been utilized in a number of different settings.

Millán and colleagues (2003) proposed a communication BCI allowing participants to choose between three groups of letters. By splitting the chosen group of letters into three groups after each step participants were able to select a single letter after several steps. Blankertz and colleagues (2007) demonstrated a similar approach where they grouped the alphabet into six different groups arranged in a circle around a selection cursor. Using movement imagination of right and left hand the cursor could be directed towards the desired group, allowing selection of the group letters in a second step. Galán and colleagues (2008) demonstrated a SMR-BCI intended for wheelchair control and two subjects successfully navigated a simulated route with high accuracy. Likewise, a SMR-BCI could also be used to navigate a robot within several rooms (Millan et al., 2004). Furthermore, SMR-BCI have been used for prosthetic devices (Pfurtscheller et al., 2000; Pfurtscheller et al., 2003) and stroke rehabilitation (Grosse-Wentrup et al., 2011; Pichiorri et al., 2011). SMR-BCI have been shown to be viable for users suffering from neurodegenerative diseases (Kübler et al., 2005; Neuper et al., 2003).

2.2.2 *Slow cortical potentials (SCP)*

Slow cortical potentials (SCPs) are slow direct current shifts evoked after performing an adequate mental task and last for one to ten seconds, see Figure 5. Due to the nature of slow direct current shifts they require specialized recording equipment. They originate from the thalamo-cortical system controlling cortical inhibition and excitation. Therefore, SCPs represent changes in cortical activity levels of large cell assemblies. Negative SCP shifts represent a reduction in excitation threshold and can be voluntarily evoked by concentration or movement imagination (Birbaumer et al., 1990). In line with this, negative SCP shifts have also be been observed seconds before epileptic seizures (Ikeda et al., 1996). Positive SCP shifts represent cortical inhibition and can be evoked by relaxation tasks (Birbaumer et al., 1990). Similar to SMR usage of SCPs needs to be trained before it can be used for BCI control. SCP-BCIs have successfully being utilized by healthy participants as well as ALS patients (Kübler et al., 1999). However, due to SCP being a slow binary signal it is not universally usable for all BCI application. For a review of BCIs using SCP see Allison et al. (2012).

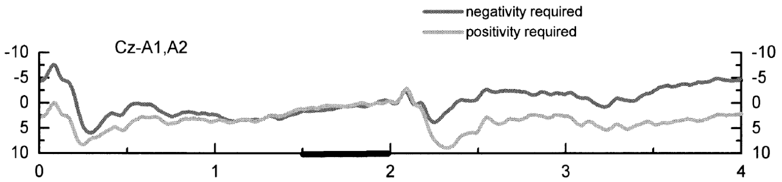


Figure 5: Average SCPs evoked by 13 healthy subjects. Baseline was recorded between seconds 1.5 and 2, brain response was regulated between seconds 2 and 4. Modified from Kübler et al., (1999).

2.2.3 *Steady-state evoked potentials (SSEP)*

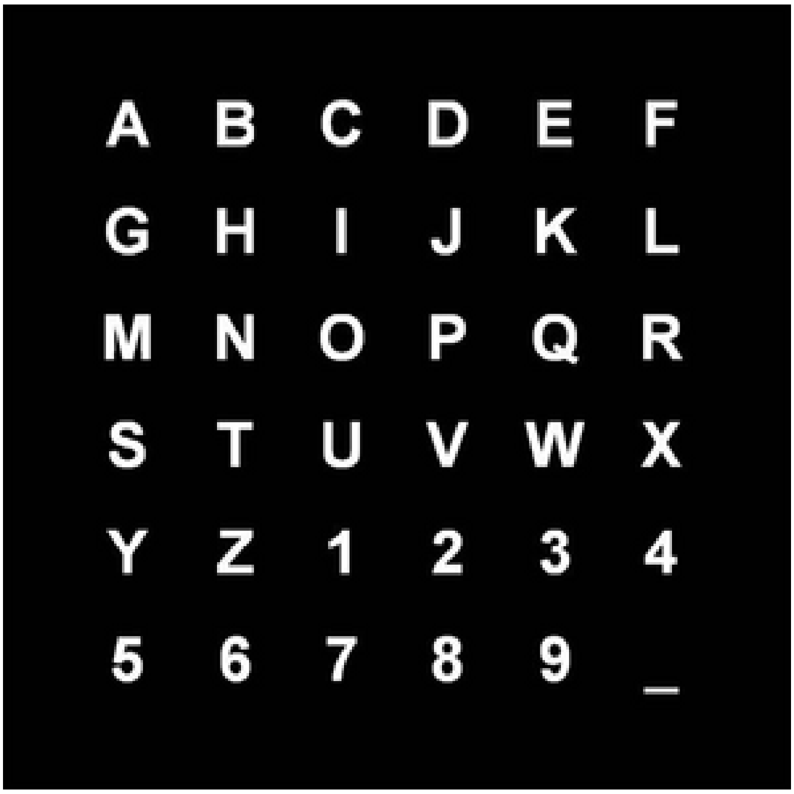
Perception of a stimulus with a fixed frequency elicits a steady-state brain response in the same frequency and its harmonics, a steady-state evoked potential (SSEP). The most commonly used steady-state evoked potentials are the steady-state visual-evoked potentials (SSVEP). Visual stimulation with a frequency ranging from 3.5 to 75 Hz elicits sensory areas of the brain in the same or a multiple of the stimulation frequency. Detection of this frequency within the brain allows determination of the frequency of the attended stimulus. By providing several stimulation frequencies and allowing users to choose which frequency they want to attend BCI control can be established. The minimum detectable difference between visual frequencies has been found to be 0.2 Hz (Gao et al., 2003). Highest SSVEP amplitudes are observed for low frequencies around 15 Hz. Nevertheless, visual stimuli in this frequency range are rarely used as they have been reported as annoying and prone to induce photo eplileptic seizures (Pastor et al., 2003). Steady-state evoked potentials (SSEPs) can also be evoked by somatosensory (SSSEP) or auditory (SSAEP) stimulation. Furthermore, SSEPs are commonly used for clinical purpose to diagnose sensory pathways. Cheng and colleagues (2002) presented a SSVEP-based BCI utilizing 13 flickering lights to input phone numbers. Eight out of 13 subjects were able to successfully call a predefined number using the BCI. Müller-Putz and colleagues (2005) demonstrated increased classification accuracy when including harmonics into classification. Chen and colleagues (2014) demonstrated viability of up to 45 different targets on a LCD monitor, achieving accuracies up to 90.2% and high ITRs above 80 bits / min. In conclusion SSVEP-based BCI are viable for a number of applications, they do, however, require intact vision. For a review of BCIs using SSVEP see Allison et al. (2012), steady-state somatosensory-evoked potentialss (SSSEPs) are discussed in chapter 2.3.3.

2.2.4 *Event-related potentials (ERP)*

Event-related potentials (ERPs) are characteristic brain responses elicited by certain stimuli (Donchin et al., 1978). ERPs can be used as a non-invasive mean to evaluate brain functions of healthy or cognitively effected individuals.

The first ERP being extensively documented and related to cognitive processes was the contingent negative variation (Walter et al., 1964). The main brain-response used for ERP-BCIs is the P300 response, first described by Sutton and colleagues (1965). ERPs are named by direction of the potentials and time of appearance, the P300 response being a positive response 300ms (200-500ms) after stimulus. The P300 response is affected by variables such as vigilance, attention, distraction, meaningfulness, discrimination and uncertainty (Chapman & Bragdon, 1964; Sutton et al., 1965). A P300 response can be reliably elicited using an oddball paradigm, an experimental setup where a relevant but infrequent stimulus is randomly presented within frequent but irrelevant stimuli (Sutton et al., 1965). The relevant stimulus, also called target for BCI purpose, will elicit the P300 response while the frequent stimulus, also called non-target, will not elicit a P300 response. Rare occurrence of target stimuli increases the amplitude of the P300 response (Gonsalvez & Polich, 2002). Low discrimination between target and non-target stimulus does decrease P300 amplitudes (Comerchero & Polich, 1999). Latency of such ERP responses are highly stable, therefore detection of a P300 response allows determination of the eliciting stimulus. The first published communication BCI utilized a P300 approach (Farwell & Donchin, 1988), see Figure 6.

P300 responses are robust and can be elicited by ALS patients (for review see Kleih et al., 2011). While the P300 is the most prominent potential involved in ERP-BCIs, other ERPs also contribute to classification in ERP-BCIs (Kaufmann et al., 2011a). By utilizing additional ERPs such as those elicited from facial recognition performance of



A	B	C	D	E	F
G	H	I	J	K	L
M	N	O	P	Q	R
S	T	U	V	W	X
Y	Z	1	2	3	4
5	6	7	8	9	_

Figure 6: Matrix used for P300 based communication BCIs. Rows and columns are randomly highlighted while ERP responses are recorded. Only rows and columns containing the focused letter will elicit P300 responses, therefore identifying the chosen letter. Figure taken from Schalk & Mellinger, (2010).

ERP-BCIs can be improved (Kaufmann et al., 2011b). Unlike SMR or SCP-BCI, the ERP-BCI can be used without previous training sessions.

A typical ERP-BCI session consists of three steps. First, a calibration run is performed. For calibration, the participant is required to focus on predefined targets. EEG signals are recorded but calculation is offline as no feedback is given. As the second step a personalized classifier using the previously recorded ERP responses is calculated. The most commonly used classifier is generated using stepwise linear discriminant analysis (SWLDA). SWLDA was found to be superior to other classifiers (Farwell &

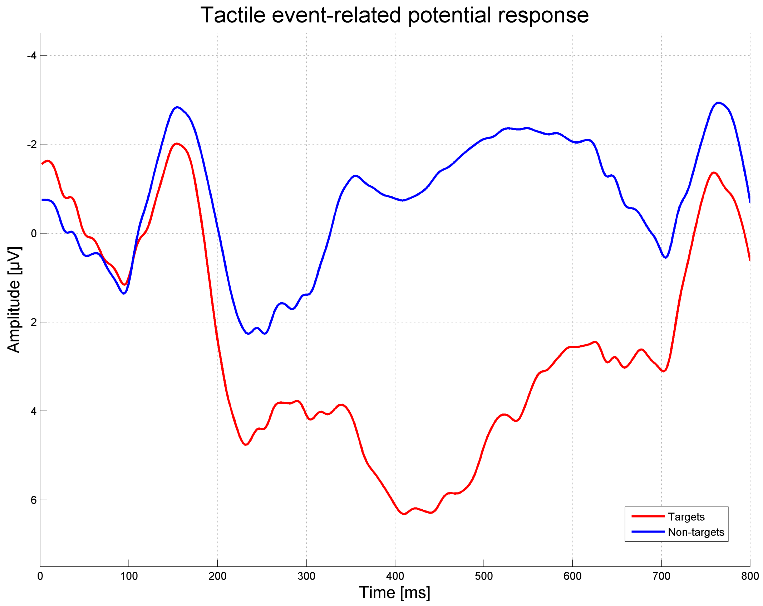


Figure 7: Mean tactile ERP response for target (red) and non-target (blue) stimuli. P300 response peaks between 400 and 450ms and is only visible for target stimuli. The N1 peak is emphasised for tactile stimulation and can be seen for all stimuli.

Donchin, 1988; Krusienski et al., 2006), for review see Kleih and colleagues (2011). The SWLDA splits the recording into 2-3ms windows, referred to as "bins". Afterwards it adds bins which contribute to separation of target and non-target signal until adequate separation is achieved. In a second step all features which can be deleted without compromising separation are removed again. In a third step this classifier allows for online classification separating target and non-target responses to determine the attended stimulus. The BCI can now be used as the user can freely choose which target he wants to attend and is given online feedback about his selections.

ERP-BCIs are mainly used for communication BCIs for healthy as well as impaired users . For reviews on ERP-BCI studies for healthy and impaired users on patients see

Kleih and colleagues (2011) and Mak and colleagues (2011).

The classical communication matrix as seen in Figure 6 can be modified to allow broader assistive technology functions like environment control (Zickler et al., 2011) or creative expression through painting applications (Botrel et al., 2015). ERP-BCIs have also been used for wheelchair control by providing several movement targets on a screen mounted on the wheelchair (Iturrate et al., 2009; Rebsamen et al., 2010). This thesis focuses on the usage of ERPs for BCI control.

2.3 GAZE-INDEPENDENT BCI

While BCI aim to provide a direct communication or control channel using brain signals only they may still be indirectly dependent on residual muscular control. The classical P300-BCI as presented in the previous chapter requires the user to focus the target letter using eye-movement (overt attention opposed to covert attention for gaze-independent tasks). Due to the loss of eye-movement in later stages of ALS and the possibility of general visual impairment development of gaze-independent BCI should be a major focus of BCI research. This chapter examines current research towards gaze-independent BCI. A conclusion will be given at the end of this chapter. For a review of gaze-independent BCI see Riccio and colleagues (2012).

2.3.1 *Visual gaze-independent BCI*

Kelly and colleagues (2004) examined the difference between covert and overt attention for a SSVEP-based paradigm. They found classification accuracy to be significantly reduced using covert attention, but were able to increase binary accuracy to 70,3% by modifying the paradigm in a follow-up study (Kelly et al., 2005).

Zhang and colleagues (2010) demonstrated viability of a SSVEP-based protocol using selective attention in a task without spatial separation of the visual stimuli. This approach was implemented using two sets of dots using different colors and flickering frequencies resulting in two superimposed surfaces. After training an average binary accuracy of 72.6% could be achieved by 18 healthy participants, resulting in an ITR of 2.17 bits / min. Treder and Blankertzs (2010) modified the interface of the Hex-O-Spell (Blankertz et al., 2007) and compared it to a regular matrix speller using overt and covert attention tasks. Instead of flashing groups of letters the targets were enlarged to avoid Troxler-fading, a phenomenon which can induce perceptual disappearance (Troxler, 1804). The regular matrix speller dropped to 40% accuracy when used with covert attention, while the modified Hex-O-Spell achieved 60% accuracy. While this did provide a significant improvement over the matrix speller the achieved accuracies were still below communication level (70%; Kübler et al., 2001).

In a follow-up study Treder and colleagues (2011) proposed three alternative speller designs to address low classification accuracies. All three spellers were designed for covert attention and were tested on 13 healthy participants. The first variation utilized the previous design but instead of enlarging groups of letters groups were highlighted by color. The second variation used triangular shapes instead of circles of letter groups, these were again highlighted by color. The third variation used only the center part of the screen, encoding letter groups and letters by colored geometric shapes. Accuracy for the 3 variations was reported as 90.4%, 88% and 97% and an average ITR of 9.8 bits / min was achieved. Acqualagna and colleagues (2010) demonstrated the RSVP speller, a design based on rapid serial visual presentation (RSVP) at one central position of the screen. In an offline study with 9 healthy participants 90% performance could be achieved. In a follow-up online study 12 healthy participants operated the RSVP speller with 93.6% accuracy and an ITR of 10.20 bits / min.

2.3.2 *Auditory BCI*

BCI using auditory modality are often by design gaze-independent. Some auditory BCI do, however, rely on visual support matrixes, i.e. users are presented visual information to use the speller.

A multitude of binary auditory BCI based on ERPs have been implemented (Halder et al., 2010; Hill & Schölkopf, 2012; Hill et al., 2005; Hill et al., 2014; Hill et al., 2004; Lopez-Gordo et al., 2012; Sellers & Donchin, 2006). Sellers and Donchin (2006) implemented a BCI using the spoken words "yes,"no","pass" and "end". Binary classification on the targets "yes" and "no" yielded an average accuracy of 65,4% for 3 healthy participants. Halder and colleagues (2010) demonstrated reliable binary communication using a three-target oddball based on tones. An average accuracy of 78.5% and an ITR of 2.46 bits/min where achieved by 20 healthy participants. Hill and colleagues (2012) utilized a protocol eliciting both P300 and SSAEP responses. Anyhow, classification of SSAEPs did not improve the performance of 13 participants above the 84% achieved using ERPs only. Hill and colleagues (2014) also demonstrated the viability of using spoken stimuli ("yes" and "no") for a binary oddball.

Based on the P300 speller matrix by Farwell and Donchin (1988) a number of auditory spellers have been developed (Furdea et al., 2009; Klobassa et al., 2009; Käthner et al., 2013; Simon et al., 2015). Furdea and colleagues (2009) used a 5x5 speller matrix with the numbers one to ten identifying the different rows and columns. Participants had to concentrate on the number indicating the desired row, afterwards the process was repeated to select a column. A mean accuracy of 65% was achieved by 13 participants. Klobassa and colleagues (2009) followed a similar approach using bell, bass, ring, thud, cord and buzz sounds instead of numbers for stimulation. Ten participants achieved a mean accuracy of 66%. Käthner and colleagues (2013) used a combination of tone pitch and direction for stimulation and 20 participants achieved a mean accuracy of 66%. Simon and colleagues (2015) also utilized directional stimulation but replaced tones by animal sounds. In a two-session experiment eleven healthy participants achieved accuracies of 76% in session one and 90% in session two. All four studies utilized visual support matrices to relay the encoding between stimuli and potential targets.

Multi-class speller, grouping letters in a two-step selection process, have also been implemented without the use of visual support matrices (Höhne et al., 2011; Schreuder et al., 2011). Schreuder and colleagues (2011) encoded grouped letters by a combination of position and basetone variation. Healthy participants were able to use this protocol with 88% accuracy. In a similar design, Höhne and Tangermann (2011) used this positional system with headphones achieving 89% accuracy which is in line with the previous study. Both studies, however, require a high workload since both word groups and group encodings have to be retained in memory while using the BCI. Recently, Höhne and colleagues (2014) created a BCI using multiple continuous streams of letter stimuli presented simultaneously. This eliminates encoding and grouping providing a more intuitive approach, but also requires users to discriminate the target stimulus within a multitude of simultaneous stimuli. Participants achieved 41% accuracy which does not satisfy the required 70% accuracy needed for meaningful communication (Kübler et al., 2001). While auditory BCI seem to benefit from natural stimuli (Höhne et al., 2012), auditory BCI appear to be universally more demanding than visual BCI (Kübler et al., 2009; Nijboer et al., 2008b).

2.3.3 *Tactile BCI*

In the following chapter the current state of the art for tactile BCI is presented.

The effect of tactile feedback on SMR-based BCI was examined in several studies. Using tactile feedback 6 participants were able to control a cursor with an accuracy of 56% using movement imagination (Chatterjee et al., 2007). In a similar study Cincotti and colleagues (2007) performed a SMR-based study with 33 participants and found no difference between performance using visual and tactile feedback. Furthermore, tactile feedback yielded higher performance in presence of a visual distractor task and was reported as "feeling more natural" (Cincotti et al., 2007). Wilson and colleagues (2012) performed an SMR-based cursor task with either visual or tactile feedback and observed similar results. Furthermore, they even demonstrated that a visually impaired person was able to achieve the same performance as normal sighted persons using tactile feedback only.

Additionally to being used as a feedback modality, tactile stimulation can be used to elicit brain signals used for BCI control. Müller and Blankertz (2006) demonstrated the first BCI based on steady-state somatosensory-evoked potentialss (SSSEPs) elicited by stimulation of the index fingers of four participants. Different stimulation frequencies were applied to each index finger and two participants were able to modulate their potentials by focusing one of the index fingers, resulting in a classification accuracy of

68%.

Nam and colleagues (2013) were able to further improve this concept with the use of common spatial patterns, increasing classification accuracy of their BCI from 70 to 75%. Spatial patterns are viable for tactile modality due to different stimulation positions being represented at different locations within the brain.
In a direct comparison steady-state somatosensory-evoked potentials (SSSEP) show lower signal-to-noise ratios than steady-state visual-evoked potentials (SSVEP), resulting in SSVEP being more reliable while the user is still able to control his eye movement (Smith et al., 2014).

Aloise and colleagues (2007) were the first to demonstrate classification of ERPs elicited by tactile stimulation, achieving 68% classification accuracy. Brouwer and van Erp (2010) developed the first working tactile BCI using 2, 4 or 6 tactuators localized around the waists of 11 participants and achieved accuracies in the range of 58% and 73%. No significant differences in accuracy for different numbers of tactuators were found. The tactuator positions used can be seen in Figure 8.

The first tactile ERP-based spelling application utilized stimulation of the fingers to allow 12 healthy participants to write a text with 67% accuracy (Waal et al., 2012). The stimulation unit is shown in Figure 8. Selection of letters was implemented in a two-step procedure, selecting a group of letters in the first and a single letter in the second step. For comparison, participants also used the Hex-O-Speller to spell which resulted in a comparable

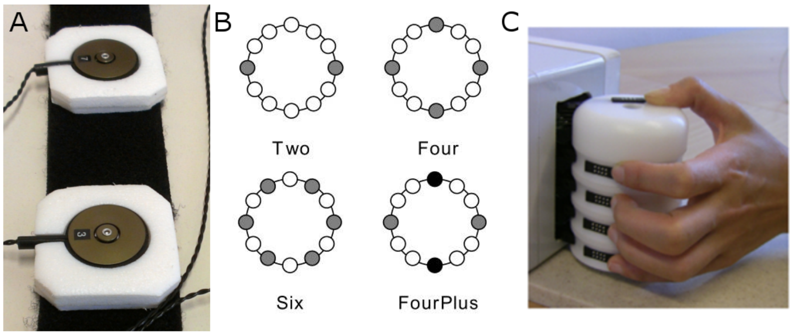


Figure 8: Different stimulators and positions used in tactile BCI studies. Part A depicts tactuators as used by Aloise and colleagues (2007) and Kaufmann and colleagues (2014). Part B depicts the tactuator positions around the waist used in Brouwer et al., (2010). Part C depicts the stimulation unit used in Waal et al., (2012). Part B and C were modified from Brouwer and colleagues (2010) and Waal and colleagues (2012) respectivly.

65% accuracy.

Kaufmann and colleagues (2014) utilized a tactile ERP-based BCI which allowed 15 participants to navigate a virtual wheelchair along a track presented on a monitor. Accuracies were above 85%, albeit still at the cost of low ITRs.

In an effort to evaluate a multimodal approach Brouwer and colleagues (2010) compared tactile, visual and tactile-visual stimulation and found similar performances for tactile and visual stimulation with both being surpassed by multimodal stimulation. However, this finding could not be confirmed in a later study where tactile stimulation produced significantly lower ITRs than visual and tactile-visual (combined) stimulation (Thurlings et al., 2012b). Rutkowski and Mori (2013) performed a tactile bone-conduction auditory BCI achieving a high mean ITR of 16.4 bits / min albeit with a mean accuracy of 64.3%.

Additionally, several hybrid BCI, i.e. systems utilizing features from multiple different control signals, were examined. Severens and colleagues (2013) demonstrated a combination of SSSEP and ERP, using continuous stimulation to evoke SSSEPs as well as intermitting stimuli to evoke ERPs at the fingertips of 12 participants. Combined classification of SSSEP and ERPs resulted in a classification accuracy of 91%, while classification based purely on ERP resulted in 93% accuracy. A combination of SSSEP and motor imagination was evaluated with 16 participants first concentrating on stimulation of the required hand followed by motor imagination of the same hand (Ahn et al., 2014). This combination surpassed motor imagination and SSSEP by themselves, but required more time due to consecutive measurement of both approaches.

2.3.4 *Conclusion gaze-independent BCI*

For a summary of gaze-independent BCI see table 1.

Table 1: Summary of recent gaze-independent BCI studies with four visual studies added for comparison.

Study	Modality	Accuracy mean (%)	ITR mean (bits/min)	Analysis	Population
Sellers & Donchin, 2006	A [1]	65,40	0.43 – 1.80	Off [2]	H [3]
Kübler et al., 2009	A	12,10	0,05	On	ALS
Halder et al., 2010	A	78,50	2,46	Off	H
Höhne et al., 2011	A	89,40	3,40	On	H
Schreuder et al., 2011	A	77,00	5,27	On	H
Hill & Schölkopf, 2012	A	84,80	4,98	On	H
Höhne & Tangermann, 2014	A	41,00	-	On	H
Hill et al., 2014	A	72,60	1,41	Off	H
Müller-Putz et al., 2006	T	68,00	1,79	On	H
Brouwer et al., 2010	T	-	3,71	On	H
Waal et al., 2012	T	67,00	7,8	Off	H
Thurlings et al., 2012b	T	-	6,54	Off	H
Ortner et al., 2013	T	68,10	3,8	On	H
Severens et al., 2013	T	77,00	1,2	On	H + ALS
Severens et al., 2014	T	55,00	2,3	On	H
Kaufmann et al., 2014	T	85,80	2,54	On	H
Kelly et al., 2005	VG	70,30	0,9	Off	H
Zhang et al., 2010	VG	72,60	2,17	On	H
Treder & Blankertz, 2010	VG	60,00	4,29	On	H
Treder et al., 2011	VG	97,10	9,33	On	H
Acqualagna & Blankertz, 2011	VG	93,60	10,2	On	H
Nijboer et al., 2008a	V	78,80	9,70	On	ALS
Lenhardt et al., 2008	V	65,5-87,5	29,35 - 50,61	On	H
Furdea et al., 2009	V	94,60	6,80	On	H
Kaufmann & Kübler, 2014	V	81,20	106,20	Off	H

[1] A = Auditory, T = Tactile, VG = Visual gaze-independent, V = Visual

[2] On = online, Off = offline

[3] H = healthy participants, ALS = participants suffering from ALS

Auditory BCI have been shown to achieve reliable control with over 70% accuracy. They have also been shown to put more workload onto users than comparable visual BCI (Nijboer et al., 2008b). Furthermore, this is enhanced if participants have to retain the encoding in memory. Encoding can be evaded by matching stimulus and target, i.e. using the sound of a letter to encode the letter, e.g. Höhne and colleagues (2014). This study, however, did not achieve the necessary accuracy for meaningful communication.

Tactile BCI benefit from the main advantage that tactile perception is rarely needed in day-to-day tasks, therefore tactile stimulation does not block an otherwise needed sensory channel. Additionally, tactile stimulators may be worn concealed below clothing. Current tactile BCI suffer from low performance with only two studies achieving adequate accuracy for communication (Kaufmann et al., 2014; Severens et al., 2013). Furthermore, ITRs are generally low as most studies achieve ITRs below 4 bits / min.

Visual gaze-independent BCI are currently the best performing alternative with accuracies above 90% and ITRs around 10 bits / min. Anyhow, all presented studies tested covert attention using participants who were actually able to focus their gaze. Furthermore, for some end-users even a gaze-independent visual BCI may be unusable due to a general lack of visual focus. Actual validation with locked–in-users has yet to be performed. Additionally, it is of high importance to have a viable toolkit for participants unable to use visual BCI, even if they are gaze-independent.

2.4 EFFECTS OF AGE ON BCI PERFORMANCE

Potential end-users for BCI application are mostly aged 50 years and older (e.g. mean age of disease onset for ALS is 56 years; Hudson, 1981). Therefore, the effects of ageing on perception might be of relevance for the development of BCI applications. Degradation of perception is well documented for auditory (Brant & Fozard, 1990; Morrell et al., 1996; Pearson et al., 1995) as well as for tactile (Deshpande et al., 2008; Gescheider et al., 1996; Lin et al., 2005; Perry, 2006; Sands et al., 1998; Wells et al., 2003) modality. Vibrotactile perception of high-frequency vibrations in the range of 60 to 250 Hz is mediated by pacinian corpuscles (Greenstein et al., 1987; Kandel et al., 2012). Decreased number and changing morphology of pacinian corpuscles has been reported as one potential reason for reduced tactile sensitivity (Cauna, 1965). Absolute vibrotactile sensitivity detoriates with age (Deshpande et al., 2008; Gescheider et al., 1996; Lin et al., 2005; Perry, 2006; Sands et al., 1998; Wells et al., 2003).

Additionally, vibrotactile sensitivity is also affected by gender and BMI with high BMI resulting in reduced sensitivity and woman of all ages being more sensitive than men (Deshpande et al., 2008). Ageing also reduces speed and accuracy of tactile pattern recognition tasks (Master et al., 2010). For a review on the effect of ageing on the sense of touch see Wickremaratchi & Llewelyn (2006).

Additionally, age does slow down the general processing speed of stimuli and promotes an inability to inhibit irrelevant distractive information (Hasher et al., 1991; Knight et al., 1999; Kok, 1999). The prefrontal cortex has been identified as a main contributor to inhibition of irrelevant distractive information (Knight et al., 1999), confirmed within both animal (Artchakov et al., 2009; Bartus & Levere, 1977) and human lesion (Chao & Knight, 1995, 1998) as well as imaging studies (Dolcos et al., 2007). Prefrontal suppression of irrelevant information happens early within the processing stream (Cao et al., 2008; Yamaguchi & Knight, 1990; Yingling & Skinner, 1976; Zikopoulos & Barbas, 2006) and is vital for high performance in working memory tasks (Zanto & Gazzaley, 2009). The prefrontal cortex is, however, one of the regions that deteriorates strongest throughout ageing (Jernigan et al., 2001; Raz et al., 1997; Resnick et al., 2003). Therefore, BCI based on tasks requiring good working memory performance might be less viable for aged end-users.

In line with these results amplitude of the tactile P300 response decreases with age (Bolton & Staines, 2012; Yamaguchi & Knight, 1991). In two meta-analyses including 1,572 participants Dinteren and colleagues (2014); (2014) found P300 amplitudes to plateau after 21 years and decrease afterwards while frontal P300 amplitudes plateaued at an age of 46 years and only decreased minimally thereafter. While frontal P300 latencies were lower than parietal latencies, both increased with age at the same rate.

Bolton and colleagues (2012) performed a tactile oddball using stimulation of the fingers and observed that P300 amplitudes were significantly lower and delayed for old compared to young adults. Additionally, the N1 response elicited by non-targets was significantly higher for old adults, which might result from reduced prefrontal inhibition. Behavioral performance for older adults was significantly reduced with only 75% of all targets reported correctly and a false positive rate of 14%. Dustman and colleagues (1993) found early ERP components to be delayed even after adjusting for the sensory threshold differences induced by aging. Similar effects could be observed for auditory and visual ERPs (Čeponien et al., 2008).

Inhibition of interfering irrelevant information and the ability to keep relevant information in working memory are regularly required for BCI paradigms. Despite prefrontal deterioration the prefrontal P300 itself has been reported stable during ageing. Nevertheless, reduced task performance and parietal P300 amplitudes might result in reduced BCI performance. Therefore age-related changes to perception and processing and potential measures to counteract these effects could be of high importance for BCI research.

2.5 EFFECT OF TRAINING ON BCI PERFORMANCE

While visual BCI performance has been shown to remain stable over multi-session studies (Nijboer et al., 2008a), training effects could be demonstrated for auditory BCI. Recently, it has been shown that training across multiple sessions can improve performance in an auditory P300 BCI for healthy participants, but the P300 amplitudes remained stable (Baykara et al., 2015). Yet, a multi-session training for end-users with motor impairment demonstrated increased performance and P300 amplitudes (Halder et al., 2015). For tactile BCI no training studies have been performed yet.

Ragert and colleagues (2004) demonstrated the effects of training on tactile discrimination thresholds. Professional pianist players had increased discrimination thresholds and higher performance gains during a training intervention than untrained subjects. In line with this, Reuter and colleagues (2014) found tactile experts to benefit more from a tactile training intervention than non-experts. Additionally, analysis of ERP responses revealed increased P300 amplitudes after training for aged subjects, partially reversing the age-induced decline in amplitudes. Most notably, tactile experts developed a stronger parietal-to-frontal gradient during the training intervention, suggesting more automated processing. For auditory processing training effects can be demonstrated for speech perception training (Kraus et al., 1995; Tremblay et al., 2001). Kraus and colleagues (1, 1995) demonstrated increased duration and magnitude of ERPs in response to speech stimuli following a training intervention. Tremblay and colleagues (2001) measured increased N1-P2 peak-to-peak amplitudes after syllable discrimination training.

Furthermore, extensive sensory training can result in cross modal activation. Utilizing sighted, but blindfolded mahjong experts Saito and colleagues (2006) were able to show activity in the primary visual cortex during tactile identification of mah-jong tiles. This effects has been previously known from blind subjects demonstrating activity in the visual cortex especially during braille reading (Sadato et al., 1996).

Taken together, sensory perception and associated brain activity can be modulated by short and long term training. Whether such training interventions can be used to increase tactile or auditory BCI performance is largely unknown.

2.6 THE USER-CENTERED DESIGN

BCI research has recently started to adapt the user-centered-design approach to bridge the gap between research use and actual end-user requirements. The user-centered design suggests iterative development incorporating user feedback and an early focus on user requirements. The user-centred approach was standardized with the International Organization for Standardization (ISO) 9241-210 (Ergonomics of human-system interaction - Part 210: Human-centred design for interactive systems). This standardization defines usability as the "extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO 9241-210:2010(E) Page 3, 2.13; Adapted from ISO 9241-11:1998). Effectiveness refers to the ability to reliably communicate desired commands and can therefore be operationalized using the system´s accuracy as defined in chapter 2. Efficiency relates the users' invested cost in relation to the achieved effectiveness. It is reflected in the information-transfer-rate (ITR) and the perceived workload of the user. User satisfaction describes the perceived comfort and acceptability of the system.

The ISO 9241-210 states that design of an interactive system does require to understand the specific context of use and to specify the user requirements. For this purpose Zickler and colleagues (2009) assessed needs and requirements of 77 potential users using a newly developed questionnaire. Average satisfaction with current assistive-technology was high with satisfaction being highest for mobility solutions. Despite this 52% listed mobility as an area in which they wanted to improve their independence. Participants being "not at all satisfied" or "not particulary satisfied" were so in the areas "environment", "communication", "computer access" and "manipulation". For future assistive-technology participants rated "functionality","independent use" and "easiness of use" as the most important aspects.

Part III

SCOPE OF THE THESIS

While extensive research regarding visual ERP BCI has been performed, the toolkit of gaze-independent BCI remains lacking. As Kaufmann and colleagues (2013) demonstrated, modality comparisons performed with healthy participants might not be representative of actual end-user needs. Additionally, individual end-user situations might require specialized non-visual BCI solutions. To better accommodate this need this thesis aims at enhancing the toolkit of available gaze-independent BCI solutions. In the following chapter the central goals of the thesis are examined.

3

SCOPE OF THE THESIS

3.1 CHALLENGES

The following section highlights challenges for gaze-independent BCI which we intend to address within this thesis.

3.1.1 *Tactile BCI*

Tactile stimulation provides innate directional information, e.g. a tap on the shoulder is intuitively connected to a direction, therefore representing an intuitive choice for direction-based tasks. Furthermore, controlling mobility devices might require visual and auditory channels for perception of the immediate environment, reducing the viability of visual and auditory stimulation for such tasks. Tactile modality has, however, been shown to perform poorly compared to visual and auditory BCI (also see Table 1).

Mean age of onset for ALS has been found to be 56 years (Hudson, 1981) and it has been shown that ageing does affect several mechanisms which are required for BCI usage:

- Vibrotactile sensitivity has been shown to deteriorate.
- Due to reduced inhibition of irrelevant stimuli workload for oddball tasks does increase, reducing be-

havioural performance and potentially P300 amplitudes.

- The ability to retain relevant task information in working memory decreases.

For auditory BCI beneficial effects evoked by training have been demonstrated for healthy participants as well as for patients. Furthermore, it has been suggested that training might partially offset decreased performances induced by aging. For tactile modality, however, no studies involving training have been performed yet.

3.1.2 *Auditory BCI*

A multitude of auditory communication BCI have been proposed and validated; for details see chapter 2.3.2. However, these BCI frequently rely on visual support matrices due to complicated stimulus to target encodings. While it has been shown that natural stimuli such as syllables used in day-to-day language can improve auditory BCI performance and ergonomics, currently only Höhne and colleagues (2014) used such stimuli for a gaze-independent speller. The BCI demonstrated by Höhne and colleagues (2014) achieved 41% accuracy which is below the required 70% needed for meaningful communication (Kübler et al., 2001). No reliable spelling applications based purely on natural auditory stimuli have been implemented yet.

3.1.3 *Sensory experts*

Studies suggest beneficial effects of sensory training on task performances and underlying EEG features. Blind participants have been shown to exhibit increased sensory performance in the tactile and auditory modality, some even recruiting the visual cortex for cross modal processing of sensory information. However, the effect of such sensory training on auditory and tactile BCI performance remains unclear.

3.2 GOALS OF THE THESIS

To address these challenges we perform three studies.

For our first study we intend to design an intuitive tactile BCI for navigation. To provide an intuitive control scheme, movement directions and related stimuli are going to be congruent. This removes the need for memorization of stimulus to target encodings. While shared-control systems can reduce the amount of control needed by the end-user, they might also obfuscate the performance of the base BCI system. In our study we avoid shared-control systems to evaluate the base performance of our designed control protocol.

Furthermore, within our first study we intend to address tactile performance of aged participants and the effect of training on tactile performance. To reduce the effect of age-related deterioration on tactile sensitivity, we provide salient stimuli to ensure adequate perception of stimulus information. By designing a spacious stimulation setup we intend to optimize target discrimination, reducing workload and increasing behavioural performance. Additionally by providing a natural and intuitive connection between stimulus and movement direction we intend to reduce the load on working memory. With these steps we aim to compensate for potential issues as identified in chapter 2.4. To evaluate the viability of this tactile BCI for potential end-users we recruit participants aged 50 years and above. Furthermore, we perform a multi-session training to evaluate the effect of training on tactile BCI performance.

For our second study we intend to design an intuitive auditory speller based on natural spoken stimuli. Instead of encoding letters using artificial stimuli we use the letters themselves as auditory stimuli. In order to reduce the total stimulation time we apply a two-step system. Letters will be grouped, but the groups themselves will be natural stimuli in form of words containing the grouped letters , e.g. the letters "W", "I", "T" and "Z" will be grouped into the word "Witz". This removes the need for visual support matrices or memorization of stimulus to target encodings, potentially reducing workload for the end-user.

For our third study we examine the effect of sensory training on BCI performance by evaluating the performance of sensory experts against that of control participants. Therefore, we recruit blind participants as highly trained sensory experts for tactile and auditory modality. Evaluating the performance of such sensory experts can provide valuable information on the effect of long-term perception training on BCI performance.

In accordance with the user-centered-design-approach BCI applications designed within this thesis should provide effectiveness, efficiency and satisfaction whenever possible. Adding features such as auto-calibration, word completion and user-friendly graphical interfaces can increase satisfaction of existing BCI applications (Kaufmann et al., 2012). Applications are designed with such future enhancements in mind, but focus primarily on providing an effective and efficient gaze-independent core control mechanism.

Therefore, the formulated goals of the thesis are:

GOAL 1 To design a tactile BCI used for mobility which is intuitive *(G1.1)*, reliable *(G1.2)* and fast *(G1.3)* while being usable by participants aged 50 years and above *(G1.4)*.

GOAL 2 To design an auditory BCI used for communication which is intuitive *(G2.1)* and reliable *(G2.2)*.

GOAL 3 To examine the effects of training on tactile *(G3.1)* and auditory *(G3.2)* BCI performance.

Part IV

METHODS AND RESULTS

To achieve the formulated goals three studies were performed. In the following chapter methods and results of these studies are outlined and discussed.

4

METHODS AND RESULTS

4.1 TRAINING THE ELDERLY USING AN INTUITIVE, RELIABLE AND FAST TACTILE BCI

4.1.1 *Aim of the study*

The aim of the study was to design and validate a tactile BCI used for mobility which is intuitive, reliable and fast. Additional goal was to examine the effects of training on tactile BCI performance and verification that tactile BCI are viable for user aged 50 years and above. These goals lead to the following hypotheses:

- Multi-session training improves tactile BCI performance (accuracy and ITR = H1a) and underlying ERP features (P300 amplitude, area between curves = H1b).
- Intuitive, reliable (> 70% accuracy = H2a) and fast ITR (> 4 bits / min = H2b) tactile BCI control is achievable by participants aged 50 years and above within a navigation task.

4.1.2 *Design*

4.1.2.1 *Participants*

We included N = 10 healthy elderly participants aged 50 to 73 years (mean = 60 years, SD = 6.7 years) in our study. One participant attended two sessions only and was, thus, excluded from analysis. Participants were recruited via postings. All participants were naïve to BCI use and none of them reported a history of neurological or psychiatric disease. Participants had normal or corrected-to-normal vision. All gave informed consent and received monetary reimbursement of 8 Euros per hour. The procedure was approved by the Ethical Review Board of the Institute of Psychology at the University of Würzburg, Germany.

4.1.2.2 *Stimulation*

Participants were stimulated at left and right thigh (top, toward knee), abdomen (above navel) and lower neck (at the height of C4 to C8) using tactile stimulators (C2 tactors; Engineering Acoustic Inc., Casselberry, USA). Stimulators were placed in pairs and fixed using Velcro belts. Prior to the experiment stimulation was adjusted until perception was reported as equally strong for all positions. Stimulus duration was 220ms and inter-stimulus interval was set to 400ms. Stimulation frequency was 250Hz, rise time was 2ms. Stimulation was implemented using Python 2.7 connected to BCI2000 (Schalk et al., 2004) via user datagram protocol (UDP).

4.1.2.3 *Data acquisition*

EEG was acquired with 16 passive Ag/AgCL electrodes at positions Fz, FC1, FC2, C3, Cz, C4, P3, Pz, P4, O1, Oz, O2 with ground and reference at the right and left mastoid. Impedance was kept below 5 kOhm. Signals were amplified and recorded at a sampling rate of 512Hz using a g.USBamp (g.tec Engineering GmbH, Graz, Austria). EEG was filtered online using a Band Pass filter between 0.1 and 60 Hz and a notch filter between 48 and 52 Hz.

4.1.2.4 *Procedure*

The study comprised 5 sessions, with no more than one week between sessions and a maximum of 3 sessions per week. Sessions began with the preparation of tactuators and EEG electrodes. Participants had to perform three calibration runs which were used to compute classifier weights. For each calibration run the participants had to concentrate on each of the four body positions twice, resulting in 8 trials for each calibration run. Every trial consisted of 10 sequences, resulting in 10 target and 30 non-target stimulations for each trial, i.e., each sequence comprised one activation of each stimulator.

Participants had to steer a virtual wheelchair trough a virtual course. Each course required arrival at three checkpoints and transversal of one door. Following the optimal course, 14 movement commands were required to complete the task. Deviating movement commands had to be corrected, therefore the number of required commands increases with false selections. Required level of control to complete the task was set to 70 % (see Kübler et al., 2001) which resulted in a maximum of 22 commands (assuming 14 required commands, a maximum number of 4 errors and 4 associated corrections). Once a participant gave 22 commands the run was terminated. For the second run of each day participants had to move back to the starting position of the first run, therefore balancing the number of right and left commands. For each session start and end point were changed. Movements that would have resulted in collisions were halted and registered as false selection. In the last session participants were encouraged to participate in an optional extra navigation task using a reduced number of sequences. The actual number of sequences was determined as the lowest estimated number of sequences which allows for reasonable control (70%).

4.1.2.5 *Data analysis*

EEG data was filtered between 0.1 and 30 Hz and divided into segments of 800ms post-stimulus using MATLAB© (v2013b). Segments were grouped into target and non-target segments and averaged respectively. Classification models were build using stepwise linear discriminant analysis (SWLDA) using 800ms following stimulus onset. SWLDA selects spatiotemporal features, which discriminate best between targets and non-targets, adding features to the linear equation until an optimization criterion is reached. As suggested in literature on BCI performance assessment (Wolpaw et al., 2002), we calculated the ITR as bits per minute (B) including information on accuracy and number of possible outputs as described in chapter 2.

IBM SPSS 20 was used for statistical analysis, the level of significance was set to $\alpha = .05$. For all reported results we decided to implement non-parametric tests for statistical analysis due to small sample size.

Previous research suggests effects of ageing on P300 amplitudes to vary between electrode positions, therefore we analysed the most commonly used electrode positions Fz, Cz and Pz. To test our hypothesis of increasing P300 amplitudes over sessions we used Friedman ANOVA, with within-subjects variables electrode (Fz, Cz and Pz) and time (sessions), dependent variables were P300 amplitude and area between curves. Likewise, to investigate the increase of accuracy and ITR over sessions, time (sessions) served as within-subjects variable and accuracy and ITR as dependent variables.

4.1.2.6 *Evaluation*

To accommodate the user-centered design approach for the development of user-friendly BCI (Kübler et al., 2014), we asked participants about their subjective experience with the BCI. They were provided with a custom-made forced-choice questionnaire (see Table 3 for questions and answers).

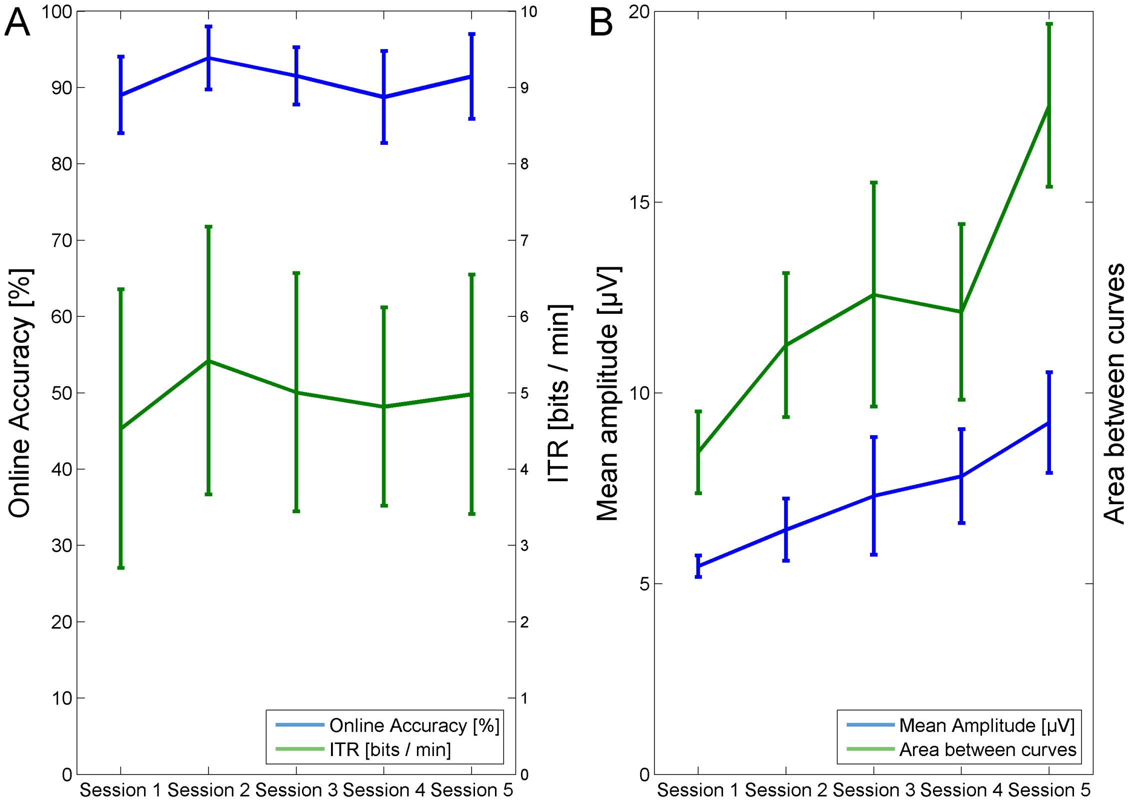


Figure 9: Average accuracy, ITRs, P300 amplitude and area between curves (target vs. non-target) for all participants within online navigation tasks performed on days 1 to 5. Accuracy and ITR were higher in session 5 as compared to session 1 (statistically ns), mean amplitude and area between target and non-target response increased over the course of training. Error bars represent the standard error of the mean (SEM).

4.1.3 *Results*

4.1.3.1 *A multi-session training to improve tactile BCI performance and underlying ERP features*

Training was performed with eight stimulation sequences, with one sequence activating each tactuator once. To compensate for ceiling-effects, we also calculated offline single-trial accuracy and ITR. Average accuracy on the first day was 89.02% and 2 participants were able to navigate without any wrong selections. Average accuracy in the fifth session was 91.46% and 6 participants were able to navigate without any wrong selections (see figure 1). This increase was not significant $(X2(4) = 6.50, p = .17)$, using Friedman Anova due to small sample size. However, single trial accuracy (offline) significantly increased with training $(X2(4) = 11.86, p < .05, r_{\text{rsession 1 to 5}} = .33)$. Mean ITR increased with training from 4.53 bits / min to 4.98 bits / min. As for accuracy, online ITR did not increase with session $(X2(4) = 6.50, p = .17)$, but single trial ITR (offline) did $(X2(4) = 11.86, p < .05, r_{\text{session 1 to 5}} = .43)$.

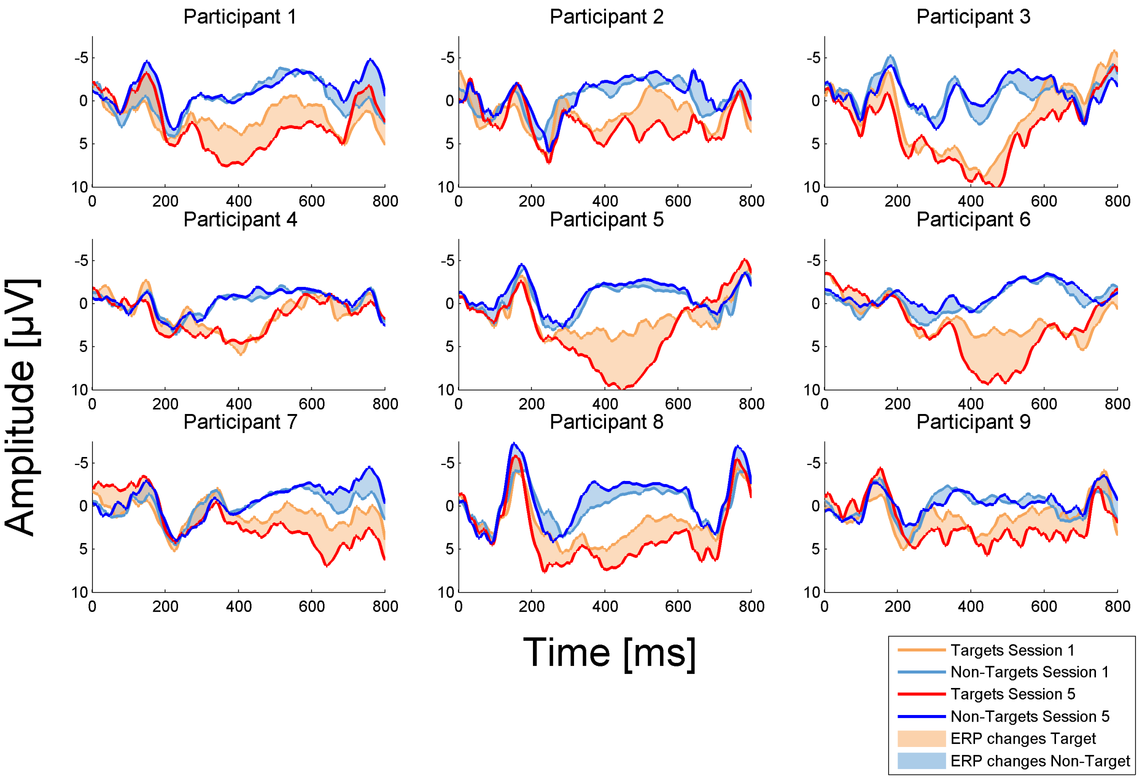


Figure 10: ERP changes at position Fz as a function of training for each participant. Averaged target and non-target response for session 1 (light orange and light blue line) and session 5 (red and blue line). Areas of difference between session 1 and 5 are shaded light orange and blue respectively.

We analyzed P300 amplitudes for positions Fz, Cz and Pz (Figure 9 and Table 2). We found significant increases with training in P300 amplitudes for Fz and Cz, but not for Pz (see Table 2). Area between target and non-target responses (area between curves, ABC) was calculated to represent separation between target and non-target responses and is illustrated in Figure 1. Figure 2 illustrates the individual ERP changes as a function of training. We found significant increases in ABCs for positions Fz and Cz but not for Pz (see Table 2).

Table 2: P300 amplitude and statistics for amplitude and area between curves (ABC) for electrode positions Fz, Cz and Pz. Mean ERP-amplitude and ABCs increased significantly with training for positions Fz and Cz.

Electrode position	**Fz**	**Cz**	**Pz**
Mean P300 amplitude Session 1 [µV]	5.5 (SEM 0.28)	6.0 (SEM 0.41)	5.0 (SEM 0.54)
Mean P300 amplitude Session 5 [µV]	9.2 (SEM 1.32)	7.9 (SEM 0.63)	5.7 (SEM 0.67)
Amplitude: Chi-square value ($X^2(4)$)	10,04	9,69	6,76
Amplitude: Significance (p)	<.05	<.05	0,15
Amplitude: Effect size (r)	0,52	0,52	-
ABC: Chi-square value ($X^2(4)$)	10,04	9,69	6,76
ABC: Significance (p)	<.05	<.05	0,15
ABC: Effect size (r)	0,52	0,52	-

4.1.3.2 *An Intuitive, reliable and fast tactile BCI for movement control, used by participants aged 50 and above*

Since participant 2 did not wish to participate in the extra task, data of n = 8 participants are evaluated. Participants needed on average 2.25 vibrations to navigate the course during the extra task (during training a fixed number of 8 vibrations was delivered). Mean task performance for the extra task was 95.56% with a mean ITR of 20.73 bits / min.

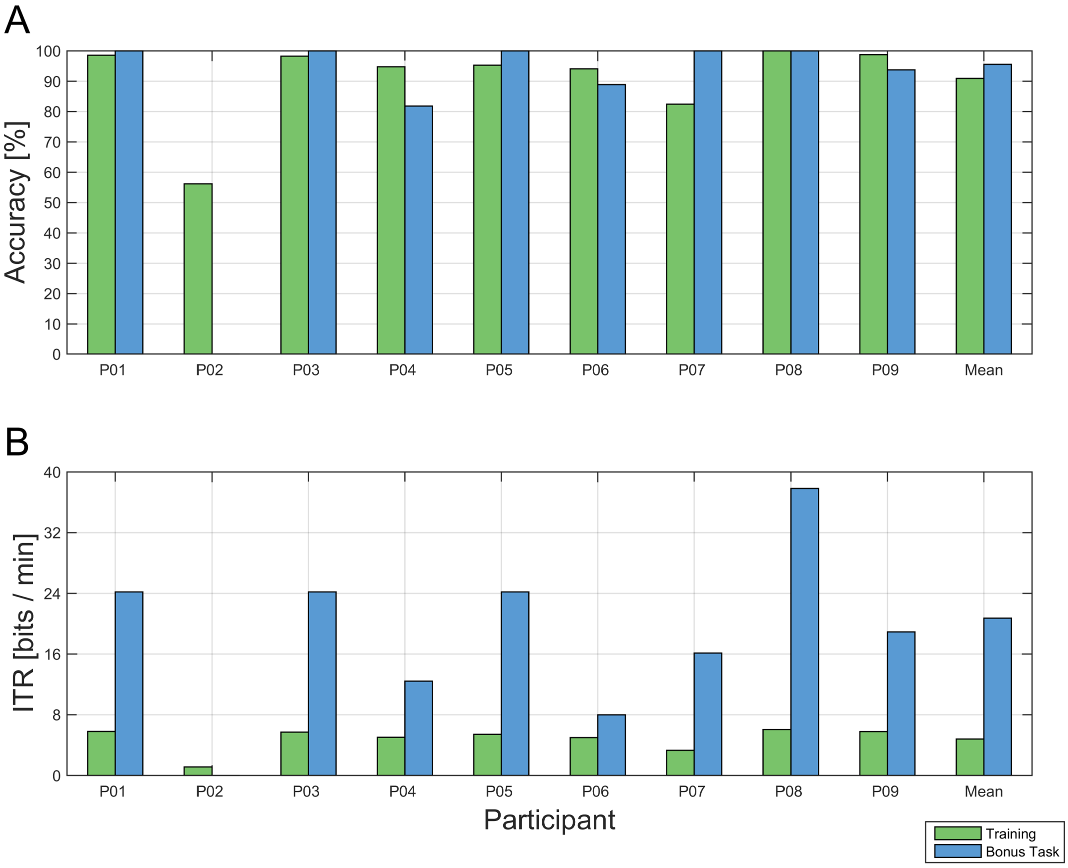


Figure 11: Online performance during training and extra navigation task. A depicts the average accuracy during training and extra task. B depicts ITRs during training and extra navigation task. For the extra task speed was adjusted to the participants' individual abilities, therefore ITR values differ from those achieved during training. Participant 2 did not wish to perform the extra task.

For individual accuracy and ITR values see Figure 11.

All participants stated that it was easy to learn controlling the BCI. Out of 9 participants 8 found the system intuitive, accurate and controllable during wheelchair navigation. In accordance with his performance participant 2 did not agree with these statements. Participant 4 felt that wheelchair control was too demanding and participants 2, 4 and 5 felt that control of the wheelchair was too slow. Evaluation results are summarized in Table 3.

Table 3: Results of the questionnaire on satisfaction with the tactile ERP-BCI based wheelchair control (answers of subjects in %).

	I do not agree at all [%]	I do not really agree [%]	I mostly agree [%]	I fully agree [%]
Control of the wheelchair was quickly learnable	0	0	0	100
Connection of body parts and movement direction was intuitive	11	0	11	78
The wheelchair correctly recognized the delivered commands	11	0	78	11
I always had full control over the wheelchair	11	0	56	33
Control of the wheelchair was too demanding	44	44	11	0
Control of the wheelchair was too slow	56	11	33	0

4.1.4 *Discussion*

4.1.4.1 *Effects of multi-session training on BCI performance (accuracy and ITR, H1a) and underlying ERP features (P300 amplitude, area between curves, H1b)*

We performed a multi-session training with a virtual navigation task. Tactile ERP-amplitudes and area between curves increased significantly during training for electrode positions Fz and Cz. This confirms that regions previously reported to contribute to tactile ERP-BCI (Brouwer & Erp, 2010; Kaufmann et al., 2014; Waal et al., 2012) are in fact the ones that increase most during user training.

Physiological changes induced by training lead to an increase of ITR and accuracy, however, this effect was non-significant for online performance. This may be due to initial performance being already considerably high (5 participants above 90%, 2 participants at 100% on day 1). From previous results (see Table 3) we could not expect such high a performance and encountered, therefore, a ceiling-effect which could not be remedied at that point in time, and did not leave room for any improvement on the behavioural level. We accounted for this limitation by calculating offline single trial accuracies and ITRs and then found significant improvement as a function of training. The P300 ERP also significantly increased with training as did the area between curves of target and non-target response. Taken together, these results confirm our hypotheses H1a and H1b.

Reuter and colleagues (2014) demonstrated increased tactile frequency and pattern discrimination following a tactile stimulation intervention. Not only did this repetitive tactile stimulation increase somatosensory processing but also higher order processing leading to increased P300 amplitudes. While participants of all ages were able to benefit from this intervention, participants with trained tactile perception (e.g. due to job requirements) benefited the most. Our training may rely on similar mechanisms to increase spatial discrimination and therefore P300 amplitudes and is in line with low target discrimination following decreased P300 amplitudes (Comerchero & Polich, 1999).

In our study P300 amplitudes on day 1 were comparable to those elicited by similar tactuators used in previous studies (Brouwer et al., 2010; Thurlings et al., 2012b) and higher than those induced by braille stimulators

(Severens et al., 2013; Waal et al., 2012). During training mean amplitudes surpassed those reported in comparable studies. Furthermore, the time window in which target and non-target differed increased, as reflected in the area between curves, which leads to more reliable classification.

While this is the first multi-session training for tactile BCI, multi-session trainings for visual and auditory BCI have already been published. In a 20-session longitudinal study Nijboer and colleagues (2010) found visual ERP-BCI performance to be stable in ALS patients. Baykara and colleagues (2015) performed a multi-session auditory ERP-BCI training and found increasing BCI performance in healthy participants. This increase in BCI performance did, however, not increase ERP amplitudes. Using a similar multi-session training Halder and colleagues (2015) were able to demonstrate an increase in ERP amplitudes for 3 end-users, similar to the one seen within our study.

While there are many daily life situations where discrimination of visual cues is required, e.g. traffic signals, there are virtually no situations which require discrimination of vibrotactile cues. This could explain why tactile discrimination and to a lesser degree auditory discrimination can be trained, while visual discrimination is already exhausted.

4.1.4.2 *An intuitive, reliable (H2a) and fast (H2b) tactile BCI for navigation tasks*

Participants navigated a wheelchair through a virtual building using a tactile BCI. All participants were able to establish control over the BCI (above random accuracy) on session 1. Notably, 8 out of 9 participants completed the navigation task at least 8 times. Average accuracy during training was above 90% and average performance within the extra task after training was above 95%.

While we were able to achieve mean accuracies as high as 85.8% in a previous study we did so at the price of low ITRs (Kaufmann et al., 2014). Within this study participants were able to reach mean accuracies of 95.56% while maintaining a mean ITR of 20.73 bits / min. This confirms hypotheses H1a and H1b.

One major design goal for our protocol was intuitiveness and ease of use. Common tactuator placements used in previous studies include the trunk (Brouwer et al., 2010; Thurlings et al., 2012b) or the fingertips (Severens et al., 2014; Severens et al., 2013; Waal et al., 2012) of participants. Our tactuator arrangement was spacious with tactuators spread among different body parts as well as congruent with the intended movement directions. Comerchero and Polich (1999) demonstrated the beneficial effect of high target discrimination on P300 amplitudes, therefore the high BCI performance achieved within our study could have been facilitated by good target discrimination due to intuitive and spacious placement of tactuators.

Furthermore, we were able to demonstrate a fast and reliable tactile BCI with participants aged 50 to 73 years, representing the age range of targeted end-user. Commonly targeted end-users for BCI replacing lost functions are patients with amyotrophic lateral sclerosis (Wolpaw et al., 2002) and mean onset age for sporadic ALS is 56 years (Hudson, 1981), underlining the importance of these results. Severens and colleagues (2014) reported tactile performance of 5 patients with ALS in an oddball paradigm using stimulation of the fingertips. Two patients were aged 50 and 56 years, overall performance was below 60% for patients. All other tactile studies as shown in Table 1 had mean participant ages below 30 years, further highlighting the importance of our results.

4.1.4.3 *Age-related effects on tactile performance*

In this study we wanted to examine the viability of tactile BCI for participants aged above 50 years. 9 Participants aged 50 to 73 years performed a navigation task using our tactile BCI. Participants were able to achieve high levels of control and speed, demonstrating high viability despite age-related changes to somatosensory capabilities. This suggests that reduced tactile sensibility may be negligible as stimuli are expected to be above detection threshold anyway and were well tolerated by participants.

4.1.4.4 *Toward wheelchair control*

While we were able to demonstrate accuracies high enough for critical tasks such as wheelchair control in our previous study we did so at the price of low speed. Due to limitations of the BCI2000 software our original protocol used eight vibrations instead of four per sequence, i.e., each tactor was activated twice. Therefore, individual adaptation was limited because odd numbers of stimulations were not possible. Furthermore, the original protocol used one calibration task lasting ten minutes while the current protocol used three calibration tasks each lasting less than four minutes with breaks in between. Taken together the amount of continuous attention required for the current protocol was lower, potentially reducing workload and improving attention. Using our original protocol participants required an average time of 14.5 minutes to complete the navigation task. Within this study participants were able to complete the same task with an average completion time below two minutes. This greatly increases usability, reduces fatigue and improves quality of use.

Tactuators can be concealed under clothing and do not engage visual and auditory senses for stimulus discrimination. Body location of our tactuators was congruent with movement direction and thus, stimulation was rated intuitive by eight out of nine participants. Furthermore, all participants stated that control of the wheelchair was quickly learnable. High acceptance of the protocol might have facilitated high motivation, which has been shown to influence P300 amplitudes (Kleih et al., 2010).

The virtual wheelchair was able to stop a movement command if the wheelchair was near a wall. Most participants however navigated without this support. To evaluate the core BCI performance we did not include any additional support functions. Nevertheless, a shared-control system could allow the user to focus on more global movement commands instead of micromanaging each single step. When navigating familiar spaces good usage of a priori knowledge could reduce the required number of commands significantly. In one of our movement tasks participants had to move from the entrance of the virtual house into a target room. In this setting the first 8 movement commands were issued to traverse an otherwise empty corridor. A sufficiently intelligent system could combine these eight steps into one, as no meaningful decisions have to be made when traversing this corridor. Such a shared control system would need to be carefully balanced to allow the user to feel in control of the system while reducing his workload. Combining high levels of control and speed with such an intelligent shared control system would further improve usability while decreasing fatigue from long-term usage.

4.1.4.5 *Limitations*

Despite participants being aged 50 years and above, which represents the age group of our target end-user population, this cannot replace testing of actual end-users. Silvoni and colleagues (2015) found no significant differences between tactile ERP classification results of ALS patients and healthy participants, supporting the validity of our results. Nevertheless, future studies should focus on testing actual end-users. Generalizability of results is limited due to only 9 participants taking part in our study. Furthermore, we could not detect a peaked learning effect for amplitudes, area between curves, single trial accuracy and ITR. Results might increase with additional sessions.

We performed our study using virtual reality. Navigation of a real world wheelchair will impose additional challenges. Future development will focus on utilizing our protocol for an actual wheelchair.

4.1.5 *Conclusion*

In conclusion, using our protocol participants were able to achieve accuracies and ITRs which surpass not only our previous study but those of all known tactile BCI (for reference see Table 1). Tactile BCI often fail to compete with their visual counterparts as shown in past studies (Aloise et al., 2007; Thurlings et al., 2012b). We were able to demonstrate that an optimized tactile BCI can provide a viable alternative to visual and auditory BCI. Since Kaufmann and colleagues (2013) demonstrated that for some end-users tactile BCI seem to be the most suitable option, it is of great importance to add such high performance tactile BCI to the available toolkit of BCI.

Additionally, our protocol was able to facilitate learning and did significantly improve BCI performance (single trial accuracy and ITRs) and EEG features (ERP amplitudes, area between curves). This is the first tactile BCI study demonstrating the effects of training. Notably, ERP amplitudes, area between curves, single trial accuracy and ITR did not plateau during training, so additional sessions might further improve performance. Reduced tactile perception due to ageing appeared to be negligible within our protocol.

Taken together, our results indicate a promising future for the development of tactile BCI. With an intuitive stimulation design and training, a tactile BCI can provide a fast and reliable gaze-independent alternative to current BCI.

4.2 THE WIN-SPELLER, AN INTUITIVE AUDITORY COMMUNICATION BCI USING NATURAL SPEECH STIMULI

The following study has been published (Kleih et al., 2015). The methodological approach and the results were adopted.

4.2.1 *Aim of the study*

The aim of the study was to design and validate an auditory BCI (WIN-Speller) used for communication which is intuitive and reliable. Additionally, we intend to validate our BCI in motor-impaired end-users who are the target population of auditory BCI research. These goals lead to the following hypotheses:

- Reliable communication with at least 80% accuracy can be achieved by healthy participants (H1) as well as by end-users (H2).

4.2.2 *Design*

4.2.2.1 *Participants*

N = 11 healthy participants (age M = 23.64 years, SD = 3.61) and 4 end-users with motor-impairment were recruited. All end-users were male and able to communicate either by voice (n=1) or by assistive technology for communication (n = 3). Description of the end-users can be seen in table 4. End-user A used a joystick-based communication device but could also whisper sounds which can be translated to language by people who know the patient. End-user B used a voice translator which translated the words detected on the larynx into words that can be heard and understood. End-user C used a joystick-based technology, but most often relied on his caregiver who has known him for years and can translate his expressions to language. End-user D was not yet in need of assistive technology or caregivers for communication. We categorized the level of impairment as suggested by Kübler and Birbaumer (2008). The category minor indicates only slight impairment but normal speech, while moderate refers to patients who are in need of a wheelchair but speech is unaffected. Patients who are tetraplegic with restricted speech are categorized as majorly impaired. All participants had normal or corrected-to-normal vision. They received monetary reimbursement of 8 Euros per hour and gave informed consent to the procedure which was approved by the Ethical Review Board of the Medical Faculty, Eberhard-Karls-Universit of Tübingen.

4.2.2.2 *Stimulation*

For stimulation we collected 6 spoken stimuli which contained at most two syllables, were phonetically diverse and together contained all letters of the alphabet. Selected stimuli were the five German words “Buch”, “Feder”, “Klang”, ”Mops”, Witz” and the non-word “JQVXY”. The five meaningful words were easy and memorable German words translating to: Buch = book, Feder = feather,

Table 4: End-user participant description

End-user	Age	Diagnosis	Level of impairment	Year of -diagnosis
A	43	Traumatic accident	moderate	2004
B	49	Muscle dystrophy (Duchenne)	major	1972
C	58	Traumatic accident	major	2000
D	72	Amyotrophic Lateral Sclerosis	major	2012

Klang = sound, Mops = pug dog and Witz = joke. These words were used for auditory, visual and multimodal presentation. For auditory presentation the words and all individual letters were recorded by a female voice using a TBone microphone and the Cubase LE5 Software. Stimuli were normalized for auditory presentation. For auditory modality stimulus duration ranged between 400 and 1160ms and inter-stimulus-interval was 200ms. For multimodal stimulation the word was shown on screen for 125ms during auditory stimulation. For visual stimulation only on-screen presentation was active. Stimuli were presented using Python scripts (version 2.7, Python Software Foundation) linked to BCI2000 version 3 (Schalk et al., 2004), using UDP.

4.2.2.3 *Data acquisition*

EEG was acquired using 12 AG/AGcl electrodes located at position F3, Fz, F4, C3, Cz, C4, P3, PZ, P4, PO7, PO8 and Oz, referenced to the right and grounded to the left mastoid. Signal was amplified and recorded at 256Hz sampling rate using a g.USBamp (Guger Technologies, Austria). Impedance was kept below 5kOhm and data was filtered online with a high pass of 0.1Hz, a low pass of 30Hz and a notch filter at 50Hz.

4.2.2.4 *Procedure*

Healthy participants took part in two different sessions, with one modality being tested in the first session and the other two modalities in the second session. Measurements were performed in two sessions to balance inconvenience of having multiple measurements against concentration loss due to long sessions. Auditory, multimodal and visual modality were counterbalanced across subjects. For each modality a respective calibration was performed prior to the corresponding task.

Words were continuously presented in randomized order and participants had to focus their attention to one predefined word. One such trial consisted of 10 sequences which equals 20 repetitions per word stimulus. Each of the 6 words was the target word once, resulting in 6 trials for calibration. Afterwards, the number of sequences required to spell with 80% accuracy was calculated for each participant. During calibration no feedback was provided. After calibration participants had to spell the German words "Boje (eng. buoy)", "Sylt" and "Harz" (eng. resin). Words were selected to contain each stimulus word while avoiding duplication of target letters.

End-users only participated in one session using the auditory paradigm only. Otherwise calibration and copy-spelling were performed as reported for healthy participants.

4.2.2.5 *Data analysis*

EEG data was corrected for artifacts (>70µV) and baseline (-100-0ms) using MATLAB (v2013b). P300 were determined using semi-automatic peak detection 200 and 600ms after stimulus onset. Targets and non-targets were averaged and grand averages were shown for the three spelling paradigms. Dependent variables were spelling accuracy as measured in percent of correctly spelled characters, required sequences to reach an accuracy of at least 80% and P300 amplitude. IBM SPSS 20 was used for statistical analysis, the level of significance was set to α = .05.

4.2.3 *Results*

Average online accuracy was 83,69% (SD = 20,73), see table 5 for individual performances. All but 3 participants were able to reach over 70% accuracy, the required minimum accuracy for communication (Kübler et al., 2001) and 8 participants spelled with above 90% accuracy.

While average accuracies achieved in the visual and multimodal paradigms were higher than in the auditory condition (M_{visual} = 97.73%, SD = 4.73; $M_{multimodal}$ = 92.68%, SD = 10.40), three-way repeated measures ANOVA with modality as within-subject factor and accuracy as dependent variable yielded no significant differences between the paradigms (F (2,20) = 3.26, p = .06). When comparing the number of required sequences to reach an accuracy of at least 80% (see Figure 12), three-way repeated mea-

Table 5: Individual online performances of healthy participants (in %).

	BOJE [%]	SYLT [%]	HARZ [%]	Mean	SD
VP1	90	83,33	100	91,11	8,39
VP2	50	16,67	62,5	43,06	23,69
VP3	100	87,5	100	95,83	7,22
VP4	40	80	75	65	21,79
VP5	100	100	100	100	0
VP6	100	100	100	100	0
VP7	90	100	83,33	91,11	8,39
VP8	100	100	100	100	0
VP9	100	90	100	96,67	5,77
VP10	100	90	90	93,33	5,77
VP11	41,67	10	100	50,56	45,65
Mean	82,88	77,95	91,89		
SD	25,45	32,76	12,99		

sures ANOVA with modality as within-subject factor and sequences as dependent variable yielded significant differences between the paradigms (F (2,20) = 10.64, p= .001). In the visual paradigm participants needed significantly less sequences (M = 4.73, SD = 1.27) to achieve 80% accuracy as compared to in the WIN-speller (M = 8.0; SD = 2.41, post hoc contrast (F(1,10) = 18.36, p =.002), but no difference as compared to the multimodal speller was found (M = 5.08, SD = 1.50, post hoc contrast F(1,10) = 3.45, p =.09).

We also compared the Information Transfer Rates in the three paradigms using three-way repeated measures ANOVA and found a significant difference between modalities (F(2,20) = 6.24, p = .008). Post hoc comparisons revealed that the WIN-speller ITR was significantly lower (M = 1.11 SD = .71) as compared to the visual modality ITR (F(1,10) = 12.57, p = .005, (M = 2.04, SD = .68)), but only marginally different from the multimodal paradigm

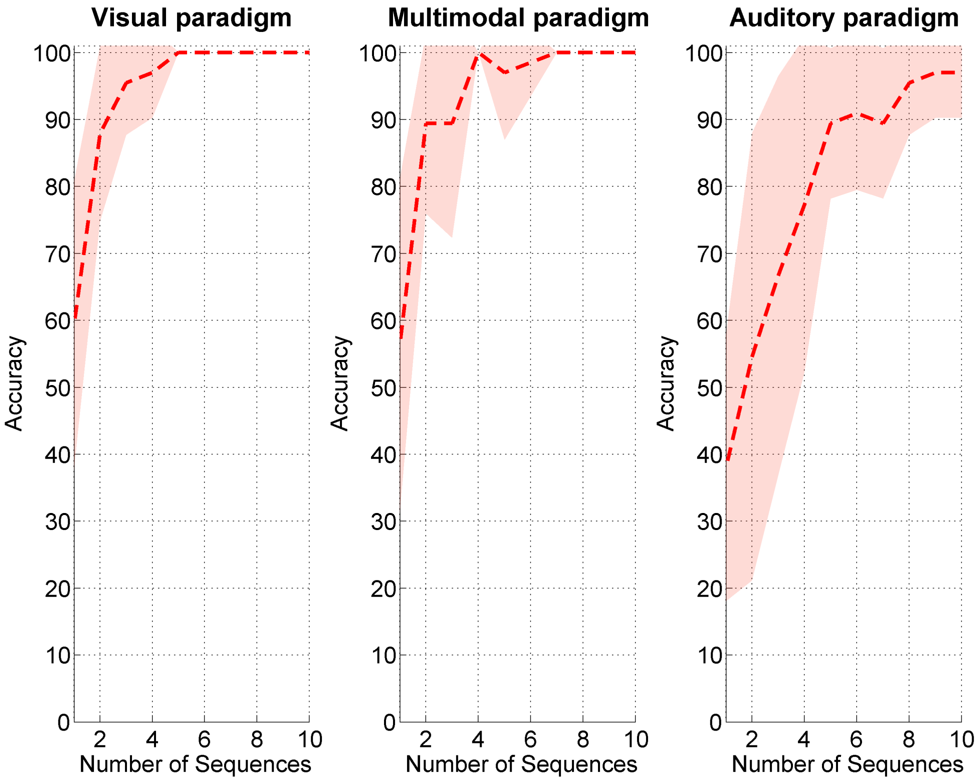


Figure 12: Sequences needed to spell 80% correct in the three spelling paradigms. Standard deviation is depicted in light red.

ITR (F(1,10) = 4.71, p = .06, (M = 1.70, SD = .70)). P300 amplitudes on Cz did not significantly differ between paradigms (F (2,10) = .94, p = .12, see Figure 13, M_{visual} = 9.38, SD = 5.86; M_{multi} = 8.56, SD = 5.83; M_{win} = 6.27, SD = 3.20)) as tested with three-way repeated measures ANOVA (modality as factor and P300 amplitude as dependent variables).

Three end-user participants (B, C and D) achieved average online accuracies of 84.17% (range 75% - 100%), 80% (range 50% - 100%) and 80.83% (range 62.5% - 100%, see Figure 14). Participant A achieved an average online accuracy of 51.85% (range 50% - 55.56%, see Figure 14). While in participant B the P300 was very clearly detectable

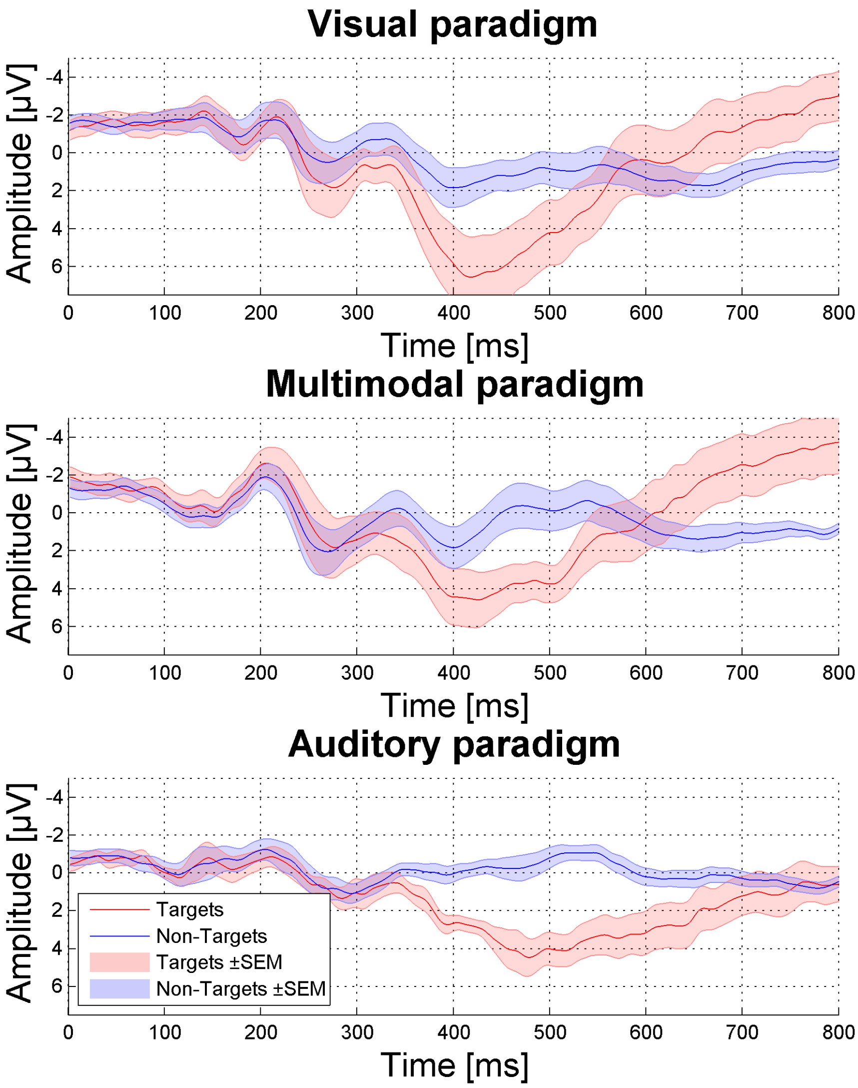


Figure 13: Amplitudes for the three spelling paradigms depicted from Cz. Red and blue shades indicate the standard error of the mean (SEM).

(see Figure 15), targets and non-targets were less distinguishable in participant A (see Figure 15). In participant C immense muscle spasms were triggered by the target stimulus presentation. These muscle spasms caused heavy artifacts but did not hinder the patient from selecting the target letters correctly. The Information Transfer Rate (ITR) was 0.28 for participant A, 1.14 for participant B, 2.13 for participant C and 1.77 for participant D.

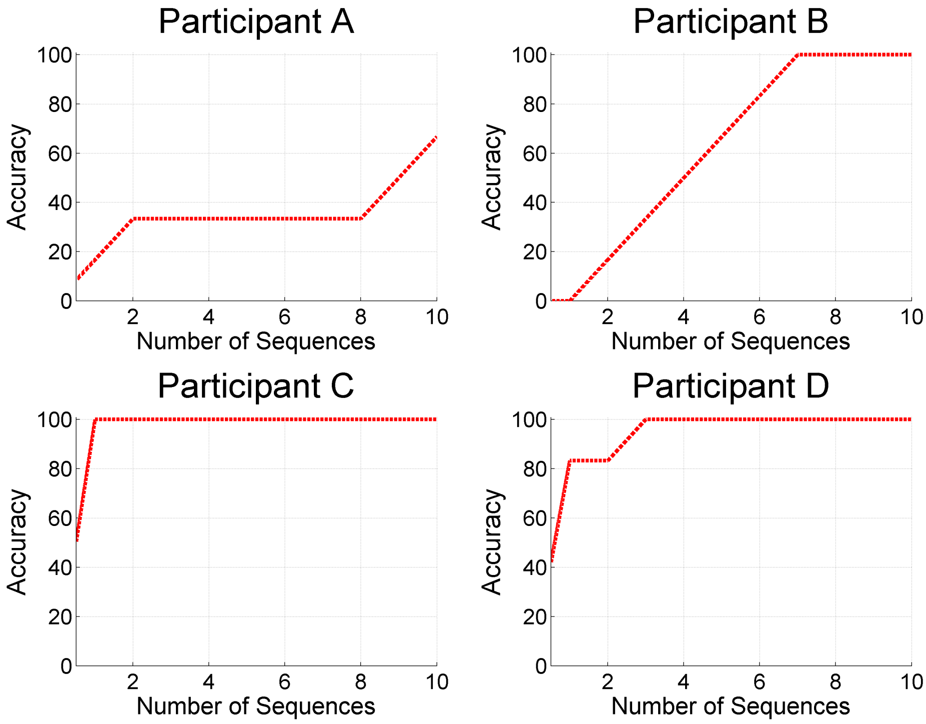


Figure 14: Accuracies reached by motor-impaired end-user participants and according required number of sequences.

4.2.4 *Discussion*

4.2.4.1 *Usability of the auditory speller*

Our auditory speller was successfully used by healthy participants as well as by end-users with motor impairment. Accuracies achieved were comparable to visual spellers (e.g. Kaufmann et al., 2013; Kleih et al., 2010; Treder et al., 2011). Importantly, we demonstrated a speller using an intuitive connection between letters/groups and stimuli. Therefore, no visual support matrixes were needed to utilize our speller. We did so at the price of rather low

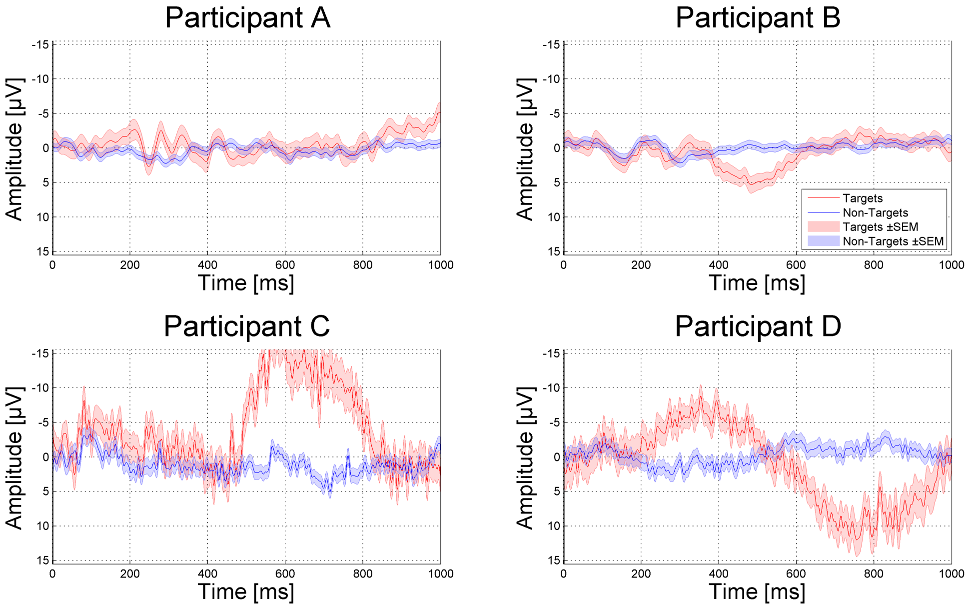


Figure 15: P300 evoked by targets (red) compared to non-targets (blue) depicted from Cz. Red and blue shades indicate the standard error of the mean (SEM).

ITRs. Comparing our speller to other auditory studies as seen in table 1 our ITR ranges among the lower ranks. It is, however, notable that the only other study with intuitive stimuli as performed by Höhne and colleagues (2014) did not achieve the required accuracy for meaningful communication. Therefore, our protocol is currently the only viable auditory speller using neither visual support nor artificial target to stimulus encoding.

For end-users with severe motor impairement our intuitive design and decrease in workload might be of higher value than increased speed of communication. A multiclass speller encoding targets using unrelated stimuli might even be unviable for some end-users due to higher cognitive demand.

4.2.4.2 *Words as stimuli*

For our auditory speller we choose a collection of two-syllabi words containing all 26 letters of the alphabet. The ideal choice of words should, however, be determined in future studies. Current results regarding the frequency of words within the spoken language and the amplitudes they elicit are conflicting. On the one hand it has been demonstrated that frequent words elicit smaller P300 amplitudes as compared to infrequent words (Hauk & Pulvermüller, 2004; Rugg, 1990, e.g.). These studies state that frequent activation of word representations increases neuronal connectivity and therefore requires less activation resulting in smaller P300 amplitudes. On the other hand studies reported higher P300 amplitudes in response to frequent words (Polich & Donchin, 1988; Scott et al., 2009). Authors of these studies suggest that frequent word usage facilitates increased connectivity ultimatively increasing P300 amplitudes. Therefore, word frequency within the spoken language of the stimulus words used in the WIN-Speller paradigm is a variable to be thoroughly investigated in the future. Furthermore, the inclusion of speakers of both sexes as well as inclusion of spatial information (Käthner et al., 2013; Schreuder et al., 2010) might increase discriminability of word stimuli.

4.2.5 *Conclusion*

We presented a new auditory spelling paradigm, the WIN-speller, which is easy to use and, most importantly, applicable with high accuracies in motor-impaired end-users. No visual support is needed to control the speller. Possibly the WIN-speller paradigm might also be usable for end-users who cannot operate other auditory multi-class spellers which impose higher working memory load as codes and goals (words to spell) have to be maintained in mind. Following the user-centered design (Kübler et al., 2014), different auditory paradigms could be presented to an individual end-user and the most successful one with respect to effectiveness, efficiency and satisfaction could be chosen as an individualized solution. The possible benefit of using the WIN-speller has to be evaluated in the future by end-users who cannot operate visual spellers.

4.3 TACTILE AND AUDITORY PERFORMANCE OF SENSORY EXPERTS

4.3.1 *Aim of the study*

BCI based on visual stimulation perform higher than those based on tactile or auditory stimulation (see Table 1). This might be due to visual perception being the primary information channel in most day-to-day activities. Goal of this study was to evaluate whether visual stimuli do inherently elicit higher ERP responses or whether this effect is due to increased training in the visual modality. For this purpose we intend to compare EEG features and performance of visually impaired participants (referred to as sensory experts) to those of control participants.
These goals lead to the following hypotheses:

- Sensory experts perform better utilizing a tactile or auditory BCI than control participants (H1)
- Sensory experts' EEG features are higher for tactile or auditory modality than those of control participants (H2)
- Sensory experts perform as high in tactile (H3.1) and auditory (H3.2) modality as control participants do in visual modality.

4.3.2 *Design*

4.3.2.1 *Participants*

Healthy (n = 9) and visually impaired (n = 9) participants (age M = 32.77 years, SD = 9.23 years) were recruited for this study. All participants were naïve to BCI and all healthy participants reported normal or corrected-to-normal vision. None of the control participants reported regular participation in activities that might result in relevant sensory expertise, e.g. playing an instrument or job-related demand of fine motor control of the hands. All of the visually impaired participants, however, were able to read braille and legally blind. Visually impaired participants were recruited via support groups and specialized educational facilities, control participants were recruited via postings. All participants received monetary reimbursement of 8 Euros per hour and gave informed consent to the procedure.

4.3.2.2 *Stimulation*

Healthy participants took part in tactile, auditory and visual stimulation while sensory experts only performed tactile and auditory modality.

For tactile stimulation we adapted the tactile stimulation protocol used in our wheelchair training study by changing the tactor positions. To exploit the potential training effects of braille readers we stimulated fingers commonly used for braille reading, i.e. index and middle finger of both hands . Tactile stimulation was applied using C2 tactors (Engineering Acoustic Inc., Casselberry, USA), stimulus duration was 220ms and inter-stimulus-interval was 400ms .

To keep in line with the tactile protocol we used a four-class auditory protocol. Similar to the WIN-Speller we utilized spoken words as auditory stimuli and recorded german translations of the words used in a four-class speller by Sellers and Donchin (2006)("ja", "nein", "weiter" and "stop"). Additionally, to be more in line with our tactile protocol we changed the stimulation parameters compared to those used by Sellers and Donchin (2006). To allow reasonable presentation of the spoken words while maintaining stimulus duration was between 300 and 500ms with inter-stimulus-interval ranging from 500 to 300ms accordingly.

For visual stimulation we presented the words "ja", "nein", "weiter" and "stop" in the center of the screen for 300ms followed by a 500ms inter-stimulus-interval.

4.3.2.3 *Data acquisition*

EEG was acquired using 12 passive Ag/AgCL electrodes at positions Fz, FC1, FC2, C3, Cz, C4, P3, Pz, P4, O1, Oz, O2 with ground and reference at the right and left mastoid. Impedance was kept below 5 kOhm. Signals were amplified and recorded at a sampling rate of 512Hz using a g.USBamp (g.tec Engineering GmbH, Graz, Austria). EEG was filtered online using a Band Pass filter between 0.1 and 60Hz and a notch filter between 48 and 52 Hz.

4.3.2.4 *Procedure*

Control participants and sensory experts recruited via postings were measured within our laboratory in Würzburg, sensory experts recruited via educational facilities were measured on-site. Experimental procedure was identical for all modalities.

Participants performed three calibration runs before classifiers were generated. Stimuli were presented continuously in randomized order while participants had to focus on a predefined target stimulus. Each stimulus had to be attended twice, resulting in eight trials for each calibration run. For each such trial each target was stimulated 10 times, resulting in a total of 40 stimulations per trial. During calibration no feedback was given.

Participants then performed four copy-tasks using seven, five, three and one sequence for classification. Participants had to focus on each target twice again, but received auditory feedback (selected command) after each selection.

This procedure (calibration and copy-task) was then repeated for the remaining modalities. The order in which the modalities were tested was counterbalanced across subjects. All modalities were tested within one session lasting between 2 and 2.5 hours.

4.3.2.5 *Data analysis*

EEG data was filtered between 0.1 and 30Hz and divided into segments of 800ms post-stimulus using MATLAB© (v2013b). Segments were grouped into target and non-target segments and averaged respectively. Classification models were build using SWLDA using 800ms following stimulus onset.

Statistical analysis was performed using IBM SPSS 22®. Performance differences between modalities within control participants were tested using repeated-measures anova with modality and number of sequences as within-subject variables and performance as dependend variable. Our hypothesis of increased performance in sensory experts compared to control participants (H1) was tested using a repeated-measure anova with modality and number of sequences as within-subject variables, group as between subject variable and performance as dependent variable. Exploratory we tested between groups for number of sequences not effected by ceiling-effects using t-tests. Hypothesis H2 was tested using t-tests with amplitudes and area between curves as dependent variables testing experts against control participants. Unless stated otherwise amplitudes and area between curves were extracted from electrode position Cz using data from all three calibration runs. For hypotheses H3.1 and H3.2 visual performance of control participants was tested against auditory and tactile performance of sensory experts using t-tests, α was adjusted to .0125 due to multiple testing.

4.3.3 *Results*

Expert participants' performance was above 70% for all number of sequences using tactile stimulation but below 70% using auditory stimulation. Control participants achieved above 70% performance using tactile stimulation with 7, 5 and 3 sequences but not using single trial classification. For details see table 6.

Table 6: Mean performance of sensory experts and control participants in tactile, auditory and visual (for control only) modality. Values shown in brackets are the standard deviation.

Modality	Number of sequences	Accuracy [%] Control	Accuracy[%] Experts
Tactile	7	90.6 (11)	97.2 (8)
	5	92.2 (9)	93.1 (11)
	3	71.9 (17)	88.9 (15)
	1	56.3 (12)	73.6 (19)
Auditory	7	62.5 (28)	67.9 (30)
	5	64.1 (25)	66.1 (26)
	3	37.5 (22)	53.6 (27)
	1	39.6 (16)	51.8 (30)
Visual	7	100.0 (0)	
	5	97.5 (5)	
	3	92.5 (6)	
	1	65.0 (12)	

For control participants, we found significant differences between tactile, auditory and visual modality (F(2,14) = 26,867, p <.01) and between sequences (F(3,21) = 31.919, p<.01). Mean performance was higher for expert participants compared to control participants in tactile and auditory modality, see Figure 16. This difference was, however, non-significant. For tactile performance this might be due to ceiling-effects, therefore we performed an exploratory analysis and tested performance using three and one sequence only. This analysis revealed significant results (α corrected due to multiple testing) for tactile modality using three sequences (t(15) = 2.197, p < .025) and one sequence (t(15) = 2.219, p < .025)

Comparing visual performance of control participants to auditory performance of experts, we found significantly higher visual performance for seven (t(13) = 3.085, p < .01 , r= 0.65), five (t(13) = 3.430, p < .01 , r = 0.689) and three (t(13) = 4.058, p < .01 , r = 0.748) sequences. Visual performance of control participants was, however, not significantly higher than tactile performance of sensory experts for all numbers of sequences.

Mean ERP amplitude was higher for experts than for control for tactile and auditory modality (see Figure 17). This effect was, however, not significant. Mean area between curves of experts was significantly higher for tactile modality (t(15) = 1.866, p < .05, r = 0.434), while being non-significantly higher for auditory modality. Mean ERPs are shown in Figure 18.

Amplitudes for visual modality were significantly higher than those for tactile (t(14) = 2.074, p < .05, r = 0.485) and auditory (t(14) = 5.247, p < .001, r = 0.814) modality (sensory experts). Area between curves of visual ERPs, however, was only significantly higher against auditory modality (t(14) = 2.348, p < .05, r = 0.518).

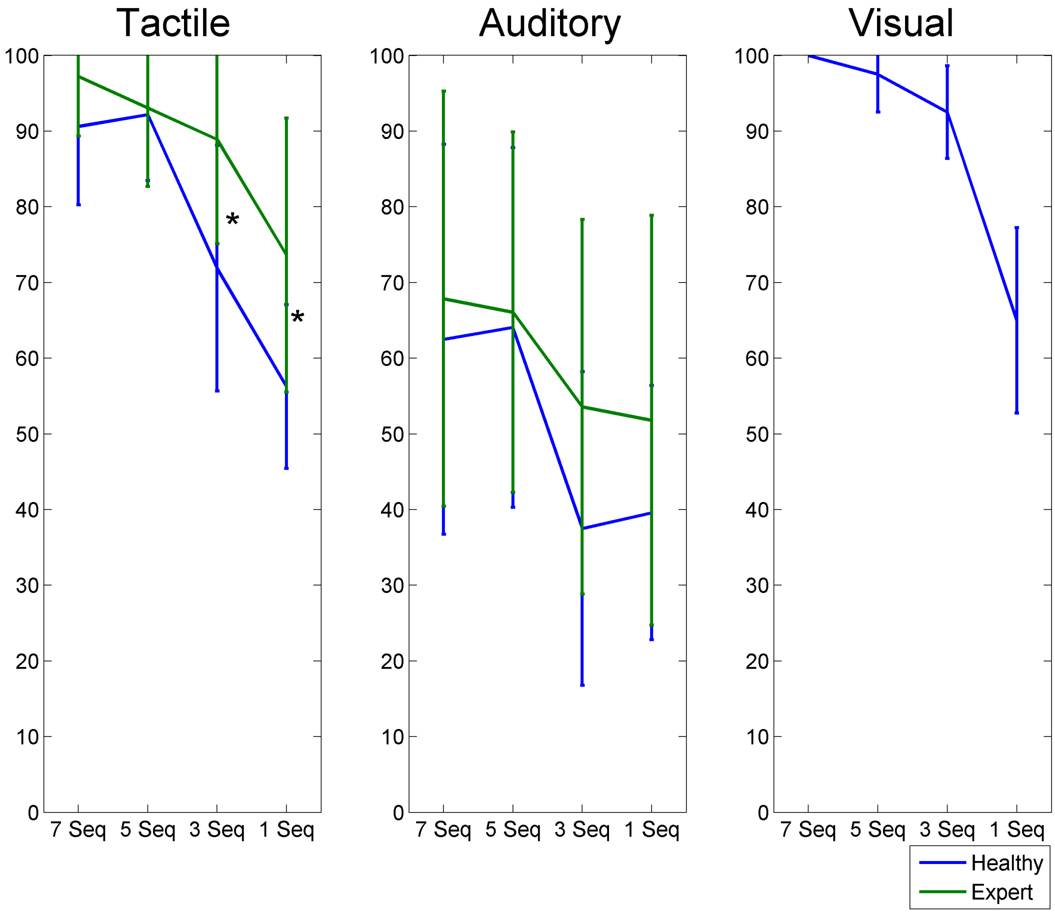


Figure 16: Copy-spelling performance of expert and control group using tactile, auditory and visual (for control only) modality for 7, 5, 3 and 1 sequence(s). Green lines indicate experts, blue lines indicate control participants. Error bars indicate standard deviation.

4.3.4 *Discussion*

4.3.4.1 *BCI performance of sensory experts*

Sensory experts and control participants took part in a copy-spelling experiment utilizing different modalities. Participants were able to establish above random control in all modalities. Performance was higher for tactile modality (up to 90.6% for control and 97.2% for experts) compared to auditory modality (62.5% for control and 67.9% for experts). For all numbers of sequences experts performed

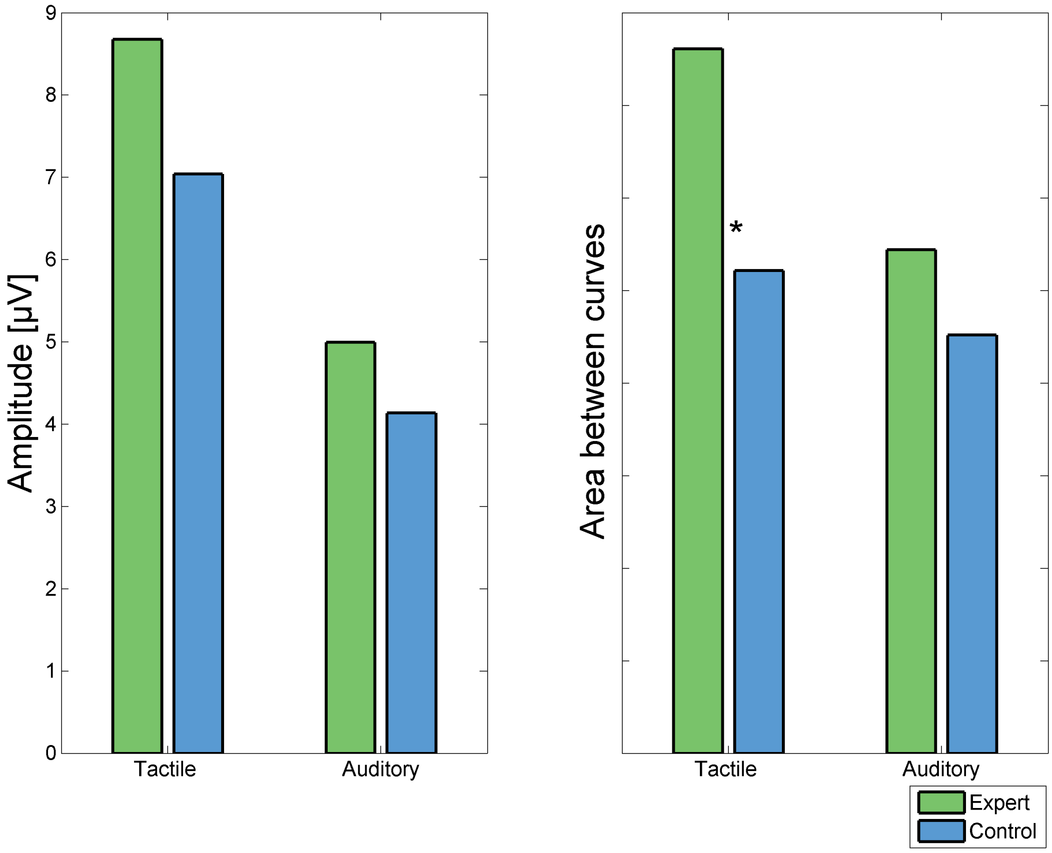


Figure 17: Amplitude and area between curves for tactile and auditory modality for expert and control groups.

higher than control participants, however only for tactile modality using 1 or 3 sequences this effect was significant. Nevertheless, we partially accept hypothesis 1 of sensory experts performing higher than control participants.

Sensory experts were able to achieve tactile BCI performance on the same level as control participants did in the visual modality. This results is of high importance, as it suggests that tactile performance can match that of visual BCI after extensive training. Performance within the auditory modality was significantly lower than visual performance. Therefore we accept hypothesis H3.1, but reject H3.2.

While we expect sensory experts to be better trained in tactile and auditory modality, it is reasonable to assume that

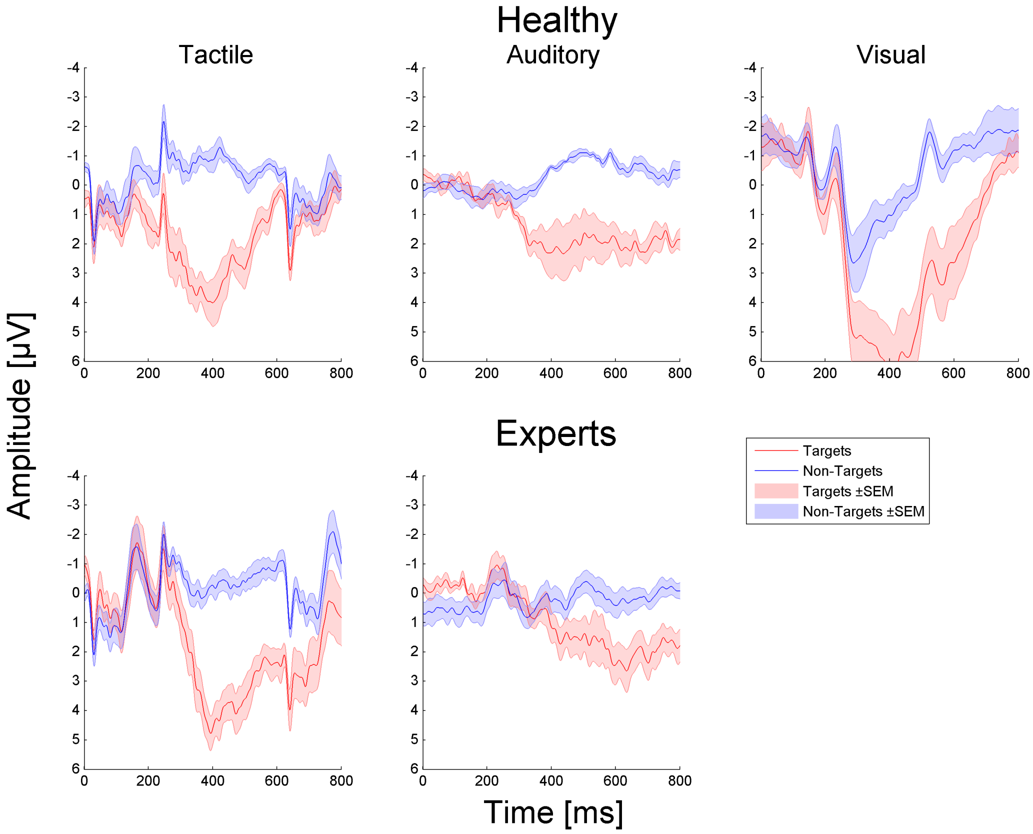


Figure 18: Mean ERPs for experts and controls for tactile, auditory and visual (control only) modality at position CZ. Target response is indicated in red, non-target response shown in blue. Shaded areas indicate standard error of the mean.

this effect is much more pronounced in the tactile modality. All sensory experts were able to read braille using their fingertips. This extensive training might be the reason due to which we were able to observe significant performance differences in the tactile modality albeit only during exploratory analysis. For the higher number of sequences in the tactile modality we likely observed a ceiling-effect with both experts and control group achieving accuracies above 90%.

Within this study control participants achieved a mean accuracy of 92.2% with five stimulation sequences. This result is in line with results from our first study in chapter 4.1 and demonstrates the validity of our results.

4.3.4.2 *ERP and Area between curves of sensory experts*

P300 amplitudes were higher for experts in both tactile and auditory modality. This effect, however, was not significant. Yet, area between curves was significantly higher for tactile modality. Again we partially accept hypothesis 2 due to experts demonstrating increases in relevant EEG features.

While we found significantly higher P300 amplitudes for visual modality compared to tactile modality (sensory experts) we found no significant difference in the area between curves. This is in line with our results demonstrating no significant differences in performance between tactile (sensory experts) and visual modality. This also suggests that classification for tactile modality is less driven by the P300 amplitude than it is for visual modality.

It has been previously shown that blind subjects sometimes recruit regions inside the visual cortex for processing of tactile stimuli when reading braille (Sadato et al., 1996). More recently, Saito and colleagues (2006) were able to demonstrate similar effects for sighted individuals with highly trained tactile perception. Such changes in the processing of tactile stimuli might explain differences in ERP responses between experts and control participants.

For auditory perception similar cross-modal activity can be observed for experts using echolocation for navigation (Thaler et al., 2011). Echolocation experts listening to their own echolocation sounds show activity in regions typically devoted to vision, suggesting basic visual representation. Anyhow, none of the participants of our study reported the ability to utilize echolocation. Recruiting participants with a skillset more balanced towards auditory expertise might have shown increased effects in the auditory modality.

Even without echolocation training we assume sensory experts to be more trained in auditory perception than control participants. Anyhow, the difference between experts and control participants might be less severe for auditory than for tactile modality. Reading braille is a task not performed by control participants at all. Therefore, if braille reading does produce relevant expertise we would expect sufficient differences between experts and control. Most tasks related to auditory perception, however, are performed by control participants as well as by experts, potentially resulting in a smaller difference in expertise. This would explain why our small sample size did not yield a significant difference for the auditory modality.

4.3.4.3 *Limitations and outlook*

While we were able to demonstrate the effects of extensive training on BCI performance, we were unable to observe significant changes for the auditory modality. Our group consisted primarily of tactile experts with extensive braille reading training. Future studies should include auditory experts with experience in using echolocation which would most likely be more adequate to examine auditory performance. Additionally, a greater sample size would be needed to strengthen our results. Future studies should also focus on sensory experts not suffering from visual impairment to identify tasks which could serve as potential training interventions to improve BCI performance.

4.3.4.4 *Conclusion*

Sensory experts demonstrated increased BCI performance and EEG features for tactile modality, partially on the level of visual modality. For auditory modality, however, no significant effects could be observed. Participants of our study were trained braille readers. None of our participants were, however, trained in using echolocation, possibly explaining why tactile performance benefited more. Despite our small sample size were able to show a significant effect of training on tactile performance, demonstrating the importance of training for tactile BCI. Future research is required in order to find potential training interventions to increase BCI performance.

Part V

GENERAL DISCUSSION

In the following chapter the extend to which the formulated goals were achieved, how results can be related to current studies and which questions should be examined in future studies are discussed.

5

GENERAL DISCUSSION

In chapter 3.2 the following goals for this thesis were formulated:

GOAL 1 To design a tactile BCI used for mobility which is intuitive *(G1.1)*, reliable *(G1.2)* and fast *(G1.3)* while being usable by participants aged 50 years and above *(G1.4)*.

GOAL 2 To design an auditory BCI used for communication which is intuitive *(G2.1)* and reliable *(G2.2)*.

GOAL 3 To examine the effects of training on tactile *(G3.1)* and auditory *(G3.2)* BCI performance.

5.1 GOAL 1: INTUITIVE, RELIABLE AND FAST TACTILE BRAIN-COMPUTER-INTERFACING

Tactile modality can be utilized in a very unobtrusive way without blocking commonly needed perception channels while being wearable concealed beneath clothing. Additionally, tactile stimulation inherently carries positional information, e.g. a person receiving a "tap on the shoulder" does intuitively know where to turn to. This opportunity to intuitively link the information contained within the stimulus to an application using corresponding directions has not been used before and despite these advantages, tactile stimulation is rarely used for BCI, most likely due to low reported accuracy and ITR values (see table 1).

In chapter 4.1 we evaluated a tactile mobility BCI which was designed to be intuitive, reliable and fast. Out of nine participants aged 50 years and above eight were able to navigate a virtual wheelchair with mean accuracies above 95% and ITR above 20 bits / min while rating the control as intuitive and easy-to-use.
We were therefore able to demonstrate the viability of tactile stimulation for a highly reliable and fast BCI application.

5.2 GOAL 2: INTUITIVE AND RELIABLE AUDITORY BRAIN-COMPUTER-INTERFACING

Speech as the primary carrier of human communication is linked to the auditory modality. Nevertheless, most auditory communication BCI use artificial stimuli to encode target selections (e.g. Höhne et al., 2011; Schreuder et al., 2011). Translation keys need to be kept in working memory or visual support matrices are utilized (Furdea et al., 2009). Höhne and Tangermann (2014) recently presented a BCI utilizing multiple continuous streams of spoken letters, removing additional encoding, but failing to achieve accuracy required for meaningful communication.

In chapter 4.2 we evaluated an auditory communication BCI which was designed to be intuitive and reliable, the WIN-Speller. It was applicable with high accuracies in motor-impaired end-users as well as in healthy participants. While speed of the system rates low compared to other auditory BCI (see 1) we demonstrated the first viable auditory gaze-independent spelling BCI using intuitive and natural stimuli.

5.3 GOAL 3: TRAINING FOR NON-VISUAL BCI

Performance for visual BCI has been reported to be stable over the course of 20 sessions (Nijboer et al., 2010). For auditory BCI, however, beneficial effects induced by training have been reported (Baykara et al., 2015; Halder et al., 2015). No studies examining the effect of training on tactile BCI performance have been performed before.
In chapters 4.1 and 4.3 we examined the effects of a multi-session training and compared performance of sensory experts to that of control participants. During a multi-session training participants were able to significantly increase tactile BCI performance. Pretrained sensory experts performed significantly higher than control participants using a tactile BCI. Sensory experts, however, did not significantly outperform control participants in the auditory modality. This might be due to higher expertise in tactile than in auditory modality.

5.4 IMPLICATIONS TOWARDS BCI RESEARCH

BCI research has recently started adopting the user-centered design approach (Kübler et al., 2014) to improve usability of BCI-systems. Several approaches have been taken to improve usability of the BCI system for end-users, family and caregivers. Within this study, we focused on improving the usability of the control task itself. It has previously been shown that ERP amplitudes are effected by task difficulty (Kok, 1997; Polich, 2007). In line with this we tried to reduce task difficulty by utilizing intuitive auditory and tactile stimuli.

During usage of a classical visual p300-matrix users will focus on the required letter and automatically ignore most non-target stimuli. This is not possible when using tactile or auditory BCI and all stimuli, target and non-target, will always be perceived. This amplifies the need for stimuli which are congruent to the desired command to emphasize easy identification and interpretation of stimuli. Thurlings and colleagues (2012) have previously shown that incongruent control-display mapping does decrease task performance and corresponding p300-responses. The authors suggest that these effects are related to increased errors during target determination stage and less available attentional resources during target attending stage. Furthermore, in a direct comparison congruent horizontal mapping yielded higher p300-responses than congruent vertical mapping, which might be based on daily life navigation being mainly horizontal. Our tactile navigation BCI mapped stimuli to their corresponding movement directions congruent and horizontal, potentially contributing to the high performance of the system.
Höhne and Tangermann (2014) recently presented the CharStreamer Paradigm utilizing stimuli congruently mapped to commands. While stimuli from the CharStreamer Paradigm are similar to the stimuli used within the WIN-Speller some noteworthy differences exist.

The CharStreamer and the WIN-Speller both use stimuli which represent themselves, instead of using an artificial target to stimulus encoding. The CharStreamer Paradigm does use a continuous stream of up to three simultaneous stimuli with up to 12 stimuli each second. This approach does facilitate high speed, however, mean accuracy for this high speed condition was 47%, which is below the required level for communication of 70%(Kübler et al., 2001). Nevertheless, usability of the system was rated high. In conclusion, both tactile and auditory BCI seem to benefit from congruent and therefore potentially intuitive stimuli.

Within this thesis we evaluated an intuitive tactile BCI and achieved performance levels previously unreported for tactile modality. This might be due to our intuitive design facilitating ease-of-use. While demonstrating causality between performance and intuitivness was out of scope for this work an intuitive design can be expected to increase the overall satisfaction when using the BCI. Therefore optimizing the used stimuli towards being intuitive and easy-to-use should always present a priority when designing a BCI. Delivering the user an intuitive and easy-to-use approach might be of special relevance when working with end-users unable to utilize high workload applications.

Utilizing multi-session training has so far been neglected for tactile BCI and only recently started being addressed for auditory BCI (Baykara et al., 2015; Halder et al., 2015). Baykara and colleagues (2015) performed a five session training with healthy participants and observed significant performance increases which saturated at the third session. Halder and colleagues (2015) performed a five session training with end-users. Performance and p300-amplitude did increase for three out of five end-users. Our results demonstrate a similar beneficial effect of training on tactile BCI performance. During our five session training no saturation of amplitude or area between curves could be detected, therefore performance might be further increased by more training sessions. These results emphasizes the need to include multi-session studies in tactile BCI research. Tactile discrimination is rarely needed in normal day-to-day activities and might therefore be the modality which benefits most from adequate user training. To evaluate potential end-user performance it is crucial to include trained users.

Patients suffering from ALS, the major target population for BCI applications, tend to lose the ability to use visual BCI during later stages of disease progression. Therefore, auditory and tactile BCI are of high relevance for later disease stages and for all applications where users should retain visual perception.

Nevertheless, tactile stimulation is rarely used as revealed by a search on the US National Library of Medicines Platform PubMed. Searching for the terms BCI AND (P300 OR ERP) reveals a total of 833 published scientific articles. Of these 833 articles 21 (2.5%) revolve around tactile stimulation. For those articles reporting accuracy and ITR both are generally below those reported for visual BCI (see table 1) and in direct comparison tactile modality has been shown to perform lower than visual modality (Thurlings et al., 2012b). Additionally, all modern computers are equipped with adequate visual and auditory capabilities usable for BCI studies while tactile stimulators have to be acquired separately. Furthermore, tactile stimulators are unlikely to be natively supported by most BCI software platforms, imposing additional investment. For these reasons tactile BCI research might appear unattractive despite the modalities' unique advantages.

Our tactile BCI for movement control demonstrated previously unreported levels of accuracy and speed, approaching those achieved by visual BCI. Additionally, this high level of accuracy was reproduced by control participants within our sensory experts study, solidifying the validity of our results. Furthermore, we were able to demonstrate the beneficial effects of training on tactile performance.

Demonstrating a tactile BCI with high effectiveness and efficiency, the main evaluation criteria for BCI applications, could partially remedy a perceived unattractiveness of tactile BCI research. Therefore, our results are of great impact for tactile BCI research and should further the development and optimization of tactile BCI.

5.5 CONCLUSIVE RECOMMENDATION

Based on the results of the thesis the following recommendations for future research can be made:

- Intuitive design should be a focus for future BCI control schemes. Not only might well-designed stimuli potentially increase ease-of-use and decrease workload, they can also increase effectiveness and efficiency, therefore addressing important aspects of the user-centred design approach.

- Performance of tactile BCI application should be evaluated after training. For long-term usage an end-user can be expected to be trained by continuous usage of the BCI, therefore target performance will be that of a trained user. Failing to adequately include training effects into evaluation will bias towards visual BCI which seem unaffected by training.
- While sensory experts can be used to demonstrate the effect of training on BCI performance, we were also able to show significant effects using healthy participants within just five sessions. When recruiting sensory experts existence of adequate skills should be checked, e.g. braille reading for tactile expertise or echolocation for auditory expertise.

5.6 OUTLOOK ON FUTURE STUDIES

After demonstrating a highly viable protocol for tactile BCI, a multitude of minor improvements can further increase efficiency, ease-of-use and satisfaction of the system. Several studies were able to demonstrate the usefulness of shared-control approaches (Carlson et al., 2011; Galán et al., 2008; Philips et al., 2007; Tonin et al., 2010; Vanacker et al., 2007). Shared-control mechanism can shift operation from process control towards goal selection or weight users' EEG-features based on additional context information. Due to the very high accuracy that participants achieved with our BCI, the main focus should be to reduce the number of commands needed to achieve a specified goal, further increasing the ease-of-use. Our current protocol moves the digital equivalent of one meter with each forward or backward selection. In many cases distances between meaningful navigation decisions will be several meter at least. For such cases a sufficient intelligent shared-control system could perform several movement commands with only one user input, reducing the time needed to reach the target. For known environments an intelligent wheelchair could also traverse whole obstacles such as doors with only one adequate BCI command. Such changes would greatly increase usability and further reduce the workload imposed on the user.

Furthermore, the system should be evaluated using a real wheelchair, as navigating the real world will provide additional challenges. Debener and colleagues (2012) were able to demonstrate reasonable classification accuracies when performing an auditory oddball task while walking in outdoor environments. Classification accuracy was lower for outdoor compared to indoor measurements, whether this resulted from additional residual noise or a difference in cognitive processing resources invested while walking remains open. Potential influences due to walking can be ignored for wheelchair control, other distractors not found in a controlled environment, however, could potentially influence BCI performance. Resilience of tactile BCI control to distraction has yet to be examined. Additionally, for a real wheelchair a switch to start and stop navigation should be implemented, e.g. by adding an additional feature such as SSEP.

Similarly, our auditory BCI could also benefit from a system to reduce the number of commands required. It has been shown that communication BCI can benefit from text autocompletion (Felton et al., 2007) and predictive text entry (Kaufmann et al., 2012). Similar approaches could be applied to an auditory communication BCI. Additionally, current studies provide inconsistent results towards the ideal choice of stimulus words for a p300-based BCI (Hauk & Pulvermüller, 2004; Polich & Donchin, 1988; Rugg, 1990; Scott et al., 2009). Optimization of stimulus material should be a focus of future studies.

Regarding the effect of training on BCI performance we observed a continuous improvement over five sessions without saturation. Additional sessions might provide additional benefits towards BCI performance. The existence of predictors for potential increases in tactile performance due to training should be examined. Future studies should also explore whether there are more efficient training protocols which allow for faster learning than usage of the target protocol. For end-users it will be desirable to achieve training by usage of the target protocol, but for research purpose reducing the number of sessions required for an accurate performance estimate might be desirable.

6

GENERAL CONCLUSION

This thesis successfully contributed to BCI research by further enhancing the current toolkit of available BCI protocols. A high performing and intuitive tactile BCI for mobility was designed and evaluated, demonstrating that tactile BCI can achieve performances as seen in visual BCI. Furthermore, viability of tactile stimulation for users aged above 50 was demonstrated and significant effects of training on tactile BCI performance were found. Additionally, a reliable and intuitive gaze-independent auditory BCI for communication was developed. Our auditory BCI was usable by motor impaired end-users and might provide a viable alternative for end-users unable to use gaze-dependent spellers. Results show promising avenues for future research in the field of gaze-independent BCI.

Part VI

APPENDIX

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APPENDIX

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EIDESSTATTLICHE ERKLÄRUNG

Hiermit versichere ich, Andreas Herweg, geboren am 22.06.1986 in Bergisch Gladbach, an Eides statt, die Dissertation
Beyond the state of the art,towards intuitive and reliable non-visual brain-computer-interfacing
eigenständig, d.h. insbesondere selbständig und ohne Hilfe eines kommerziellen Promotionsberaters, angefertigt und keine anderen als die von mir angegebenen Quellen und Hilfsmittel verwendet zu haben.

Ich erkläre außerdem, dass die Dissertation weder in gleicher noch in ähnlicher Form bereits in einem anderen Prüfungsverfahren vorgelegen hat.

Würzburg, Januar 2016

Andreas Herweg