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USING A LOW-COST GYRO AND EEG-BASED INPUT DEVICE IN INTERACTIVE GAME DESIGN

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Abstract

Brain-Computer interfaces (BCIs) and computer games have long enjoyed a strong connection - a connection that has only gotten stronger over the years. BCI research applies games to motivate subjects in user studies and to validate new control concepts. Modern game design can in return benefit from BCIs as a new input modality that has the potential to enable yet undiscovered new types of gameplay. Although these two fields relate to each other in many ways, there is still a gap inbetween. BCI technologies have become robust enough to bring forth the first affordable consumer BCI devices, but still they are not incorporated by modern game design. Conversely, there is no easy solution to control proprietary commercial games using non-standard input devices like BCIs. Additionally, the lack of haptic feedback from keys and buttons needs to be compensated with a customized graphical user interface (GUI). Many proprietary (game) applications do not provide the possibility to enrich GUIs with additional feedback elements.

With the herein presented Graz BCI Game Controller (GBGC) a profound solution is described that provides a control interface for commercial game titles. Any input device with an open application programming interface (API) can be incorporated by, and therefore be used to control, popular games. The proposed GBGC interface extension engine (IEE) demonstrates how GUIs of third-party applications can be tailored to provide sufficient visual feedback for the user of non-standard input devices.

The potential of the low-cost Electroencephalogram (EEG), Electromyogram (EMG), and gyro sensor based EPOC headset, provided by Emotiv Systems, Inc., is systematically investigated. Firstly, the EPOC is assessed by a steady state visual evoked potential (SSVEP) measurement and a 10-subject user study. Secondly, the results of the SSVEP experiment show that this device can acquire EEG signals from the visual cortex of the brain. The results of the user study reveal that the 12 facial expressions, detectable by the headset, have an average reaction time (RT) of 1150 ms and an accuracy of 89.6%. The comparison between two gaming tasks depicted that the measured affective values of the EPOC show a correlation to the affective state of a player. Two out of the ten subjects showed that the headset could be trained to detect the user's intent imagining to perform actions on a virtual object.

The results of this thesis should encourage future work to make use of the wide variety of already-existing, high-quality game titles. As demonstrated by this study, it is not necessary to develop a game specifically for BCI application to get the desired controlled behavior. The potential for low-cost EEG solutions needs further attention to successfully establish BCIs in everyday life.

Keywords: Brain-computer interface, game design, human-computer interaction, Emotiv EPOC, Electroencephalogram, Electromyogram, steady state visual evoked potential, reaction time

Zusammenfassung

Brain-Computer Interfaces (BCIs) und Computer Spiele weisen seit jeher eine starke Beziehung zueinander auf. BCI Forschung verwendet Spiele zur Motivation von Probanden und zur Validierung neuer Kontrollkonzepte. Im Gegenzug kann modernes Spieldesign von BCI Forschung profitieren, denn diese Eingabegeräte besitzen das Potential, gänzlich neue Arten von Spielmechanismen zu eröffnen. Obwohl die beiden Bereiche in vielerlei Hinsicht miteinander verbunden sind, gilt es dennoch einige Hürden zu überwinden. BCI Technologie ist bereits ausreichend robust, um erste, darauf basierende, erschwingliche Geräte hervorzubringen. Diese werden jedoch noch nicht durch modernes Spiel Design berücksichtigt. Zusätzlich gibt es keine einfache Lösung, um proprietäre Spiele mit nichtstandard Eingabegeräten, wie BCIs, zu steuern. Es ist zudem erforderlich den Mangel an haptischer Rückmeldung von Tasten und Knöpfen durch angepasste grafische Benutzeroberflächen auszugleichen. Die meisten proprietären (Spiel-) Anwendungen bieten jedoch keine Möglichkeit, die Benutzeroberfläche mit zusätzlichen Elementen zu erweitern.

Mit dem Graz BCI Game Controller (GBGC) wird eine Lösung präsentiert, welche eine Kontrollschnittstelle für kommerzielle Spieltitel bereitstellt. Jedes Eingabegerät mit einer offenen Programmierschnittstelle kann zur Kontrolle von Spielen eingebunden werden. Die vorgestellte GBGC Interface Extension Engine (IEE) demonstriert, wie Benutzeroberflächen von Drittanwendungen zurechtgeschnitten werden können, um ausreichend visuelles Feedback bereitzustellen.

Im Detail untersucht werden die Möglichkeiten des günstigen Elektroenzephalogramm (EEG), Elektromyogramm (EMG) und Gyro Sensor basierten EPOC Headset von Emotiv Systems, Inc. Das EPOC wurde mittels einer Steady State Visual Evoked Potential (SSVEP) Messung und einer Studie mit 10 Teilnehmern evaluiert. Die Ergebnisse der SSVEP Messung zeigen, dass es mit diesem Gerät möglich ist, EEG Signale im Bereich des visuellen Cortex zu messen. In der Studie wurde erfasst, dass die 12 Gesichtsausdrücke, welche vom Headset detektiert werden können, eine mittlere Reaktionszeit von 1150 ms haben und eine Genauigkeit von 89.6%. Der Vergleich zweier Messungen wärend Spielaufgaben hat gezeigt, dass das Headset den Gefühlszustand eines Users einschätzen kann. Zwei von zehn Teilnehmern zeigten, dass das Headset die Intention eines Users, virtuelle Objekte zu beeinflussen, erkennen kann.

Die Ergebnisse dieser Abschlussarbeit sollen künftige Arbeiten überzeugen, von der Vielfalt an hochqualitativen Spielen Gebrauch zu machen. Um ein kontrolliertes Verhalten in Spielen zu erzielen, ist es nicht immer notwendig, eigens eine Lösung für BCI Anwendungen zu erstellen. Damit sich günstige EEG Geräte im täglichen Leben etablieren können, bedarf es auch in Zukunft weiterer Aufmerksamkeit.

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Vielen Dank, ich liebe euch,

Markus

Abbreviations

ADC	Analog to Digital Converter
API	Application Programming Interface
AUC	Area Under Curve
BCI	Brain-Computer Interface
CMS	Common Mode Sense
DRL	Driven Right Leg
DTD	Document Type Definition
EEG	Electroencephalogram
EMG	Electromyogram
EMS	Electromyographic Signal
ERP	Event Related Potential
ERT	Electromyographic Reaction Time
EUR	Euro
FFT	Fast Fourier transform
fNIR	Functional Near-Infrared Imaging
FP	False Positive
FPR	False Positive Rate
FPS	First Person Shooter
GBGC	Graz BCI Game Controller
GS	Gute-Schlechte Stimmung
GUI	Graphical User Interface
HAWC	Hand and Wrist Classier
HCI	Human-Computer Interaction
HD	High Delivery
Hz	Hertz
IEE	Interface Extension Engine
ITR	Information Transfer Rate
LSB	Least Significant Bit
MDBF	Mehrdimensionaler Bendlichkeitsfragebogen
MI	Motor Imagery
MLTL	Mean Lift Time during Lift Trials
MLTN	Mean Lift Time during Neutral Trials
MMORPG	Massively Multiplayer Online Role Playing Game
OS	Operating System
PNS	Peripheral Nervous System
ROC	Receiver Operating Characteristic
RT	Reaction Time

RTS	Real Time Strategy
RU	Ruhe-Unruhe
SDK	Software Development Kit
SNR	Signal to Noise Ratio
SPS	Samples per Second
SSVEP	Steady State Visual Evoked Potential
STD	Standard Deviation
TN	True Negative
TP	True Positive
TPR	True Positive Rate
TT	Trial Time
UI	User Interface
USD	United States Dollar
VAS	Visual Analog Scale
VRE	Virtual Reality Environment
WM	Wach-Müdigkeit
WoW	World of Warcraft
XML	Extensible Markup Language

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1. Introduction

In face-to-face conversations humans rely on many other signals besides verbal communication in order to convey information to one another. Body posture, gestures, facial expressions, and eye contact are significant components of nonverbal communication. Facial expressions and body gestures are the most important of these behavioral cues with respect to human judgment [63]. Although humans are used to expressing themselves both verbally and non-verbally when interacting with each other, they are mostly limited only to their hands when it comes to human-computer interaction (HCI).

New input modalities can help to improve HCI. Additional controllers that do not rely on a user's hands can increase the information transfer rate (ITR) by providing additional input channels. Interaction becomes more efficient and intuitive if the communication channels for computer systems reflect those that are also applied in social life. Hands-free controllers also can improve the quality of life for disabled individuals by providing them with new means of communication with their electronic environment.

| | | |
| (a) | (b) | (c) |
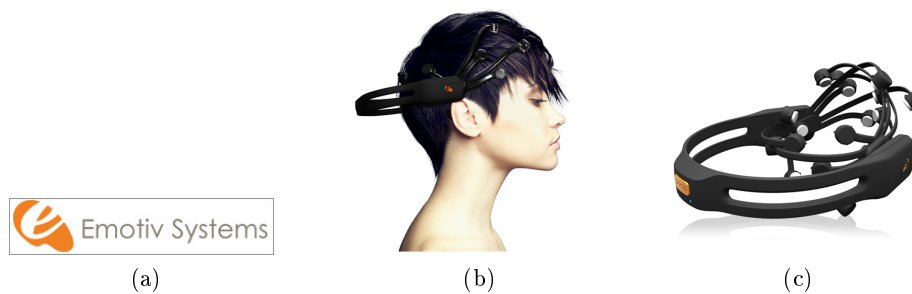
Figure 1.0.1.: The Emotiv EPOC. (a) showing the Emotiv Systems, Inc. logo and (b - c) the EPOC headset.

Brain-computer interfaces (BCIs) are input devices which rely on electrical potentials emitted by neurons of the human brain. Electrodes can be used to derive an electrical signal which represents neuronal activity. This signal encodes characteristic patterns that can be associated with a user's intent [33]. A BCI classifies these patterns and translates them into control commands. In this way, peripheral nervous system is bypassed and the human brain is used directly for communication with BCI applications.

BCI technology has become increasingly robust over the last few years and the first affordable consumer devices have hit the market. One of these devices is the EPOC headset by Emotiv Systems, Inc. (San Francisco, CA, US) (see Figure 1.0.1). This input device makes use of facial expressions, head movements, and brain signals as a source of input. The full potential of such devices is still unknown. In this work, the focus is on

applications in the area of recreation, particularly modern game design.

1.1. Signal types

The Emotiv EPOC headset relies on bio signals that are generally found in medical applications. There are many types of bio signals. They measure electrical potential differences with electrodes placed on the human body. Some of those bio signals can be influenced consciously and are therefore eligible for control. These techniques are mostly used in clinical settings or in rehabilitation for paralyzed people with assistive technologies, like communication devices or robotic prosthesis [35, 59].

1.1.1. Electromyogram (EMG)

The electrical activity emitted by muscle cells is measured using electrodes in Electromyography (EMG). This electromyogram does not require significant physical body movements to register electrical activity. It is sufficient to flex a muscle to generate detectable differences in the electrical potential. EMG can be either measured by implanting electrodes directly into the human body (invasive methods) or from the surface of the skin (non-invasive methods). Although invasive methods provide a better signal quality, they do require surgery and are therefore not applicable in the area of recreation. The EMG measures signals from 100 microvolt (µV) to about 1 millivolt (mV) and requires at least three electrodes to be placed on the skin [13]. For more detailed information on EMG, see [56, 59].

Although EMG is mostly used in clinical settings, research, or rehabilitation, recently there are emerging attempts to use EMG to control mobile devices and games. [71] uses a set of electrodes mounted on the forearm to distinguish between several hand gestures. This system is then used to control a mobile mp3 player and the game *Guitar Hero* (published by RedOctane, 2005) by measuring EMG from the forearm.

1.1.2. Electroencephalogram (EEG)

Electroencephalography (EEG) measures electrical activity from neuron assemblies in the human brain. The EEG signal is acquired non-invasively with electrodes placed on the human scalp. Besides EEG there are also other technologies that are capable to measure neuronal activity, but EEG is most suited for HCI because it is relatively inexpensive, portable, non-invasive, and safe [88]. For more detailed information on EEG, see [82, 60, 7].

Signal to Noise Ratio (SNR)
Compared to EMG, the electrical potential difference of EEG is vastly weaker (5 - 100 µV). This leads to one of the major drawbacks of EEG. The signal is very susceptible to noise and interferences caused by environmental influences or muscle movements. The signal to noise ratio (SNR) compares the signal to the amount of noise. EEG suffers from a very low SNR. A more detailed discussion on information transfer and SNR can be found in [79].

1.2. Brain-Computer Interface (BCI)

With the technology of brain-computer interfaces (BCIs) it is possible to use the brain as an input source for various applications. A BCI provides the brain with a new, non-muscular communication and control channel [94]. This input technology offers individuals that cannot rely on their motor abilities due to disability or nervous disease the chance to communicate without being dependent on their peripheral nervous system (PNS) [40, 39, 41, 42, 5, 4, 64, 21, 12]. BCIs have already been applied successfully in neurological rehabilitation [18].

EEG based BCIs measure electrical activity in various regions on the human scalp. Pattern recognition algorithms are applied to classify spatial or temporal characteristics in the recorded EEG signal. In a real-time setup, these classifications can be used for controlling various BCI applications.

There is a general misconception that BCIs are able to read a person's mind or thoughts, but BCIs simply detect patterns in brainwave signals. Neurophysiological measurements obtained from EEG are inherent variable and non-stationary [91]. Still, there are detectable patterns included in the EEG signal that occur if a user performs various (mental) tasks or focuses on certain events [33].

In this thesis, BCI only refers to EEG based, non-invasive BCIs. Even though other methods can provide better signal quality or spatial resolution they are not practicable for home-use. For a further discussion on BCIs, see [33, 88].

1.2.1. Information Transfer Rate (ITR)

The information transfer rate (ITR) quantifies the bit rate of a communication channel [79]. It is generally calculated by the following formula:

$$B = log_2N + P\,log_2P + (1 - P)\,log_2[\frac{1 - P}{N - 1}]$$

Where N is the number of possible selections, P the accuracy, and B the bits per trial.

State-of-the-art BCIs still provide a very limited ITR (approximately 30 bits/min). This bit rate is insufficient by far to fully control a modern game title without limitations or automation.

1.2.2. Accuracy

If BCIs are applied in assistive technologies, accuracy is highly important [11, 58]. In the context of gaming, accuracy is also important but it may not be crucial. Sometimes less accuracy can even act as a design feature to give lower skilled players a chance to overcome better players from time to time. [73] identifies chance as a design feature in games.
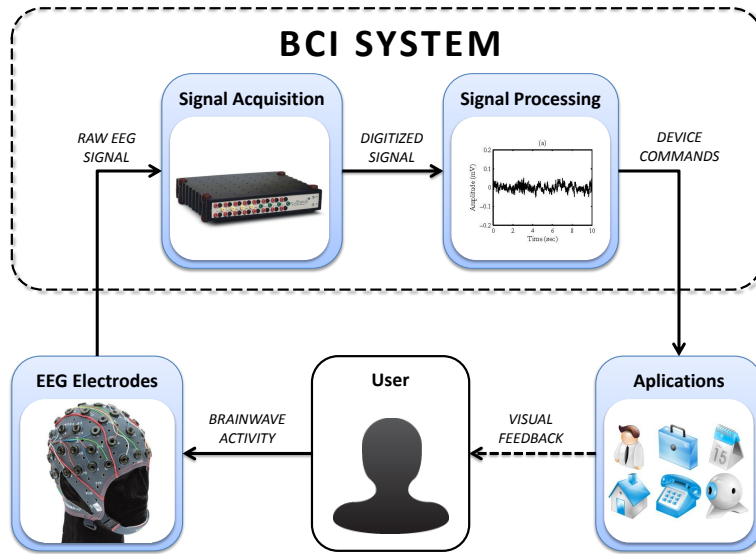
Figure 1.2.1.: The parts of a BCI system. The EEG signal is derived by a set of electrodes placed on the scalp of a user. An electrode cap is typically used to hold the electrodes in position on the head. They need to make good contact with the scalp of the user. An abrasive contact gel is usually used to connect the electrodes directly to the skin. The electrodes are attached to a signal acquisition unit (or amplifier), which is responsible for amplifying and digitizing the signal. Signal processing filters prepare the signal for performing classifications. These classifications are translated to device commands to control various applications. Figure adapted from [94].

1.2.3. BCI Structure

[94] identifies the typical parts of a BCI and their relations (shown in Figure 1.2.1). First, the raw signal acquired with EEG electrodes from the scalp needs to be amplified since the voltage of the input signal is in the range of μV. An analog-to-digital (A/D or ADC) converter then translates the analog input signal to a digitized format that can be processed by a computer. In the next step, signal-processing algorithms are applied to remove artifacts from the signal [14]. Feature extraction identifies several characteristics from the EEG signal. These distinctive patterns can be classified to related actions– actions the subject is able to produce by performing mental tasks [74] or by focusing on an external stimulus. Such an external stimulus can be a flickering light source, as it is used for steady state visual evoked potentials (SSVEPs) [57].

1.2.4. Steady State Visual Evoked Potentials (SSVEP)

BCIs detect reoccurring patterns in brainwave activity. A subject has to be able to produce these patterns intentionally to operate a BCI. The strategies to create these

characteristic EEG signals can be categorized as dependent or independent systems. If an external stimulus is required to create an activation, it is a dependent implementation. If no such external influence is required, the BCI is considered to be independent.

Dependent BCIs rely on event related potentials (ERPs), which produce time-locked series of positive and negative deflections in the EEG signal [33, 60]. ERPs occur when the brain processes an external stimulus. In this thesis, the SSVEPs are used to assess the EEG capability of the low-cost Emotiv device [2, 59]. If a subject looks at a light source or an on-screen icon flickering at a certain Hertz rate, the exact same frequency can be found in the frequency spectrum of the EEG signal. If multiple stimuli flickering at different frequencies are presented, a subject can choose between these selections by shifting the focus.

SSVEP-based BCIs provide a good ITR and are very robust compared to other methods. The downside of SSVEP is that the flickering stimuli can be unpleasant or disturbing for the subject. Additionally SSVEP requires that the subject's gaze is directed at the stimulus.

1.3. Low-cost EEG based input devices

Since EEG technology has become more accessible and robust over the past few years, the first consumer EEG/EMG devices have arrived in commercial markets. They are primarily found in recreational markets for controlling games, toys, music applications, or for mental training. In this work, "low-cost" is defined as a price below USD $1,000 (approximately EUR 763). A high-end EEG setup, which is typically priced at several thousand dollars, usually offers a much better signal quality but at the expense of mobility and comfort and often requires significant effort to set up.

1.3.1. Comparison

[83] performed a comparison between inexpensive EEG devices using a usability score. This score was calculated based on device features for low-cost EEG devices priced below USD $1,000 in this study. The results showed that the Emotiv EPOC system had the highest score within this particular rating system. An overview of available low-cost consumer BCI devices is given in Figure 1.3.1 and their features and prices are shown in Table 1.3.1.

1.3.2. Emotiv EPOC

The EPOC headset by Emotiv is a low-cost gyro, EMG, and EEG-based input device, which is connected wireless to a PC (see Figure 1.3.1(c)). This allows the user to move freely without any connected cables. With 14 EEG channels and two built-in gyro sensors, it is currently the most advanced EEG device in the low-cost segment [83]. It is an easy-to-use device, which is set up in a few minutes. The EEG sensors have to be equipped with felt pads. These felt pads have to be moistened using a saline solution (contact lens cleaning solution, see Figure 3.4.5) as a contact agent to the skin.

(a) Neurosky Mind- (b) Neurosky Mindset   (c) Emotiv EPOC   (d) MyndPlay BrainBand
Wave

(e) Mattel Mindflex   (f) Uncle Milton Star Wars Science (g) PLX Devices XWave
                              - Force Trainer

Figure 1.3.1.: A non-exhaustive overview (a–g) of the currently available low-cost consumer EEG devices.

Device	Producer	Electrodes	SDK	Price (in USD)
MindWave	NeuroSky	1	Yes	$ 99.95
MindSet	NeuroSky	1	Yes	$ 199.95
EPOC	Emotiv	14	Yes	$ 299
Mindflex	Mattel	1	No	$ 50
Star Wars Science - Force Trainer	Uncle Milton	1	No	$ 45
XWave	PLX Devices	1	Yes	$ 90
MyndPlay BrainBand	MyndPlay	1	Yes	$ 205

Table 1.3.1.: A list of low-cost consumer EEG devices.
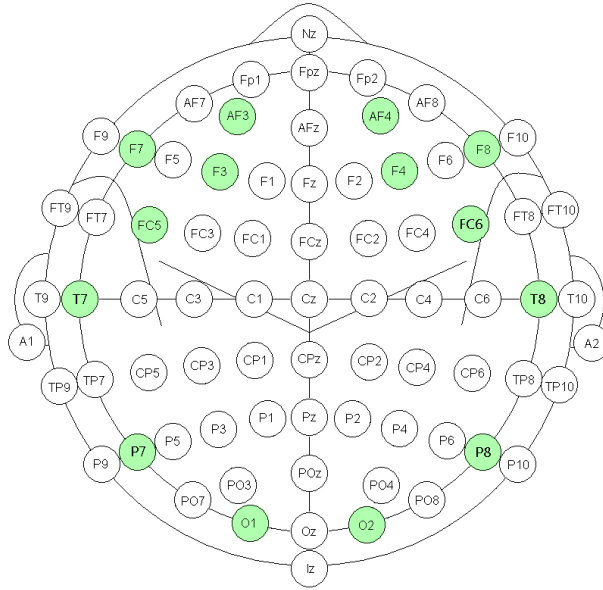
Figure 1.3.2.: The international 10-20 positions of the 14 channels provided by the Emotiv
EPOC.

The channel names, based on the International 10-20 locations, are: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4 (see Figure 1.3.2). The headset provides two references, Common Mode Sense (CMS) and Driven Right Leg (DRL) and two in P3/P4. For more information on the 10-20 electrode system see [38, 81, 80]. The detailed technical specifications of the EPOC system are listed in Table 1.3.2.

The headset includes a software detection suite called "Emotiv Control Panel" (see Figure 3.4.6). This application combines three different detection suites: the Affectiv Suite (see Figure 3.4.10), Expressiv Suite (see Figure 3.4.13), and Cognitiv Suite (see Figure 3.4.7). The Emotiv Affective Suite provides values for five emotions: instantaneous excitement, long term excitement, engagement/boredom, meditation and frustration. Emotiv does not publish how these values are actually calculated or which signal sources are included. The Expressiv Suite detects 12 different facial expressions. The Cognitiv Suite is used to train and classify mental states which relate to a user's intent to perform physical actions on a real or virtual object [24]. All these detections can be addressed by an application programming interface (API), which is only part of the software development kit (SDK) versions of the headset.

SDK Headset	
Number of channels	14 (plus CMS/DRL references, P3/P4 locations)
Sampling method	Sequential sampling. Single ADC
Sampling rate	128 SPS (2048 Hz internal)
Resolution	16 bits (14 bits effective) 1 LSB = 1.95 µV
Bandwidth	0.2 - 45 Hz, digital notch filters at 50 Hz and 60 Hz
Filtering	Built in digital 5th order Sinc filter
Dynamic range (input referred)	256 mVpp
Coupling mode	AC coupled
Connectivity	Proprietary wireless, 2.4 GHz band
Power	LiPoly
Battery life (typical)	12 hours
Impedance Measurement	Contact quality using patented system

Table 1.3.2.: Technical specifications of the Emotiv EPOC SDK headset [24].

1.4. New Input Modalities in Modern Game Design

Innovative possibilities to interact with computers in more intuitive, efficient, or just more exciting ways are a success factor for recent gadgets, devices, and game consoles. In game design, new input modalities can even enable a completely new type of game-play that has never been used before.

Consider, for example, the computer mouse. The mouse was introduced 1963 [23] but the entertainment industry made use of it much later. Due to the novel concept of commanding units with the mouse, the real time strategy game (RTS) *Dune II: The Building of a Dynasty* became very successful. Westwood published this game in 1992. The basic concept of RTS games is to collect resources for building an army. The player takes the role of a commander and directs his units in combat from a top down perspective. Other titles picked up this idea and formed a strong game genre out of these mechanics. The RTS game genre is only possible because of mouse control, and this too is only predicated on the initial establishment of the mouse as a computer interface tool.

To name another example, *Quake* (published by id Software in 1996) was the first first-person shooter (FPS) game, which made use of a mouse to provide a "free aim" mode. In FPS games, the player's viewing camera is directly attached to the aim of the player. Up to this point, the player was only able to rotate right and left at a constant speed in a 3D environment using the arrow keys on a keyboard. The mouse made it possible for this game genre that a player can conveniently look and precisely aim in any direction.

Figure 1.4.1.: Recent input controllers which use a completely different concept for HCI. Although some of the systems still have buttons and joysticks, they focus on body movements to control games.

Advancements in technology often drive these novel input modalities in the gaming world; moreover, gamers are typically early adopters for new technologies since they are used to training with different input modalities in order to improve their skills [61]. The gaming industry recently brought forth a wide variety of new input devices based on body movements (see Figure 1.4.1). These new game controllers have been well accepted by the gaming community because they provide the possibility for more engagement while playing a computer game. Gamers in general are considered as early adopters of new technologies since they are used to training in order to improve their skills

Emotiv markets the EPOC headset as a gaming device. It is not feasible to think of the EPOC as a replacement for a mouse and a keyboard since it simply cannot provide the accuracy and speed of traditional input devices. Buttons, joysticks and mice are still the most common input modalities, because they offer an almost flawless accuracy and are very accessible for healthy people. Most individuals are familiar with the concept of these analog input controls since they are very common on many devices. The advantages of the EPOC system lie in the variety of input signals that can be used complementary to hand movements. The challenge is up to the game designers to make clever use of these additional input signals.

1.4.1. Optimal Flow Channel

Good game design tries to find the optimal balance between challenge and skill. This will keep the player engaged and in the so-called "flow channel" (see Figure 1.4.2). The flow-channel describes a state, where the challenges of a game exactly match the player's skills. [15] marks the maximum for the dimension Skills as ∞ in the flow channel chart, but this does not hold true for computer games. The skills within interactive games are limited. Yet, the number of controllable actions has increased significantly since the first generation of computer games. Comparing a game controller from the Nintendo Entertainment System (NES) from 1986 and a game controller from the Sony Playstation 3 (PS3) manufactured 20 years later (2006), the number of controls increased from 8 to 17 "pushable" buttons and analog sticks (not counting gyro sensors) (see Figure 1.4.3). For more information on the evolution of game controllers, see [16].

[73] distinguishes between two types of skill: virtual and real. The real skill focuses
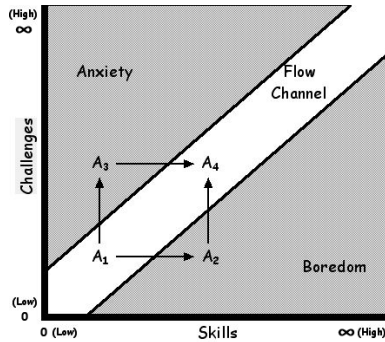
Figure 1.4.2.: Flow Channel chart. According to [15], the most important dimensions of the experience are challenges and skills. If the player is not challenged by a game he will become bored (A2). Otherwise, if the player's skills are not sufficient to complete the game tasks, he is likely to be overwhelmed by the game and become anxious (A3). The position A1 describes a player when he starts playing a new game. He does not have any skills and good games respect the skill level of a player at all times. By practicing and facing new challenges, the player can improve his skills (A4). If this process of improving skills and presenting more demanding challenges is well balanced, the player stays in the "flow channel" and he is more likely to be engaged in the game.

(a) (b)

Figure 1.4.3.: A comparison of the number of joysticks and buttons between early and recent game console controllers: (a) shows the original Nintendo NES controller from 1986 featuring eight buttons; (b) shows a Sony PS3 controller from 2006 including 17 "pushable" buttons (including analog sticks, not counting gyro sensors).

Figure 1.4.4.: The game controller layout of Halo 3: ODST released September 2009 on the Microsoft Xbox console.

on the player and his ability to exercise the controls of a game in order to get better, stronger, or faster. The virtual skill is related to the in-game representation of the player. The avatar may for example improve his fighting skills by two points and can do more damage. This is what is called the virtual skill and does not relate to the real skill of a player.

Challenging the real skills of a player gives game designers the possibility to create a more engaging experience. Therefore many successful modern game titles became very complex concerning controls. Many buttons are necessary to control all the abilities and skills within a recent game (see Figure 1.4.4).

However, having a high number of controls creates a problem where the controls become hard to memorize for gamers. This is a barrier to entry for players that are new to the game. It also creates difficulties for players returning to a game after not playing that game for a long time, as it is not easy to recall all of the complex controlling actions. This does not necessarily mean that games should have only a limited amount of input possibilities, rather it implies that controls should be intuitive so that they are simple to learn and easy to recall again after a long pause in gameplay.

A device like the EPOC headset could satisfy the need for further controls. Head movements, facial expressions and neuronal activity have huge potential to enrich games with a set of intuitive, unified controls. Furthermore, these controls could easily be used across various titles and genres.

1.4.2. Virtual Embodiment

In most modern role playing games (RPGs), the player is represented by a digital character (avatar) in a virtual environment. The avatar is used to communicate with other players, who are also represented in the virtual world by their digital avatars. In massively multilayer online role playing games (MMORPGs) many thousand players get together to experience adventures in these fantasy worlds.

Lately it has become very important for this game genre that a player can reflect

emotions with his digital representation. In World of Warcraft (WoW) by Blizzard, Inc., one of the most successful MMORPGs, it is possible to trigger various character animations by text commands. These animations can express a feeling or reaction of a player, like laughing, being tired, or being bored (see Figure 1.4.5). Although players make extensive use of these animations, it is very tedious to type the required text commands into a chat window. In fighting scenarios, a player is occupied controlling his avatar and there is not enough time to type words into the chat.

The EPOC headset offers detections that can be associated with an affective state of a player. There is currently no native support in games for such input devices as the EPOC. Including real feelings and reactions into these virtual game environments could make video gaming much more emotional and immersive. This is also referred to as affective gaming.

1.4.3. Affective Gaming

[30] defines affective gaming as:

> "This form of gameplay is commonly referred to as *affective gaming*; where the player's current emotional state is used to manipulate gameplay." ... "In order to have truly affective videogames the system needs to be able to sense aspects of the player's emotions more directly."

Following this definition, the gaming industry has high interest in potential new input controllers that can increase the immersion experience for game players. Innovative new input devices have impacted the games market significantly in the last couple of years. An EEG-based device as an input controller would not only be innovative, but also increase the user experience for a player as it can be used for adapting the game environment based on biofeedback. EEG and EMG of facial muscles are viable sources for estimating the mood or state of a player [36, 50, 52, 17, 72]. The Emotiv EPOC Affectiv Suite already provides for values such as excitement, boredom, frustration, and mediation.

To create the perfect individual experience for every player a game needs to adapt to the user. Passive BCIs (see [96]), which detect the affective state of a player, can open opportunities in game design. A game could easily change the difficulty level, tasks, story, or surroundings based on the (affective) state of the player [19].

1.4.4. Social Era in Video Games

Recent game titles are trending toward more social user experiences. These games offer the players the opportunity to play with other gamers all over the world, form groups, and establish new friendships. Synchronous and asynchronous multiplayer modes in games are characteristic for the social era in game development. Players that are not able to use standard input devices like a mouse or keyboard are mostly barred from these rapidly growing communities.

Many physically disabled people can lack social interaction in their everyday life due to their handicap. Adapted game control devices can lower the barriers to entry within the

(a)   (b)

Figure 1.4.5.: By typing chat commands, the player can trigger character animations in the MMORPG WoW. These animations can be used to reflect feelings or reactions into the virtual world by the avatar. (a) Shows the character in a sleeping position (command: "/sleep"). A laughing animation can be triggered by the "/lol" chat command (b).

gaming community, enabling disabled individuals to interact with others and participate in a social arena where their handicap is not an impediment; in fact, the other players may not even be aware that a person has a physical handicap. Of course, this is only possible if short reaction times do not provide an advantage. Games that require a good strategy and do not rely on fast reactions are most applicable for this matter.[6] summarizes this topic as follows:

> "... BCI-controlled gaming applications can provide even more added value in terms of social integration, as a paralyzed player can cooperate or compete with other, possibly healthy gamers ... Interaction via BCI-controlled gaming could build up patient- or mixed communities."

1.5. BCIs and Games

Keeping a subject motivated and concentrated while using a BCI is essential in BCI research. Several studies have shown that a highly motivated BCI user can achieve better results than one that is not engaged in the process [32, 49, 48, 43]. Interactive computer games can provide a fun way to avoid apathy and boredom; consequently, engaging subjects in gaming environments in BCI research studies has the potential to increase training performance and concentration span. This is especially relevant for studies involving children in order to keep them engaged and interested. [6] states:

> "The medical use of BCI-controlled games is quite obvious - gaming can be an excellent motivation to spend time with a BCI system in order to achieve better control."
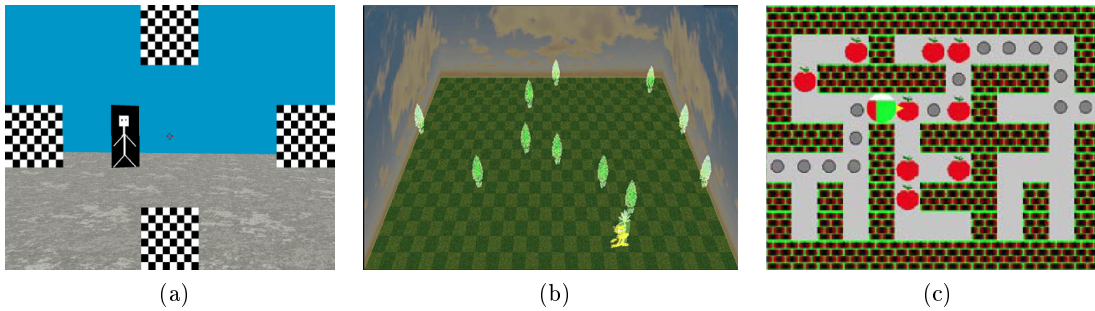
| (a) | (b) | (c) |

Figure 1.5.1.: Examples for unattractive BCI games. (a) Shows a FPS game created for SSVEP control used in [37]. (b) [25] uses a P300 paradigm to control a comic character on a 28 x 18 game board. (c) [45] uses motor imagery (MI) to direct a Pac-Man through a maze.

1.5.1. BCI Research Games

Games are also commonly used as a proof of concept in BCI research. Scientists want to demonstrate that their BCI systems are working for everyday applications, and games serve as suitable example. Games often provide some kind of score that can be used as a performance indicator between subjects or control groups.

It is common to use specially developed games for BCI research. Consequently, the resulting games are mostly very simple, if not to say unattractive (see Figure 1.5.1), and they usually lack a story component as well. These games do not in any way reflect the current state-of-the-art in game development. [6] describes this situation as follows:

> "Apart from their novel control concept (compared to standard games), these approaches do not have an outstanding attractiveness or long-time immersive character due to their simplicity whereas their usefulness for the training of patients is obvious."

1.5.2. Commercial Game Titles for BCIs

The games market is a booming. With clear goals, astonishing graphics, and fascinating stories commercial game titles compete by trying to create the perfect experience for the player. Since the development of high-quality game titles (AAA titles) requires massive budgets (see Figure 1.5.2) it may not be feasible to create state-of-the-art games, especially not for a BCI research study.

The games industry is a flourishing business and brings forth a wide variety of games. The games differ in genre, difficulty, complexity, and controls. Some publishers already ship their games with a set of development tools or APIs that allow for customization of various aspects of the game. In WoW it is possible to modify the graphical user interface (GUI) using XML and LUA [93]. Other games provide level editors and programming environments to develop completely new games with little effort using the game engine and assets from the original game.
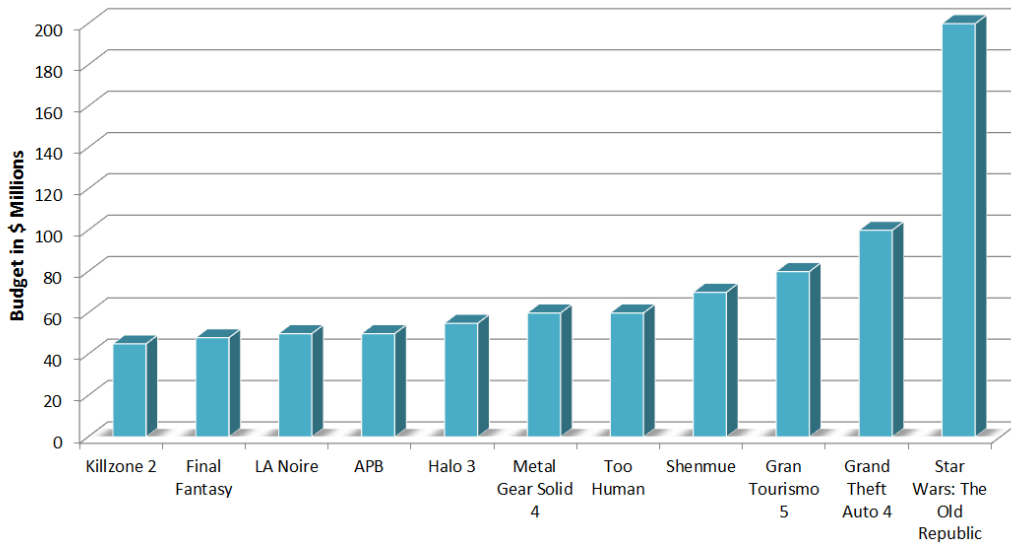
Figure 1.5.2.: The top most expensive game titles (excluding marketing and promotion costs). Sources: [27, 20].

Researchers want to be in control of multiple aspects in a game and therefore view game development from scratch as the only option. In some scenarios, it may be difficult to get the desired behavior from a readily available game title. Yet, there are games that may be already suitable for BCI applications. Using a readily available, quality game would reduce expenses and eliminate the effort of creating a new, less attractive game.

1.6. Motivation

There is already a strong relationship between BCIs and interactive games. Both fields relate to each other in various ways and yet there are still undiscovered and unutilized synergies.

Game Controller for BCIs

Using available commercial game titles for BCI research can have multiple fiscal and timesaving benefits. However, at present there is no simple solution to the issue of controlling commercial games with input devices that are not a keyboard or a mouse. It is one of the major goals of this work to develop a flexible software solution to control these readily available game titles with non-standard input devices, like BCIs.

The lack of haptic feedback from physical buttons should be compensated by visual feedback. Therefore it is necessary to extend and modify the user interfaces (UIs) of proprietary applications. A set of basic interface elements, which can be placed anywhere on the screen, needs to be identified. These interface elements are used to provide sufficient control feedback for the BCI user.

As already discussed, SSVEP-based BCIs rely on an external stimulus. It is absolutely

crucial for this type of activation that such flickering on-screen icons are presented at a constant Hertz rate. In the software solution, it should be possible to easily configure such accurate flickering icons. A measurement will verify if the implementation is fast enough to display these SSVEP icons.

Assessment of the Emotiv EPOC
With respect to recreational markets, the most applicable BCI systems are mobile, low-cost EEG devices. In this work the potentials of the Emotiv EPOC headset are investigated in further detail. A set of representative experiments conducted in a scientific user study will give better insight into the accuracy and the timings of the detectable user inputs. An investigation of facial expression reaction times can deliver valuable information whether these expressions can be leveraged as a new input modality.

By frustrating subjects on purpose the affective values measured by the headset can be compared to a user's state raised by well-established scientific questionnaires. This provides information on whether the Emotiv EPOC Affectiv Suite is capable of making a valid estimation of the user's current affective state.

Critics doubt that these low-cost systems are even capable of measuring EEG. Therefore, the question should be answered if the Emotiv EPOC device can be used for EEG signal acquisition. Furthermore, it is uncertain if such a headset is convenient for long-term use. User feedback will reveal if the mounted electrodes lead to discomfort after a longer period of time.

EPOC Game Controller Integration
Using facial EMG and gyro sensors as input sources to control off-the-shelf game applications is a demanding software engineering task. A flexible software design is necessary to incorporate these types of input into an application that can simulate a keyboard and a mouse.

For a proof of concept the head-mounted gyro sensors and facial expressions are used to control a popular MMORPG. Meaningful translations for the user inputs are to be identified. A player should be able to perform the basic game-play tasks using the Emotiv EPOC headset. This system is to be validated in a user experience study.

1.7. Gain for Future Work

The results of this thesis are a good foundation for future work that deals with BCI related games or mobile, low-cost consumer EEG devices. For future work it is essential to be aware of the efficacy of this EEG/EMG and gyro sensor based input device. Based on these results, future projects can explore whether it is possible to use a readily available game in combination with BCI systems. Additionally, this work delivers valuable information on whether the Emotiv EPOC is an appropriate solution for certain applications.

1.8. Thesis Objectives

1. A state-of-the-art analysis of related work should give insight into how games have been used in BCI research in the past.

2. Related work, using the Emotiv EPOC as an input device, is examined for evaluations about the efficacy and accuracy of the detections.

3. An already existing software solution (BCI-WoW Server [66]) for simulating keyboard and mouse commands is extended for use with various input devices. This software solution should provide a control interface for essential in-game actions in interactive games, which are not explicitly designed for BCI control.

4. The previously described software application should also provide the possibility to create interface extensions for proprietary applications. A set of essential interface elements needs to be identified and they should be useable for creating customized UIs in little time.Icons, applicable for SSVEP based BCIs, should also be supported by this interface extension engine (IEE).

5. A pilot test should demonstrate if the low-cost Emotiv EPOC headset is actually capable of measuring EEG signals. The IEE is used to present the visual stimulus to investigate if this solution is capable of displaying flickering icons accurate enough for SSVEP.

6. A major part of this work is a scientific user study conducted with 10 test subjects. A set of well-designed and controlled experiments gives insight into the reliability and accuracy of the Emotiv headset. Since the Emotiv software does require a lot of user interaction, it is necessary to develop a solution which does not require any other than the requested controls. This test application should also provide a clean UI for the subjects and record all necessary data in a proper format. Having such a controlled environment is essential to produce comparable results in the user study.

7. This thesis strives to implement meaningful controls for a commercial game title using the Emotiv EPOC headset and the provided software solution for simulating mouse and keyboard inputs. The game of choice will be WoW, a highly popular MMORPG. The user study is designed to capture the experience of participants for such a control system.

1.9. Organization of Chapters

Chapter 1, Introduction Explains the basic concept of BCIs and modern game design. Additionally, an overview of the current relations between BCI research and interactive games is given. The various aspects of how these two fields relate to each other are pointed out and an outline for the goals and motivation of this thesis is described.

Chapter 2, Related Work This chapter depicts research that has already successfully applied or investigated the Emotiv headset. Further examples of how games and BCIs have been used in previous work are discussed in this chapter.

Chapter 3, Methods Describes the software design and principles of the application used for controlling games and extending UIs. Various solutions on how to incorporate head-mounted gyro sensors into meaningful game controls are discussed. The detailed design of the conducted user study is given within this chapter.

Chapter 4, Results Presents the results acquired by an SSVEP measurement using the IEE and the Emotiv EPOC. The data provided by the scientific user study is rehashed and put into a meaningful context.

Chapter 5, Discussion This work is concluded by an in-depth discussion of the results. From the discussion a conclusion of the success of this work is drawn. Finally an outline is given for challenges to be solved in future work.

Appendix Provides additional materials used in this work.

2. Related work

In this chapter, a collection of the most important work relating to the topics of this thesis is presented. The first part provides an overview of related work using the low-cost Emotiv EPOC. In the second part, the focus is on games applied in BCI research.

2.1. Emotiv EPOC

Duvinage, Castermans, and Petieau [22] compared the Emotiv EPOC headset and a medical EEG device using a P300 speller in two conditions (sitting, walking). Their results show that the EPOC headset is capable of measuring EEG and that the performance is far above chance level. They state that the Emotiv EPOC performance is creditable for games, but problematic in rehabilitation and prosthesis control.

Cernea et al. [9] show two evaluation scenarios where the Emotiv EPOC is used for real-time support measuring subjectivity during evaluations and user studies.

Cernea, Ebert, and Kerren [8] use the Emotiv EPOC to detect moments of insight while using visualization representations of information.

Livesley [51] compares the efficacy of the headset in terms of bit-rate and accuracy to other input modalities used in assistive technologies (head switch).

Wright [95] proposes an application that elicits emotions from the Emotiv EPOC Affectiv Suite and uses them in combination with an instant messenger.

2.2. BCIs and Interactive Games

A good general description about BCIs and games is given in Chapter 6.3 "BCIs for Recreation" [88]. For a more complete list of BCI related games see [65].

Vidal [90] introduced the first BCI game in 1977. ERPs are used to implement four commands: up, down, left, and right. With these controls a subject can escape from a maze displayed on a screen.

Hjelm and Browall [34] introduce a game called "Brainball". This game involves two players who can move a ball by their state of relaxation (Alpha and Beta waves). The player who is able to move the ball into the opponent's goalmouth scores a point.

Krausz et al. [44] used a simple "ball game" where the subject has to influence a ball dropping from the top of the screen. The patients had to use motor imagery (MI) to move the ball into a preselected basket. The falling speed of the ball was constant, but they varied it across runs.

Lalor et al. [47] uses SSVEP to control a character balancing on a tightrope. The character walks towards the player and stumbles every 1.5 to 5.0 sec to the left or right side. The player has to gaze at a flickering checkerboard icon positioned on each side of the character to prevent the character from falling.

Krepki et al. [45] adapted the Pac-Man game for MI based BCI control. The Pac-Man makes one step each 1.5 - 2.0 sec on a randomly generated maze. The player can turn the Pac-Man left or right in order to walk down the shortest path or to collect as many apples as possible.

Martinez et al. [54] used four SSVEP stimuli placed around a race car. The player can steer the car in any direction on a track by focusing on one of the four flickering checkerboards.

Rapoport et al. [69] present a painting application and a dolphin game controlled with a functional near-infrared imaging (fNIR) based BCI. In the dolphin game, the player has to swim up and down to catch and eat fish.

Finke, Lenhardt, and Ritter [25] use a P300 paradigm to control a comic character on a 28 x 18 game board. The player has to collect trees that are randomly placed on the game board.

Ramsey et al. [67] used a "goalkeeper" paradigm based game to improve online BCI performance by subject training under time pressure conditions. A ball moves from the top of the screen to the bottom and the player has to use a bar to catch the ball.

Tangermann et al. [89] modified a physical pinball machine to be playable with a BCI. They reduced the slope of the game field by 50% to slow down the game and inserted limits to prevent the ball from proceeding on non-catchable routes.

Zhao et al. [97] mapped the controls of a car in a virtual reality environment (VRE) to three MI states: left hand to turn left, right hand to turn right, and foot to speed up.

Jackson et al. [37] controls a FPS game using a SSVEP based BCI. A virtual environment can be explored using four flickering checkerboards for SSVEP stimulation.

Scherer et al. [75] show a system using the three class MI based Graz-BCI to control WoW, a popular MMORPG by Blizzard, Inc.

3. Methods

The first part of this chapter presents the design of the flexible software solution to control games with non-standard input devices. A detailed description is given on how head-mounted gyro sensors are incorporated in this game controller application. Next an extension to the game controller for customizing UIs is introduced. All interface elements, which can be used to customize UIs, are described. The second part of this chapter outlines the design of the conducted user study in detail.

3.1. Graz BCI Game Controller (GBGC)

The Graz BCI Game Controller (GBGC) is an extension of a system described in [66, 75]. The GBGC provides a control interface for commercial game titles by simulating mouse/keyboard inputs and displaying additional GUI elements for user feedback. The GBGC receives control commands from input devices, which are translated to predefined actions. These actions can include modifications to the added interface elements or mouse cursor movements, mouse clicks, and key presses. These mouse and keyboard inputs are again forwarded to a game application. This allows for the mapping of in-game actions to device commands from the input devices attached to the GBGC. The setup of the GBGC is shown in Figure 3.1.1.

Several input devices are already successfully integrated and can communicate with the GBGC:

1. The Graz-BCI [78, 76, 77]

2. g.tec intendiX SOCI (www.intendix.com)

3. EMG based hand and wrist classifier (HAWC) [53]

4. Emotiv EPOC headset

5. SSVEP based BCI [62]

3.1.1. Mouse and Keyboard Input Simulation

Most commercial game titles only support mouse, keyboard, or selected game pads as input devices. The only possibility to control these titles with non-standard input devices is by simulating mouse/keyboard inputs via a software application. The Windows API system call *SendInput()* is used to generate key presses, mouse movements, and mouse clicks.
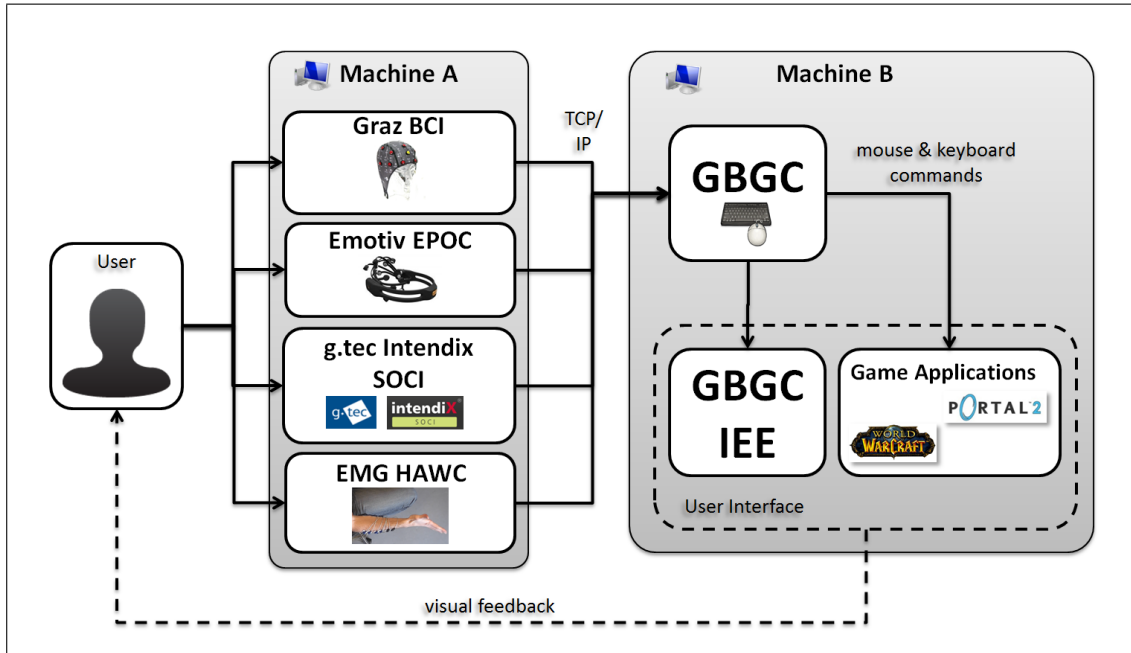
Figure 3.1.1.: The setup of the GBGC and GBGC IEE. The input controllers, which are currently integrated in the system, are shown in the left box (Machine A). These controllers usually run on separate machines and send their commands via a network connection to the GBGC (Machine B). The device commands are translated to keyboard/mouse actions and interface modifications. The game application receives simulated mouse/keyboard inputs and uses them to trigger corresponding in-game actions. The user receives visual feedback from the UI elements of the IEE and the game application.

Mouse and keyboard inputs are defined as macros in a configuration file. Each macro consists of various mouse cursor movements, mouse button clicks, key presses, and delays in any combination. The delays between inputs are very important to trigger multiple in-game actions in a timed order by one macro. These macros are identified and triggered by a unique ID. For a detailed documentation of the input macros, see [66].

3.1.2. Emotiv EPOC Support

To fully support the Emotiv EPOC system, additional features were added to the GBGC. The implementation of triggers allows for the use of the signals extracted by the Emotiv Expressiv Suite, Affectiv Suite, and Cognitiv Suite as a source of input. If the conditions defined in a trigger are satisfied they invoke input macros (see Chapter 3.1.1). The additional support for the gyro sensors of the headset is described in detail in Chapter 3.1.3.

Trigger Command
The added trigger command has the following syntax:

```
Trigger <TRIGGER_ID> <PREV_VALUE> <THRESHOLD_VALUE> <REFERENCED_ACTION>*
```

<TRIGGER_ID> An identifier for the signal type that triggers the keyboard and mouse actions. All currently available trigger signals for the Emotiv EPOC headset are listed in Table 3.1.1.

<PREV_VALUE> A quantifier for the previous value of the trigger signal that can be '<', '>', or '='. If the '<' sign is used, the trigger is activated only if the current value gets smaller than the threshold value. In the case of the '>' sign, the trigger is activated only if the current value gets greater than the threshold value. If the '=' sign is used, the current value has to be exactly equal to the threshold value to activate the actions.

<THRESHOLD_VALUE> The threshold value is used in combination with the <PREV_VALUE> to activate a trigger. This value has to be within the value range of the signal type specified in the <TRIGGER_ID>. The <TRIGGER_ID>s and their corresponding value ranges are listed in Table 3.1.1.

<REFERENCED_ACTION>* A list of input action macros is invoked in case the trigger becomes active.

3.1.3. Gyro sensor support

The gyro sensors integrated in the Emotiv EPOC provide delta values for the displacement of the headset in a horizontal (Δx) and vertical (Δy) direction (see Listing 3.1 for the gyro API function of the SDK). By continuously adding up those delta values an absolute position (x, y) of the gyro sensors can be calculated in a virtual 2D space. This information is used in a new command type, which is very similar to the mouse cursor movement command in the previous BCI-WoW system (described in [66]). It also generates a cursor movement, but the movement distance is weighted by acceleration levels of the gyro sensors. This allows, for example, for the rotation of a character or a camera in a game application at various speeds. The user can turn the avatar or the camera slowly by gently turning the head to the left or right. The more the player rotates the head, the faster the character or camera turns.

Trigger ID	Range	Trigger ID	Range
ExpressivIsLookingDown	[0; 1]	AffectiveExcitementLong	[0; 100]
ExpressivIsLookingUp	[0; 1]	AffectiveExcitementShort	[0; 100]
ExpressivIsBlink	[0; 1]	AffectiveMedidation	[0; 100]
ExpressivIsLeftWink	[0; 1]	AffectiveFrustration	[0; 100]
ExpressivIsRightWink	[0; 1]	AffectiveEngagementBoredom	[0; 100]
ExpressivIsLookingLeft	[0; 1]	CognitiveNeutral	[0; 100]
ExpressivIsLookingRight	[0; 1]	CognitivePush	[0; 100]
ExpressivIsLookingUp	[0; 1]	CognitivePull	[0; 100]
ExpressivIsEyesOpen	[0; 1]	CognitiveLift	[0; 100]
ExpressivSmile	[0; 100]	CognitiveDrop	[0; 100]
ExpressivLaugh	[0; 100]	CognitiveLeft	[0; 100]
ExpressivClench	[0; 100]	CognitiveRight	[0; 100]
ExpressivSmirkLeft	[0; 100]	CognitiveRotateLeft	[0; 100]
ExpressivSmirkRight	[0; 100]	CognitiveRotateRight	[0; 100]
ExpressivRaiseBrow	[0; 100]	CognitiveRotateClockwise	[0; 100]
ExpressivFurrowBrow	[0; 100]	CognitiveRotateCounterClockwise	[0; 100]
GyroAxisX	[-100; 100]	CognitiveRotateForwards	[0; 100]
GyroAxisY	[-100; 100]	CognitiveRotateReverse	[0; 100]
		CognitiveDisappear	[0; 100]

Table 3.1.1.: The available trigger signals and their value range available in the GBGC for the Emotiv EPOC headset.

```
//! Returns the delta of the movement of the gyro since the
   previous call for a particular user
/*!
   \param userId - user ID for query
   \param pXOut - horizontal displacement
   \param pYOut - vertical displacment

   \return EDK_ERROR_CODE - EDK_ERROR_CODE = EDK_OK if
      successful

   \sa EmoStateDll.h
   \sa edkErrorCode.h
*/
EDK_API int EE_HeadsetGetGyroDelta(unsigned int userId, int*
   pXOut, int* pYOut);
```

Listing 3.1: The documentation of the EE_HeadsetGetGyroDelta API function receiving the gyro delta in x/y from the edk.h of the Emotiv EPOC SDK.

Virtual Gyro Box

To calculate the acceleration levels ranging from 0.0 to 1.0 for the horizontal (acc X) and vertical (acc Y) axis, a virtual bounding box is created in the absolute 2D space of the gyro sensors. This box is defined by four parameters (min X, max X, min Y, and max Y). Four independently configurable border distances were chosen because of the anatomy of the human head. Usually the head can be turned to the left or right to the same degree. However, this might not apply for disabled users. For the vertical movement, the situation is different. A head cannot be lowered to the same extent from a neutral position as it can be lifted.

The bounding box defines the distances at which the acceleration levels reach their maximum value (1.0). The four parameters min X, max X, min Y, and max Y can be unlocked. The user can then set these parameters by rotating his head in each direction to a comfortable extent. The maximum displacement distances of the virtual 2D gyro box are automatically set and can be locked again to avoid unintentional changes.

Since it is highly unlikely that a user is able to reach the exact center of this box, a so-called "dead zone" is defined. If the absolute gyro positions are within this zone, the acceleration levels are 0.0. Between the dead zone and the borders of the bounding box the acceleration levels linearly scale from 0.0 to 1.0. The control box setup is explained in detail in Figure 3.1.2.

Gyro Mouse Action

This action can be integrated in the <KEY_LIST> (described in [66]). The gyro mouse action has the following syntax:

```
G <ACC_AXIS_1> <X1> <X2> <ACC_AXIS_2> <Y1> <Y2>
```
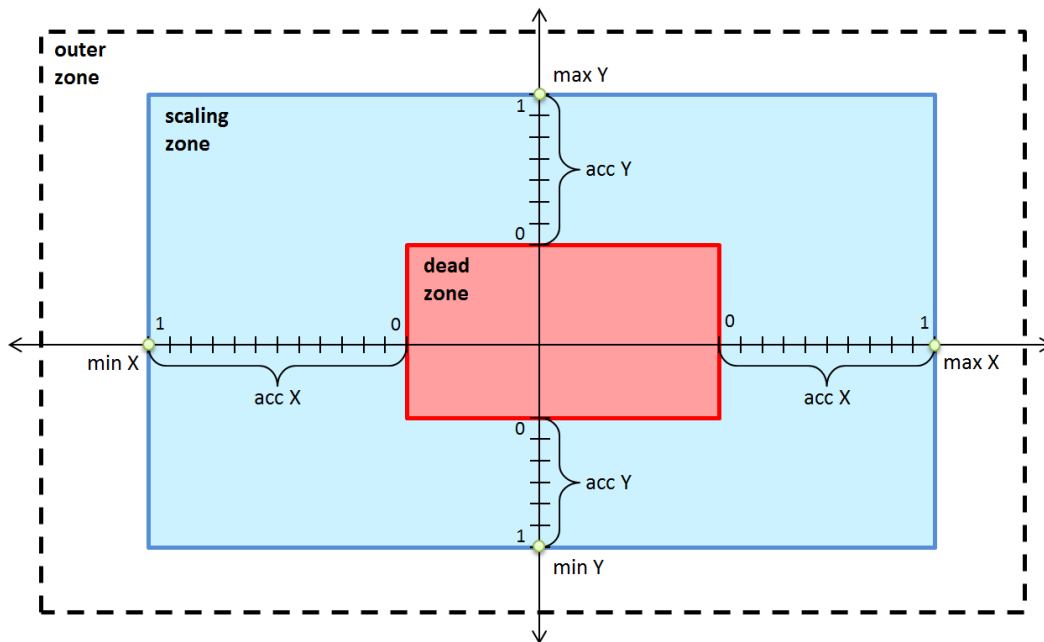
Figure 3.1.2.: The virtual gyro box is used to calculate the acceleration levels for the gyro mouse action. The size of this virtual 2D space is defined by four parameters (min X, max X, min Y, and max Y). The red box in the middle represents the "dead zone". If the virtual gyro position is placed within this zone, the acceleration levels are 0.0. Between the dead zone and the boundaries of the scaling zone (blue box) the acceleration levels scale linearly between 0.0 and 1.0 depending on the position. If the absolute gyro position leaves the scaling zone, the corresponding acceleration level stays at 1.0.

<ACC_AXIS_1> This identifier describes which level (acc X or acc Y) accelerates the mouse cursor movement in a horizontal direction. The possible values are 'x' or 'y'.

<X1> The minimum mouse cursor movement in pixels in a horizontal direction.

<X2> The maximum mouse cursor movement in pixels in a horizontal direction.

<ACC_AXIS_2> This identifier describes which level (acc X or acc Y) accelerates the mouse cursor movement in a vertical direction. The possible values are 'x' or 'y'.

<Y1> The minimum mouse cursor movement in pixels in a vertical direction.

<Y2> The maximum mouse cursor movement in pixels in a vertical direction.

The gyro mouse action can be best explained by a simple example. If the gyro mouse action "G x 10 110 y 0 0" gets activated, it moves the cursor to the right on the screen. Depending on the horizontal acceleration level (acc X), the cursor either moves a minimum of 10 pixels or a maximum of 110 pixels. In this example the acc X causes the up-scaling of the movement distance because it is defined as the <ACC_AXIS_1> parameter. In case the current acc X is 0.5, the cursor would move 60 pixels to the right. If the acc X value is equal to 1.0, the cursor would move 110 pixels to the right. The absolute movement distance is calculated by the following formulas:

$$movement\,distance\,X = X1 + ((X2 - X1) * acc\,lvl(AccAxis1))$$

$$movement\,distance\,Y = Y1 + ((Y2 - Y1) * acc\,lvl(AccAxis2))$$

The resulting function is shown in Figure 3.1.3.

Re-Centering the Gyro Position

This approach of using a virtual 2D space to weight the movement distance requires that the position of the gyro sensors in the virtual 2D space is re-centered from time to time. Measuring errors of the gyro sensors add up over time and cause a difference between the position of the gyro sensors in the virtual 2D space and the real head position. This offset can be corrected by manually activating a command to re-center the gyro sensors or by activating the so-called "bordered mode" in the GBGC. In the first approach, the user has to return his head to a neutral position and manually activate a command to reset the position of the sensors in the virtual space (see Figure 3.1.4). Since this offset can occur even after short usage, this solution is not very convenient.

Bordered Mode

To avoid binding an additional command for re-centering the gyro position the "bordered mode", which can be activated in GBGC, was developed. When this mode is activated, the user cannot move the virtual 2D position across the borders of the defined box. This allows for the correction of the offset without the need of an additional command. The bordered mode is visually explained in Figure 3.1.5.
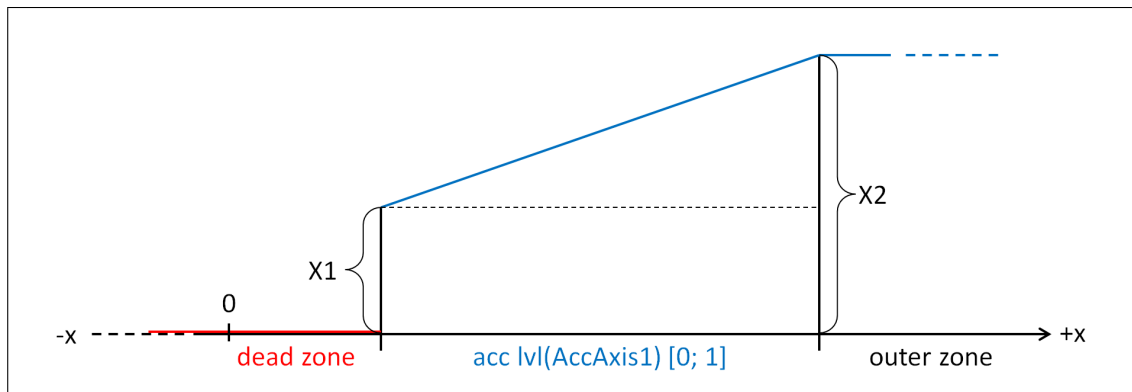
Figure 3.1.3.: The gyro mouse action distance function for the positive horizontal (right) movement of the cursor. If the gyro mouse action gets activated, the cursor moves to the right for X1 amount of pixels. The more the acceleration level of the AccAxis1 increases, the greater the movement distance gets. If the acceleration level is 1.0, the movement distance is equal to X2 and cannot increase any further.
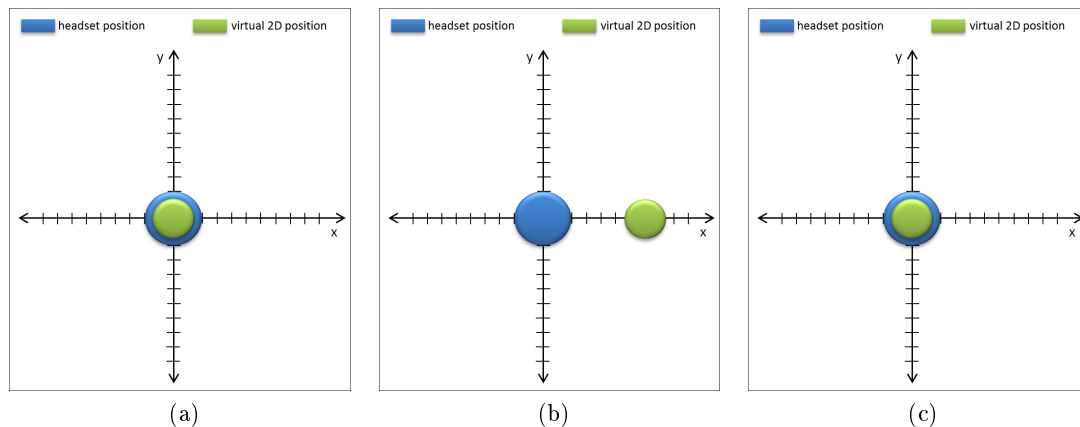

Figure 3.1.4.: The manual gyro position re-centering procedure. When the user starts using the gyro sensors or after a previous re-center command, the virtual 2D space position is aligned to the headset position (a). After some movements the measuring error adds up and these two positions do not match any more. In this example, the user's head is back in a neutral position, but in the virtual space the position is off to the right (b). If the re-center command gets activated, the virtual position gets reset to the center of the virtual coordinate system.
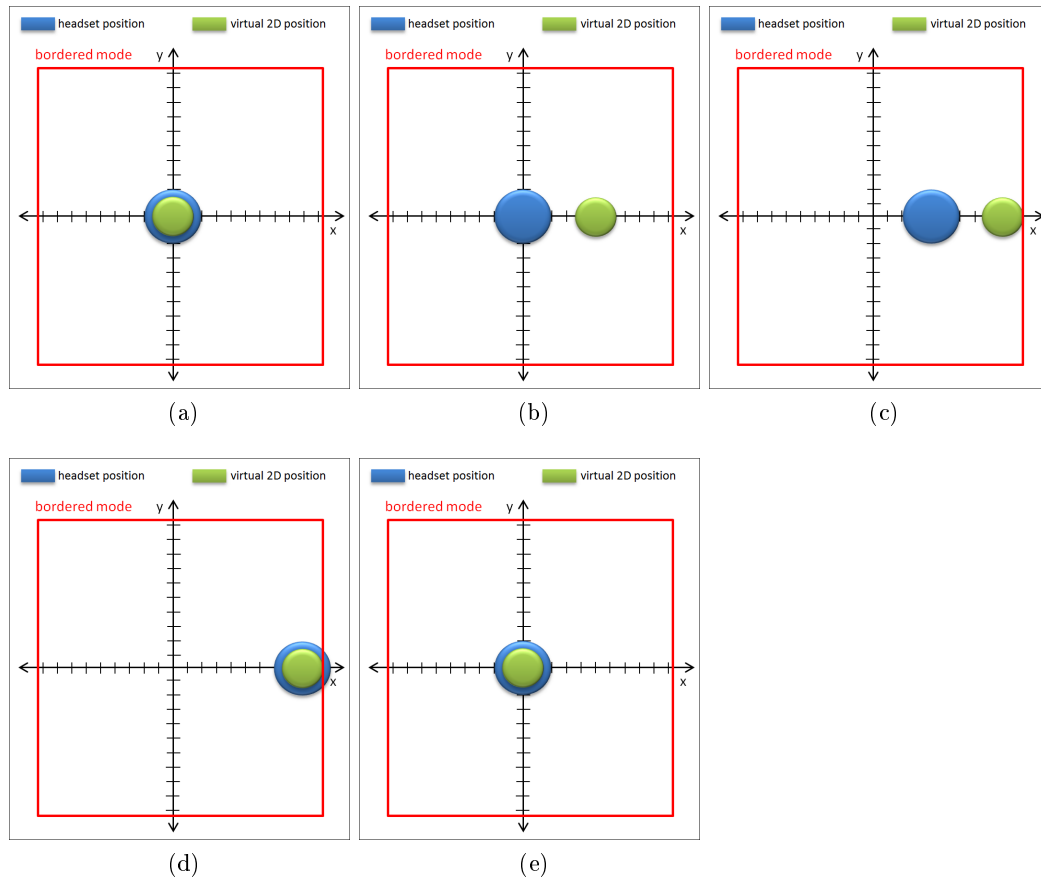
Figure 3.1.5.: The gyro position re-centering procedure using the bordered mode of the GBGC. When the user starts using the gyro sensors or after a previous re-center command, the virtual 2D space position is aligned to the headset position (a). After some movements the measuring error adds up and those two positions do not match any more. In this example, the user's head is back in a neutral position, but in the virtual space the position is off to the right (b). The user can now use the virtual border to realign the virtual and real position. In this example, he has to rotate the head to the right until the virtual position hits the border of the virtual 2D space (c). By further turning the head to the right the real position is pushed closer and closer to the virtual position. When those two positions match again (d), the user can turn the head back to the neutral position and the re-centering procedure is finished (e).

(a)   (b)   (c)

(d)   (e)
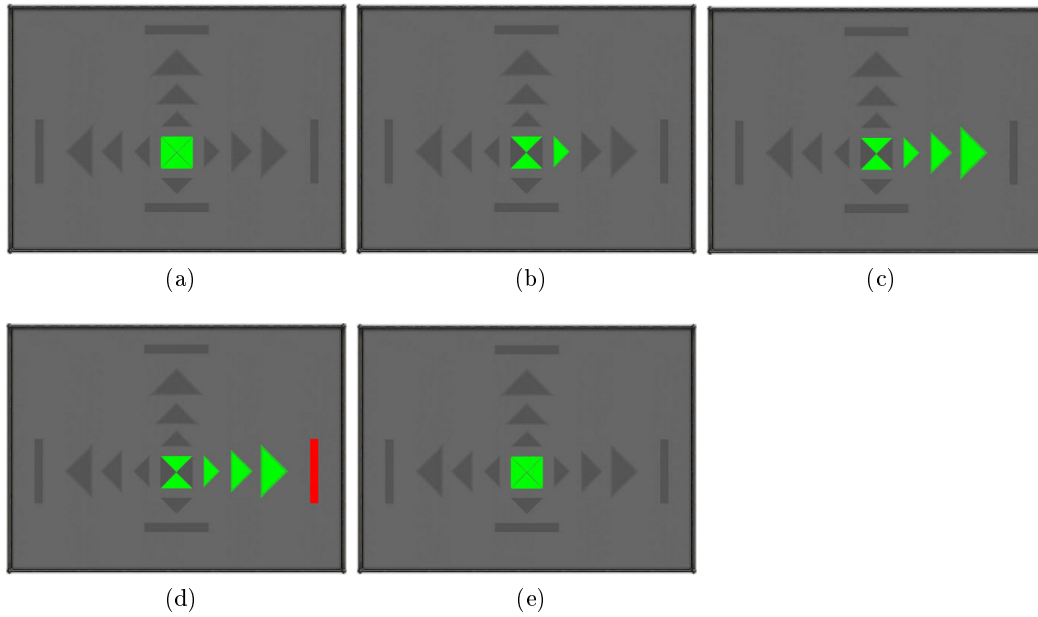
Figure 3.1.6.: The WoW add-on showing the same re-centering procedure as in Figure 3.1.5. The green arrows mark the virtual 2D position of the gyro sensors. If both axis are in a central position in the virtual space the green square is shown (a). In case the virtual position does not align with the headset position any more (b), the user can rotate his head further in the same direction as the offset (c). When the virtual 2D position is pushed against the borders of the virtual box a border marker is activated (d). The user has to estimate the offset distance. In case he rotates too far, he has to repeat the same procedure to the opposite direction until he is satisfied again with the alignment (e).

Visual Feedback for WoW

To support the user with visual feedback during the bordered mode re-centering process an interface extension (add-on) for the game WoW has been designed. This game provides an API that can be used to customize the interface using LUA and XML [93]. This add-on represents the virtual 2D position of the gyro sensors. If the user centers his head to a neutral position and one of the arrows is still activated, he knows that the virtual position needs to be re-centered. He can now perform the re-centering procedure with the help of the bordered mode described in Figure 3.1.5. The visual feedback during this procedure is shown in Figure 3.1.6. In the conducted user study the usability of this visual representation is evaluated (see Chapter 3.4.11 and Chapter 4.2.5).
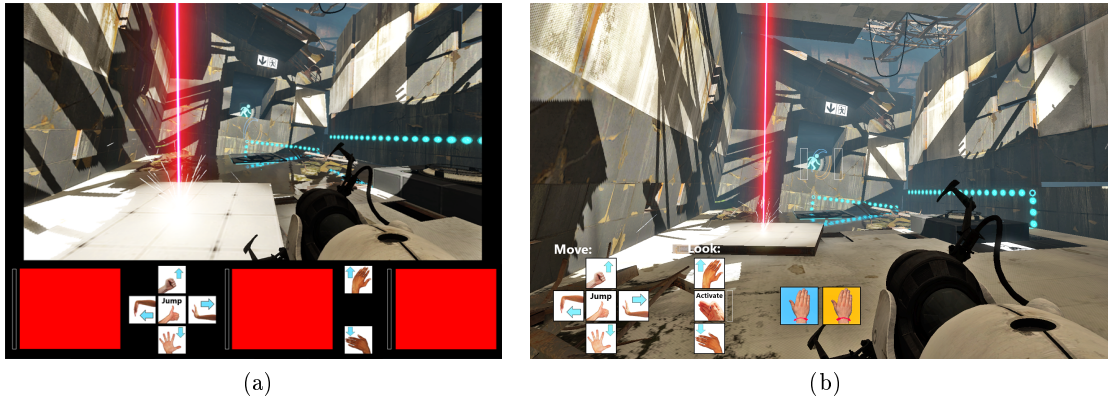
Figure 3.2.1.: Two interface examples using the GBGC IEE for the game Portal 2 (published by Valve Corporation). (a) Shows an interface where the icon elements are placed around the game window. (b) Shows a modified interface where the icons are directly placed over the game window.

3.2. GBGC Interface Extension Engine (IEE)

Very few commercial game titles provide an API to customize the game interface. The GBGC now features an interface extension engine (IEE) which is able to display additional GUI elements on the screen (see Figure 3.2.1). These elements provide user feedback for activated input signals from the devices attached to the GBGC.

Technical Specifications

The IEE uses OpenGL to draw the currently active interface elements. The configuration of the interface elements is defined in an XML file which is loaded by the GBGC using an XML-parser called RapidXML [68]. The Document Type Definition (DTD) for the XML file is listed in Appendix C.

Transparency

The IEE defines a separate window that contains all the interface elements (see Figure 3.2.1(a)). Additionally, this window can be made transparent and placed above any other applications running in background windows (see Figure 3.2.1(b)). The transparent mode achieves a look-and-feel as if the UI elements were integrated in the original GUI of the application running in the background window. The background window can be in focus and receive mouse/keyboard input since the IEE window will always stay on top of other windows.

Software Design

The IEE has a very flexible software design and allows the definition of a finite-state machine for GUI layouts. The automaton is traversed by commands that are triggered by signals sent from the connected input devices. The IEE commands consist of actions. These commands are linked to signals from the input devices. These sets of links are called

(a)   (b)
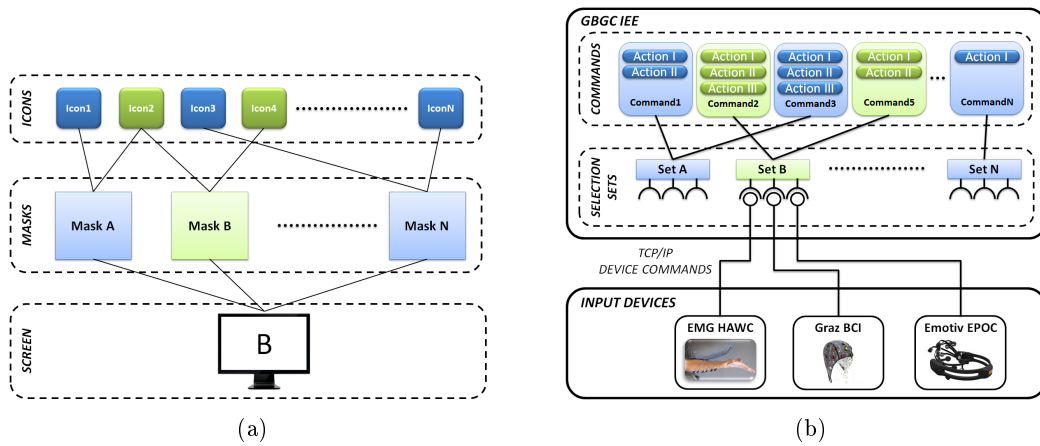
Figure 3.2.2.: The relations of all elements in the GBGC IEE. (a) Shows the relations
of the interface setups (called masks) and the interface elements (called
icons). Each mask consists of an arbitrary number of icons. Many masks
can reference one icon. Only one mask can be displayed at a time. The
masks are changed by the LoadMask action. In this example, the Mask B
is currently active, and it consists of the icons: Icon2 and Icon4. (b) Shows
the relation between Selections, SelectionSets, Commands, and Actions.
An attached input device can send a device command to the GBGC using
the TCP/IP network protocol. This message is translated into commands
which trigger several atomic actions. These translation rules are again
stored in a SelectionSet. By calling a LoadSelectionSet action, the currently
active SelectionSet can be changed. This allows to link different behavior
to device commands during run-time of the GBGC.

SelectionSets and they are, again, interchangeable. The relation between Selections,
SelectionSets, Commands, and Actions is shown in Figure 3.2.2(b).

The GUI layouts are stored in mask and icon elements. For a detailed view on the
relationship between masks and icons, see Figure 3.2.2(a).

3.2.1. Masks

A mask defines a setup of interface elements on the screen. It consists of a set of icons (see
Chapter 3.2.2) and is identified by a unique ID. These interface setups are interchangeable
during run-time and can be loaded by a LoadMask action (see Chapter 3.2.3).

3.2.2. Icons

All interface elements are called "icons". They are defined in an XML configuration
file and can be grouped in a mask. The following icon types are currently available:
CheckerIcon, BitmapIcon, TextureIcon, and BarIcon (see Figure 3.2.3). All these icon

(a)   (b)   (c)   (d)
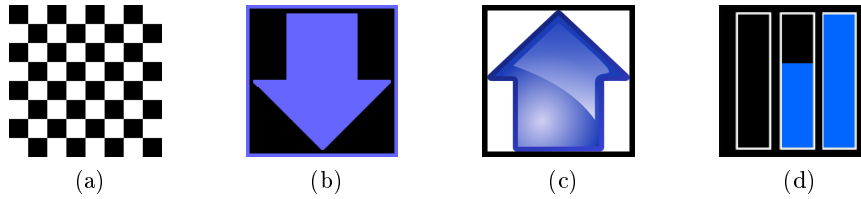
Figure 3.2.3.: The icon types currently supported in the IEE. The black areas in the icons show the background of the GBGC IEE window. (a) Shows a CheckerIcon with eight rows and eight columns colored in white. (b) Shows a bitmap icon. The arrow is loaded from a texture and every non-black pixel from the texture is colored in the specified color. (c) Shows a TextureIcon loaded from a file. (d) Shows three BarIcons. The BarIcon acts like a progress bar with color progressing from top to bottom. The left bar is empty. The middle bar shows a progress of 60% of a dwell timer and the right bar shows 100% progress.

types can create different visual representations that are used to extend the default GUI of applications. For a detailed view on the relationship between masks and icons, see Figure 3.2.2(a).

Icon Types

CheckerIcon This icon creates a checkerboard. It is mainly defined by a color, the number of columns, and the number of rows (see Figure 3.2.3(a)). It was designed to create mono-colored boxes or checkerboards that are typical for SSVEP stimulation.

BitmapIcon A bitmap icon is used to create a binary representation of a texture. The texture can be loaded from a file and all non-black pixels are rendered in the defined color. This element is suited to produce icons which are partly transparent and mono-colored. The size is determined by the texture loaded from a file (see Figure 3.2.3(b)).

TextureIcon The TextureIcon loads a texture from a file. It is displayed in the same size as the picture loaded from a file (see Figure 3.2.3(c)).

BarIcon The BarIcon provides a visual representation for dwell timers. It draws a progress bar that fills upwards whenever the delay of an action (see Chapter 3.2.3) gets activated (see Figure 3.2.3(d)).

Icon Extensions

All icon types can be extended by a SelectionFrame, a DefaultFrame, and an Animation (see Figure 3.2.4). The SelectionFrame is a colored border, which is shown in case an icon is marked as selected by an action (see Chapter 3.2.3). To display a colored frame around the icon even though it is deselected a DefaultFrame can be defined around the icon.

(a) (b) (c)
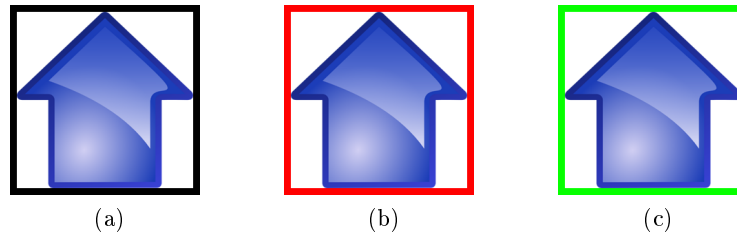
Figure 3.2.4.: The icons can be framed by various borders, indicating the selection status of an icon. (a) Shows the icon without any border on a black background. (b) Shows the icon with a red DefaultFrame. If this frame is defined in the XML configuration file, it is displayed as long as the icon is not selected. (c) Shows a green SelectionFrame. This frame is shown only when the icon is selected by a SelectIcon action. To hide this frame again, the icon needs to be deselected by a DeselectIcon action and the DefaultFrame or no frame is shown again.

To make any icon flicker on the screen an Animation child element needs to be defined in the XML configuration of the icon. The Animation element is mainly defined by an amount of frames the icon is visible (active_frames) and an amount of frames the icon is hidden (inactive_frames).

3.2.3. Actions

Actions can be best described as the most atomic events that can be triggered in the IEE. They are used to control various aspects, like marking an icon as selected or playing a sound file. These actions can be grouped as a command (see Chapter 3.2.4). The following actions are currently available in the IEE:

ActivateCommand This action triggers another command identified by a unique command ID.

DeselectIcon If an icon is marked as selected, a user defined SelectionFrame frame is drawn around the icon. This action marks an icon as deselected and hides the SelectionFrame again.

HideIcon This action hides a currently displayed icon.

LoadMask To load a different interface mask, this action has to be included into a command. The action takes a mask ID and shows all icons included into the mask on the screen.

LoadSelectionSet Loading a different SelectionSet identified by an ID exchanges the links between the selections and commands.

PlaySound Plays a sound loaded from a *.wav file.

SelectIcon Marks an icon as selected and displays the SelectionFrame if there is one defined for the icon.

ShowIcon Shows a hidden icon.

Selection Triggers a Selection as if it were activated by an attached input device. The difference to the ActivateCommand action is that the Selection command respects the link to a command defined in the current SelectionSet. It activates the command which is currently linked to the Selection. The ActivateCommand action activates a specific command independently from the currently active SelectionSet.

SendMessage Sends a network message to a network client. The message contents are also defined in this action.

3.2.4. Commands

Commands consist of a set of actions. Each command is linked to a Selection. In case the input device sends the Selection, the linked command is executed. These links are again interchangeable and are stored in the SelectionSets (see Chapter 3.2.6).

3.2.5. Selection

A Selection defines a link between a device command and an IEE command. In case an attached device detects an input from the user, it sends a device command to the GBGC. The IEE translates this device input into a chain of actions, defined as a command in the XML configuration file. These sets of links are again stored in a collection called SelectionSet (see Chapter 3.2.6).

3.2.6. SelectionSet

A SelectionSet consists of several Selections and can be changed by a LoadSelectionSet action. This allows for a completely different behavior of the GBGC to be linked to the inputs of an attached device during run-time.

3.3. IEE and Emotiv EPOC SSVEP Measurement

The experiment described in this section was designed to evaluate if the IEE can present icons on screen accurately enough for SSVEP. Additionally, EEG was recorded using the Emotiv EPOC headset while the subject focused on the flickering stimulus. The results of this measurement answered the following two questions:

1. Is the Emotiv EPOC capable of acquiring EEG?

2. Is the IEE accurate enough for use in SSVEP based BCI systems?

3.3.1. SSVEP Stimuli

The XML configurations for the two icons presented to the subject are shown in Listing 3.2. The measurements were conducted on a system attached to a screen with a refresh rate of 120 Hz and an overall resolution of 1920 x 1080 pixels.

One icon was displayed for three frames and hidden for another three frames. A cycle duration of six frames results in an icon flickering at 20 Hz on a 120 Hz display. The second icon used in this measurement was shown for four frames and hidden for three frames. A cycle duration of seven frames appears at approximately 17.14 Hz on 120 Hz display. The icons were colored in red and placed in the middle of the screen.

3.3.2. Measurement Procedure

The subject focused on each of the two icons for 60 seconds. Only one icon was presented at a time. With the Emotiv EEGLogger [24] the raw EEG was recorded from the 10–20 locations: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4 (see Figure 1.3.2).

```xml
<CheckerIcon id="icon_17HZ" pos_x="732" pos_y="312"
        height="500" width="500" color="1.0,0.0,0.0"
        lines="1" columns="1">
 <SelectionFrame width="20" color="0.0,0.0,0.0"/>
 <Animation type="ONOFF" active_frames="3" inactive_frames="3"/>
</CheckerIcon>

<CheckerIcon id="icon_20HZ" pos_x="732" pos_y="312"
        height="500" width="500" color="1.0,0.0,0.0"
        lines="1" columns="1">
 <SelectionFrame width="20" color="0.0,0.0,0.0"/>
 <Animation type="ONOFF" active_frames="4" inactive_frames="3"/>
</CheckerIcon>
```

Listing 3.2: The XML configurations for the icons presented to the subject.

3.4. User Study Design

This section describes in detail the design of the conducted user study. The major goals of this study are:

1. Capturing the wearing comfort of the consumer EEG headset EPOC over a long period of time.

2. Evaluating if it is possible for subjects to gain control over a virtual cube with the Emotiv Expressiv Suite.

3. Verifying if the Emotiv Affectiv Suite is capable of estimating the state of a player.

4. Assessing the reaction (premotor + motor) time and accuracy of facial expressions.

5. Validating if the interference matrix (explained in Chapter 3.4.10) can be applied in order to identify the most reliable and unreliable expressions.

6. Testing the Emotiv headset integration of the GBGC (see Chapter 3.1.2) with multiple users.

7. Capturing the user experience for the Emotiv EPOC as an input device for controlling a popular game application.

8. Assessing the usability of the gyro re-centering procedure using the bordered mode of the GBGC (described in Chapter 3.1.3).

The user study is not meant to be an exhaustive test that investigates the entire functionality provided by the Emotiv EPOC headset. Instead, a set of representative experiments was chosen to get an overview of the potentials of this EMG, EEG, and gyro sensor based input device. The study was designed with respect to the World Medical Association (WMA) declaration of Helsinki in the version of 2008 [1].

3.4.1. Structure

The study procedure is divided into five major parts (see Figure 3.4.1):

1. Introduction & Preparation.

2. Cognitiv Test.

3. Affectiv Test.

4. Expressiv Test.

5. Experience Test.
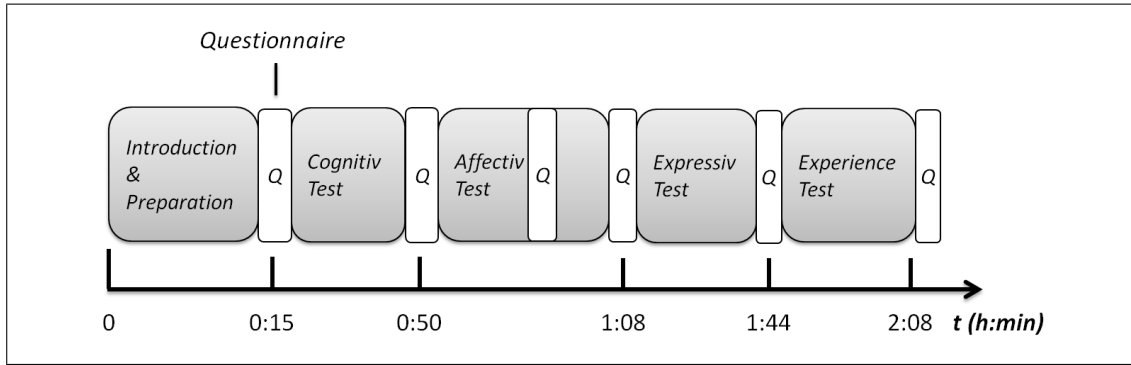
Figure 3.4.1.: The user study procedure, showing the average durations of each individual part of the user study.

In the first part, the participant is introduced to the study conditions. After mounting the EPOC on the subject's head, the Cognitiv Suite of the Emotiv Control Panel is used to determine if a new user can gain control over a virtual object. The Cognitiv Test is followed by the Affectiv Test. This part was designed to assess if the values for various emotions measured by the Affectiv Suite relate to the actual affective state of a subject. In the next part of the user study, the Expressiv Suite is used to investigate the detection accuracy for various facial expressions. To assess the reaction times of facial expressions, the premotor and motor times are recorded during the Expressiv Test. The study is concluded by an Experience Test which investigates if the Emotiv EPOC can be used to conveniently control a popular game application hands free–just using head movements and facial expressions. Between each part of the user study, a pen and paper questionnaire is used to assess the wearing comfort of the headset and the subject's state.

3.4.2. Questionnaires

The questionnaires used in this study are based on [26, 84]. The base questionnaire consists of seven different questions that had to be answered using a 10 cm long visual analog scale (VAS) ranging from 0 to 10 (see Figure 3.4.2). VASs were chosen over rating scales because of the findings of [28]. For a complete listing of the German questionnaires, see Appendix B.

The questions, which were given to the participants after each part of the study, are:

1. Do you feel relaxed? [0 = very excited; 10 = extremely relaxed]

2. Do you feel alert? [0 = very sleepy; 10 = extremely alert]

3. How is your motivation? [0 = not motivated at all; 10 = extremely motivated]

4. How is your mood? [0 = extremely bad mood; 10 = extremely good mood]

5. How does the headset feel on your head? [0 = extremely disturbing; 10 = not disturbing at all]

Fühlen Sie sich entspannt?

0 = sehr
aufgeregt

10 = sehr
entspannt
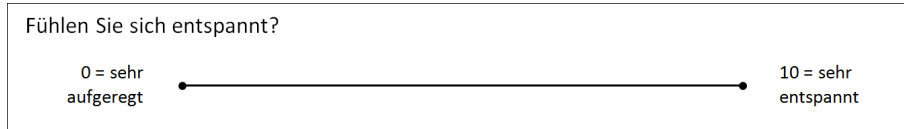
Figure 3.4.2.: The VAS style used in the questionnaires of the user study.

6. Does wearing the headset cause pain? [0 = extremely painful; 10 = not painful at all]

7. Was the task demanding? [0 = extremely demanding; 10 = not demanding at all] (not included in the Introduction & Preparation part of the study)

After each specific part of the user study the following additional questions were included:

1. Do you have the feeling that you could control the cube? [0 = no control; 10 = total control] (after Cognitiv Test)

2. Was the task hard for you? [0 = extremely hard; 10 = extremely easy] (after Experience Test)

3. How did you perceive the movement controls of your avatar? [0 = no control; 10 = total control] (after Experience Test)

4. How hard was it to re-center the gyro sensors using the border markers? [0 = extremely hard; 10 = very easy] (after Experience Test)

5. How did you perceive the control over the actions (target, attack and loot)? [0 = no control; 10 = total control] (after Experience Test)

3.4.3. Mehrdimensionaler Befindlichkeitsfragebogen

In the Affectiv Test (see Chapter 3.4.9) an additional questionnaire, called "Mehrdimensionaler Befindlichkeitsfragebogen" (MDBF) [84], was used to assess the affective state of a subject. The MDBF is a scientifically established questionnaire in German, which investigates three mood dimensions. These dimensions are:

1. "Gute-Schlechte Stimmung" (GS) (good-bad mood).

2. "Wach-Müdigkeit" (WM) (awake-tired).

3. "Ruhe-Unruhe" (RU) (calm-excited).

The possible values for all three dimensions range from 8 to 40. The MDBF used in this study is shown in Appendix B.

To quantify how playing two different games (QWOP and High Delivery, described in Chapter 3.4.9) affected the subjects, the questionnaire had to be answered three times: before playing the first game, between the two games, and after playing the second game.

CPU	Intel Core i5 661, quad core 3,33 GHz
Memory	8 GB, 1600Mhz
GPU	NVIDIA GeForce GTX 580
Display	Acer GD245HQ (1920x1080, 120 Hz)

Table 3.4.1.: The technical specifications of the PC used in the user study.

3.4.4. Subjects

For the study only healthy people were accepted. The age of the subjects ranged from 23 to 32 (mean age 28.6 years, 8 males, 2 females). No participant was taking medication that could affect his or her reaction time or cognitive function. None of the subjects drank alcohol 24 hours in advance of the study and only two out of ten subjects were smokers. Each subject stated that they had slept the usual (or more) amount the night before the study (mean hours of sleep 7.65). All subjects had normal or corrected-to-normal vision using contact lenses or glasses. Additionally, the subjects were asked not to use any hair styling products or lotions since these items can influence the EEG signal.

3.4.5. Room and Hardware Setup

The room setup used in this study (see Figure 3.4.3 (a)) was inspired by usability testing methods [3]. To avoid any distractions, the subject was seated in a position where only the required display could be seen and the window did not cause any glare on the screen. The investigator was able to see both displays that were used during the study. The subject's display was installed on a Neo-Flex LCD arm by Ergotron (see Figure 3.4.3 (b)). This LCD mount provides great flexibility and it is possible to adjust the LCD screen's position in any direction.

[10, 87] state that the Emotiv EPOC USB dongle uses a low power Bluetooth transmitter. This transmission technology can cause a bad connection even if the headset is fully charged. To avoid this problem, a USB extension cable was used to mount the dongle directly on the backrest of the subject's chair. This brings the dongle as close to the headset as possible.

The PC which used for testing ran a Microsoft Windows 7 (64-bit, Service Pack 1) operating system (OS). The detailed technical specifications of this PC are listed in Table 3.4.1.

3.4.6. Emotiv EPOC Test Suite

For providing a clean user interface and storing the measured data, a Test Suite for the Emotiv EPOC headset was implemented. This application runs on Microsoft Windows 7 and is written in Visual C++. The signals from the Emotiv EPOC headset are acquired by the Emotiv Research Edition SDK v1.0.0.5. The GUI uses the Windows Forms framework (see Figure 3.4.4).

For pilot testing purposes all timing parameters are adjustable via GUI entries. During

(a)   (b)
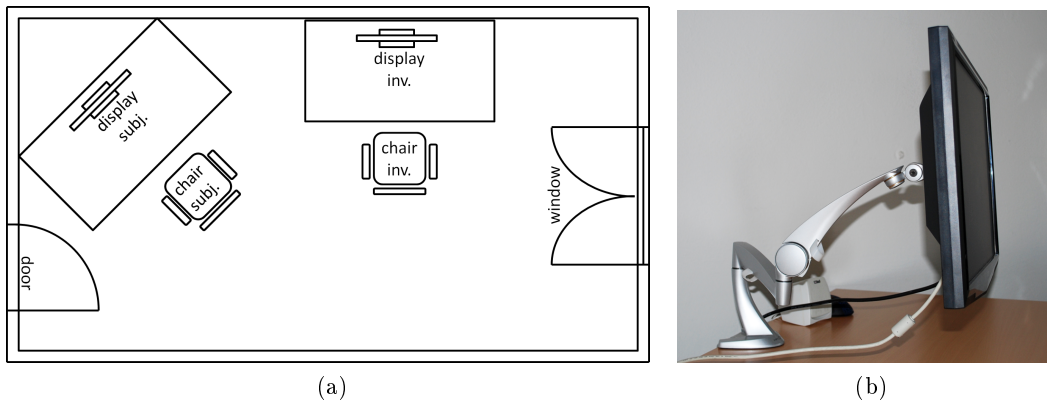
Figure 3.4.3.: (a) A map of the room used in the user study, showing the locations of the door, window, chairs, and displays. (b) Shows the Neo-Flex LCD arm by Ergotron. This LCD mount provides great flexibility and it is possible to adjust the LCD screen's position in any direction.

a test the investigator receives live feedback from a message queue to check if the recorded data is valid.

3.4.7. Preparation & Introduction

The Emotiv headset was fully charged and the electrodes were mounted with a new set of felt sensors for each test session. To respect hygiene guidelines and to maintain the same study conditions for each participant, no felt pads were reused. The two rubber ground electrodes were cleaned and sterilized with surgical alcohol prior to each session. The felt sensors were moistened using the same multi-purpose contact lens cleaning solution as the manufacturer delivered in the original Emotiv EPOC package (Bausch&Lomb ReNu MPS Sensitive Eyes, see Figure 3.4.5).

The test subjects were welcomed and introduced to the testing location by the investigator. The experiment conductor was also in charge of providing small refreshments and non-caffeinated drinks during the study, so that the subjects could feel as comfortable as possible. To avoid interferences in the EEG signal or the wireless connection of the Emotiv EPOC mobile phones and other devices using WLAN or Bluetooth were turned off or removed from the testing location prior to the study. The headset was shown and explained to each subject before they received a written explanation of the user study. An informed consent form had to be signed by each participant in order to document that he or she understood the explanation document and agreed with the study conditions. The informed consent is included in Appendix A.

The display and chair were adjusted so that each subject could sit in a relaxed position and maintain a good view on the display. The headset was placed on the head of each subject according to the user manual [24] of the manufacturer. A new user profile was created with the subject's user code in the Emotiv Control Panel and the Emotiv EPOC
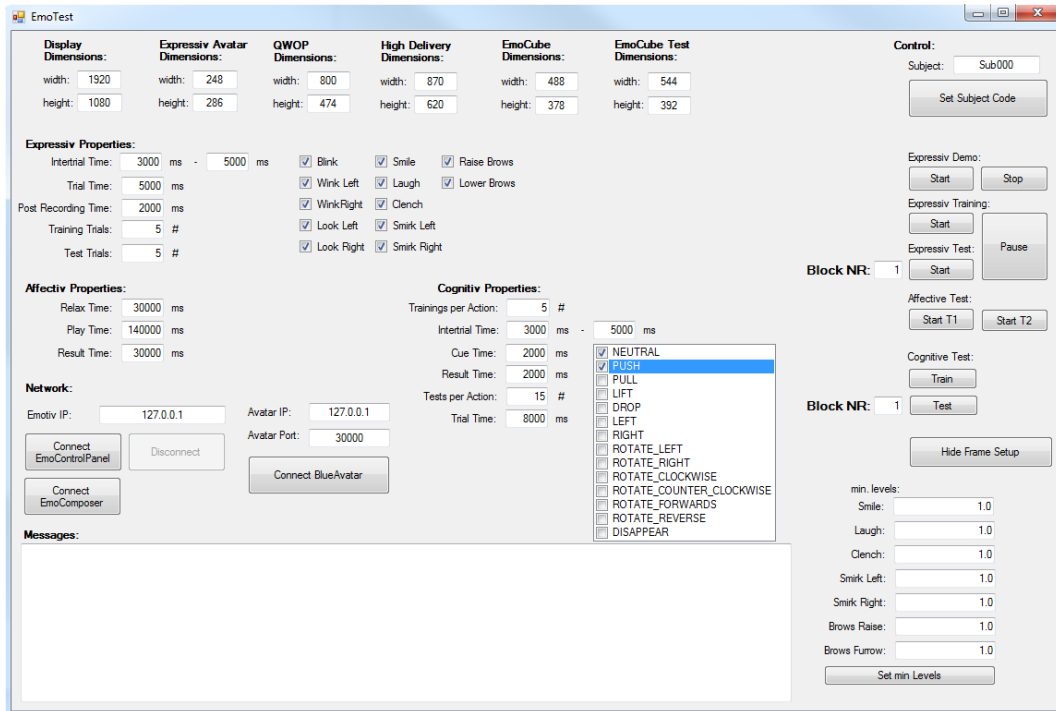
Figure 3.4.4.: The GUI of the Emotiv EPOC Test Suite. For pilot testing all time-based parameters are adjustable. The Test Suite provides clean user interfaces for the user study. Only interface elements that are used for the study are displayed on the subject's screen. On the top of the window, the screen resolution and the size of the external applications can be adjusted. The external applications are displayed in the middle of the screen and are framed with a clean white border by the Test Suite. Emotiv provided the Blue Avatar and EmoCube application. High Delivery and QWOP are Flash games running in a browser window which is also hidden by the Test Suite. The buttons to invoke the various tests are located to the right of the window.

(a)
(b)

Figure 3.4.5.: The contact lens cleaning solution is used as a contact agent for the Emotiv EPOC headset. The felt pads of the electrodes need to be moistened using this saline, disinfectant solution. (a) Shows the solution provided by Emotiv and (b) shows the one used in the user study.

Test Suite (see Chapter 3.4.6), so that each user had his own personal profile in both applications. All 16 electrodes of the headset were readjusted until they had good contact with the subject's scalp. A good contact quality is indicated by a green dot in the Emotiv Control Panel (see Figure 3.4.6).

3.4.8. Cognitiv Test

The Cognitiv Test of the user study investigates how easy it is for new users to learn to control a virtual cube only using brainwave activity. The manual of the Emotiv Research Edition SDK version 1.0.0.5 [24] describes the Cognitiv Suite (see Figure 3.4.7) as follows:

> "The Cognitiv detection suite evaluates a user's real time brainwave activity to discern the user's conscious intent to perform distinct physical actions on a real or virtual object. The detection is designed to work with up to 13 different actions: 6 directional movements (push, pull, left, right, up, and down) and 6 rotations (clockwise, counter-clockwise, left, right, forward, and backward) plus one additional action that exists only in the realm of the user's imagination: disappear. Cognitiv allows the user to choose up to 4 actions that can be recognized at any given time. The detection reports a single action or neutral (i.e. no action) at a time, along with an action power which represents the detection's certainty that the user has entered the cognitive state associated with that action ... Almost all new users readily gain control over a single action quite quickly. Learning to control multiple actions typically requires practice and becomes progressively harder as additional actions are added."

For the study, only one action (lift) was selected for the cognitive training. The subjects were given the task to move a virtual cube floating in a box (see Figure 3.4.8) by just
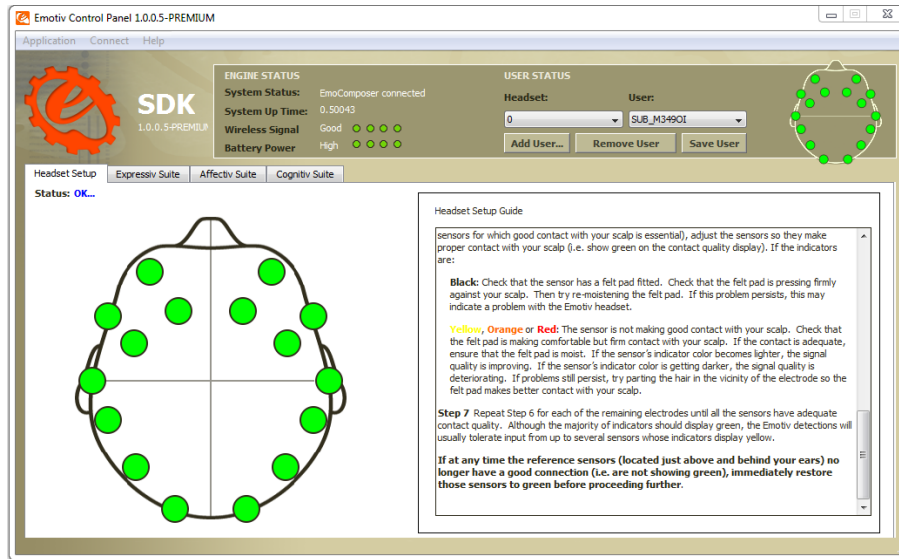
Figure 3.4.6.: The Emotiv Control Panel view, showing the contact quality of the 16 sensors. A green dot shows that the sensor has the best possible contact to the scalp of the subject's head.

using their brainwave activity.

Cognitiv Training and Test

Emotiv does not include any detailed information in the user manual of the EPOC headset on how the cognitive actions can be trained appropriately. The necessary information was extracted from postings of Emotiv officials in the support forum. Gmac (Emotiv support forum administrator) states [86] that at least five to six trainings per state are required to get a good distinction between two different states (neutral and lift).

To investigate if the performance increases with more training trials and practice, the Cognitiv Test was divided into two parts: training and test. In the first part, five trainings were performed for each state (10 trainings in total), followed by 15 test trials per state (30 in total). After clearing the training data, six trainings were used per action (12 in total) in the second part, which were again followed by 15 test trials per state (30 in total).

Although [55] states that at least 50 test trials are necessary for each state to calculate the performance of such a system, only 30 test trials per state were recorded due to overall time constraints. The detailed trial setup is depicted in Figure 3.4.9.

Instructions

For the Cognitiv Test, detailed information was extracted for the subjects from the Emotiv forums [85, 86]. The following instructions were given to the participants prior to the Cognitiv Test:

1. The EEG signal is used for detecting activations in certain brain regions.
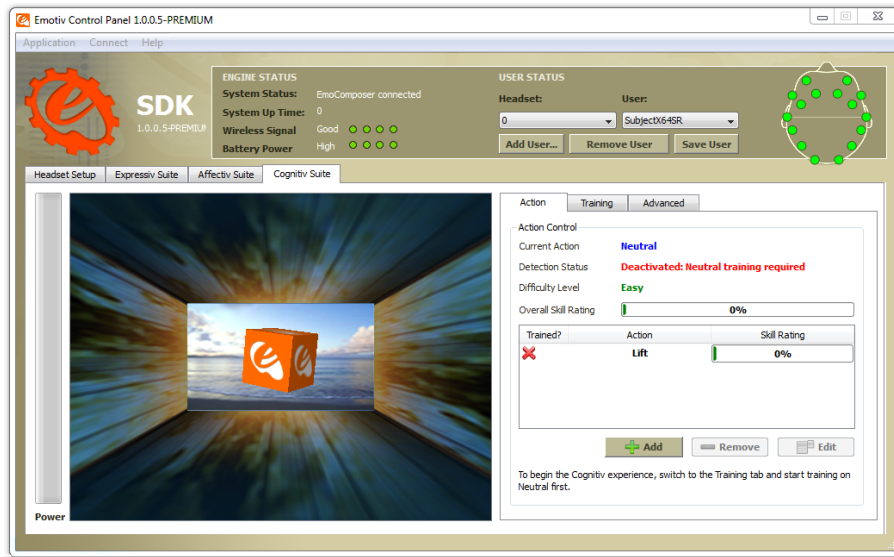
Figure 3.4.7.: The Emotiv Cognitiv Suite showing the actions, which can be applied to a virtual cube. A training progress for each activated action is shown in the right part of the window.

(a)

(b)

Figure 3.4.8.: The virtual cube provided by Emotiv. It is used to get online feedback while performing cognitive actions. (a) shows the cube in a neutral position. The subjects were asked to try to lift the cube (b) by just using brainwave activity.
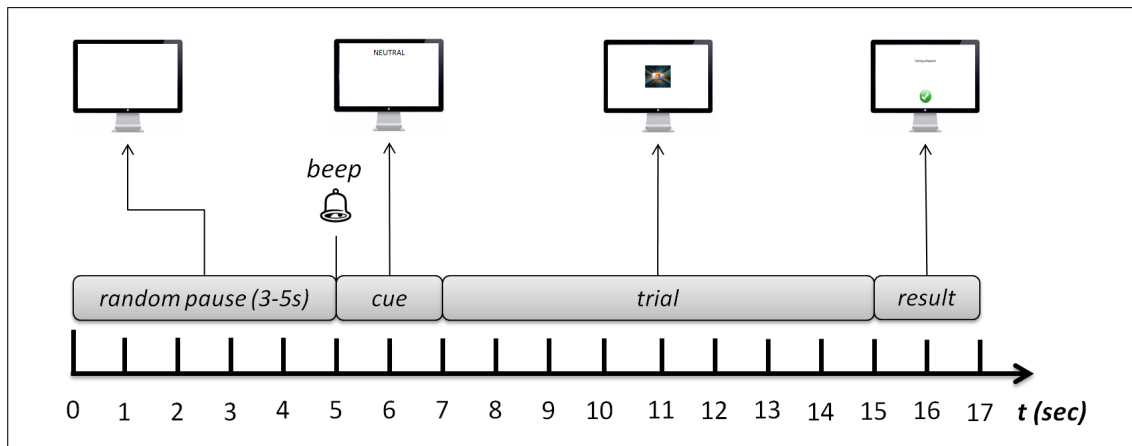
Figure 3.4.9.: The trial setup used in the Cognitiv Test for training and testing. The subjects were asked to relax during a random pause (3–5 sec). They should also try to swallow and blink only during this pause as much as possible. The cue, indicating the next cognitive action to perform, was chosen at random. During the trial time (8 sec), the virtual cube was displayed on screen, and depending on the previously given cue the subject can try to either lift the cube or hold it in a neutral position. During the result time (2 sec) a visual feedback was presented indicating if the training or test trial was successful or not.

2. To produce an appropriate activation you have to imagine a certain scene.

3. It is *not* important what this scene looks like. The system learns to recognize the activation pattern in a training phase. It is necessary that the imagined scene is constant (greater 8 sec) and reproducible.

4. Try not to flex any muscles! Especially avoid movements of the head, tongue, mouth, and jaw.

5. Try to truly relax during the imagination. Do not try to force it! This can cause muscle contractions which again will influence the EEG signal.

6. For the neutral state do not think of anything in particular. During the lift state, try to lift the virtual cube.

7. For lifting the cube you could think of ...

   - squeezing a fluid through a tube in front of your eyes.
   - your whole body beginning to float.
   - where the cube should be located.

After the instructions were explained to the subjects they were given two minutes time to relax. During this period the participants could choose and practice a good scene for their imagination to lift the virtual cube.

3.4.9. Affectiv Test

The user manual [24] for the EPOC headset describes the Affectiv Suite (see Figure 3.4.10) as follows:

> "The Affectiv Suite reports real time changes in the subjective emotions experienced by the user ... The Affectiv detections look for brainwave characteristics that are universal in nature and don't require an explicit training or signature-building step on the part of the user."

The Emotiv EPOC Affectiv Suite measures continuous values for five different emotions: engagement/boredom, frustration, meditation, instantaneous excitement, and long-term excitement. By frustrating the subjects on purpose the Affectiv Test examines if these measured values, in particular frustration, can reflect the affective state of a subject.

Frustration
[29] describes frustration in a gaming context as follows:

> "Frustration is that which arises when the progress a user is making towards achieving a given goal is impeded."
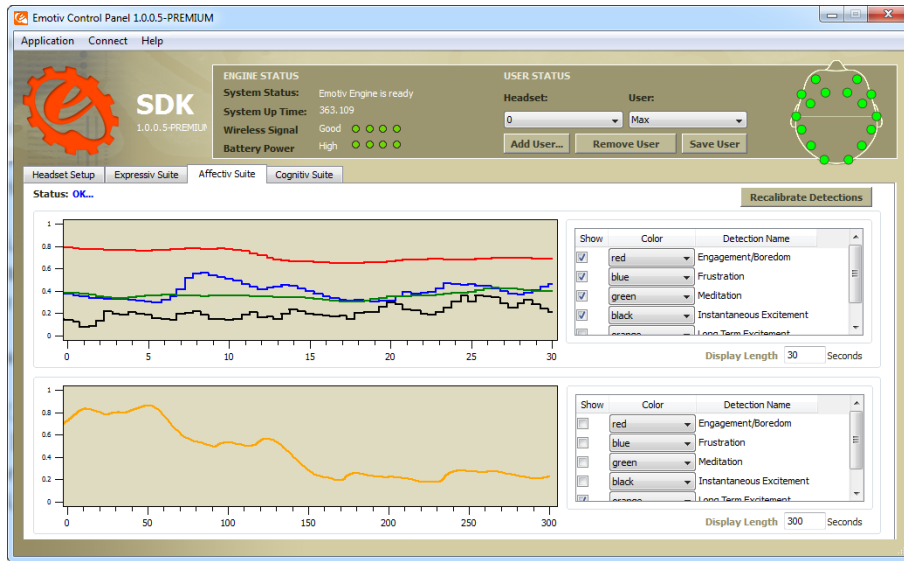
Figure 3.4.10.: The Emotiv Affectiv Suite showing the continuous graphs for engagement/boredom (red), frustration (blue), meditation (green), instantaneous excitement (black), and long-term excitement (orange).

To induce frustration the same approach as in [70] was used. Each participant was given a gaming task that could not be solved by the player. Since it was nearly impossible for the player to reach the goal in time it ensured frustration.

To get comparable results, the subject was "brought back" to the initial state by a second, manageable gaming task. This time the player could easily complete the task.

Procedure

The initial state of a subject was captured using a pen and paper questionnaire including the MDBF (see Chapter 3.4.3) and two VASs (see Chapter 3.4.2). After the subject answered the questionnaire, frustration was induced with the game QWOP. While the subject was playing the game, the Affective Suite was used to record the values of the five emotions. Afterwards, the subject was asked to answer the same questionnaire as in the beginning. Finally, the subject was given the second manageable gaming task in a game called High Delivery. The values for the emotions were also recorded during the play time, and the effect on the state of the players was again captured by a questionnaire.

The same trial setup was used for playing QWOP and High Delivery. It is shown in Figure 3.4.11.

QWOP

In the first game QWOP (see Figure 3.4.12(a)) the thighs and calves of an athlete had to be controlled by the player. The subjects were given the task to run ten meters of distance with their athlete in 2:20 min (time determined by the fixed duration of High Delivery). The athlete is very fragile and easily falls to the ground. If any other body parts other than the feet of the athlete hit the ground, the game is over and has to be
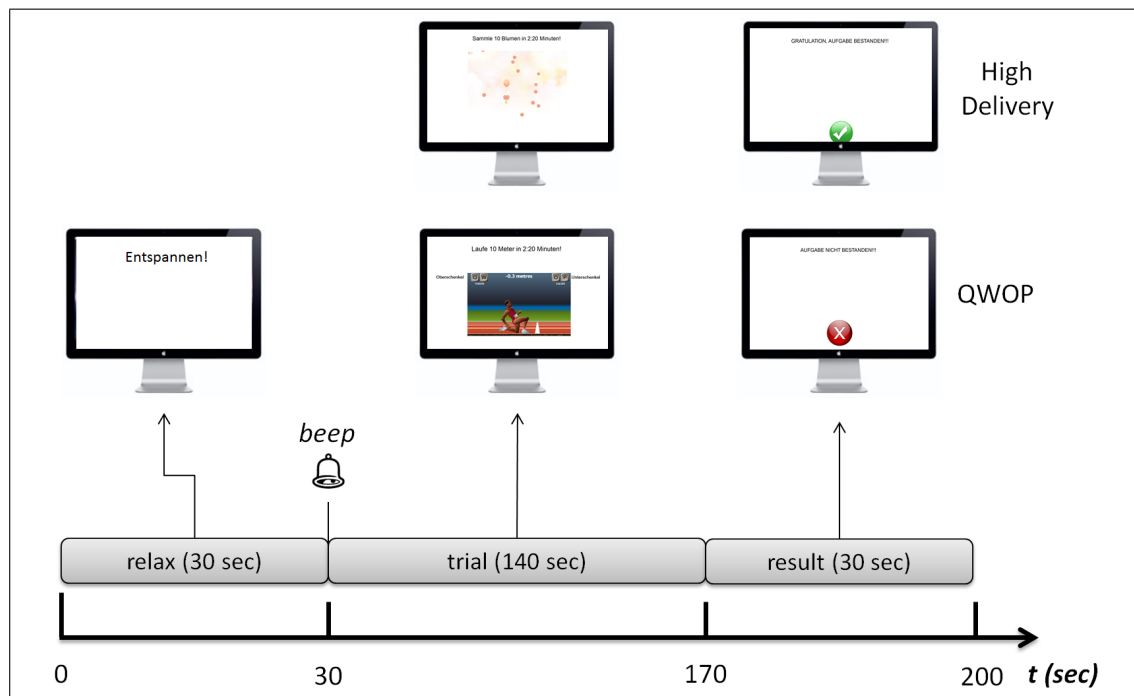
Figure 3.4.11.: The trial setup used in the Affectiv Test of the user study. After a 30 sec relax time the subjects had 2:20 min time to complete the given game task. The subjects received negative feedback after the QWOP task and positive feedback after the High Delivery task. During the result time, the subjects were advised to relax again, but this time they should think about their performance in the game task.

(a)   (b)
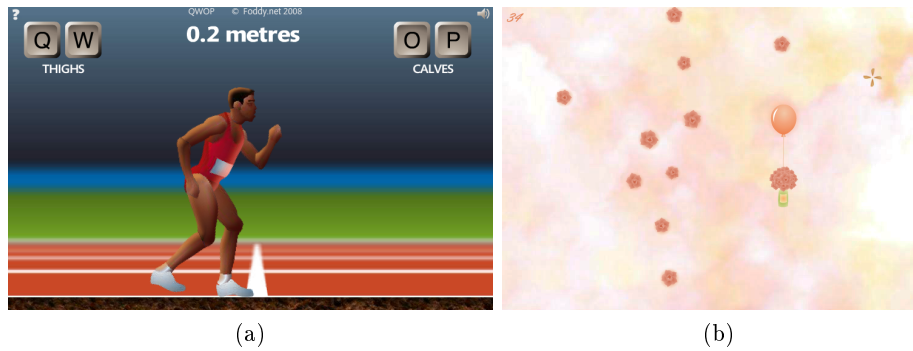
Figure 3.4.12.: The games used in the Affectiv Test of the user study. (a) Shows a game called QWOP. The player controls the thighs (buttons Q, W) and calves (buttons O, P) of an athlete to run down a track as far as possible. The achieved distance is shown on the top of the screen. In the second game, High Delivery (b), the player has to catch flowers with a bottle hanging from a balloon. The mouse pointer is represented by a small fan which can blow the balloon in different directions. The amount of flowers caught by the player is displayed in the upper left hand corner of the screen.

restarted by pressing the space bar. For a player that has never played this game before it is very hard to learn how to make the athlete run the distance within the designated time frame. The timing and sequence of button presses has to be trained to get better control over the athlete.

High Delivery

In the second task of the Affectiv Test, the subjects had to collect ten flowers within the game High Delivery (see Figure 3.4.12(b)). The flowers drop from the top of the screen and have to be caught with a bottle hanging from a balloon. The balloon can be blown in any direction with a small fan. The player controls the position of the fan with the computer mouse. The task was chosen in a way that each subject could reach the given goal easily. The game ends automatically after 2:20 min.

Compared to QWOP, High Delivery has very easy controls. It is also accompanied by a very relaxing tune which plays throughout the whole game. The flowers that have to be caught by the player drop at a very slow speed.

3.4.10. Expressiv Test

In the Expressiv Test the accuracy of recognizing facial expressions using the Emotiv EPOC headset was investigated. Additionally, the premotor and motor times of facial expressions were recorded. The Expressiv Test was again divided into three parts:

1. Demo.

2. Training.

3. Test.

Approach

The Emotiv Expressiv Suite (see Figure 3.4.13) can detect 12 different facial expressions (for a full listing, see Table 3.4.2). Since the headset is able to detect many expressions the accuracy for each expression is very low. It would not be feasible to calculate the accuracy using a cue-paced experiment where the requested expression has to occur as the next classification.

To get better accuracy for the facial expressions, [9] combined multiple expressions into groups: eyeball movements (look left, look right), frontal muscle movements (raise brows, blink, wink left, wink right), and jaw muscle movements (smile, clench). Their results show that the EPOC device is able to distinguish between groups of muscles, but the classifications of the exact muscle motion and corresponding facial expression can be inaccurate.

Accuracy can also be raised by finding the optimal settings for the sensibility sliders (see Figure 3.4.13). These sliders need to be adjusted to reduce the miss-classification rate for some highly detected expressions. According to [9], the average classification rate can be increased 12% by adjusting these sliders. To find the optimal settings, a user can only use a trial and error approach.

In this work an automated approach to find these interfering expressions is proposed with the concept of an interference matrix (see Table 3.4.5). The highly detected expressions can easily be identified and then be either excluded, adjusted in sensitivity or grouped to get a better accuracy.

Demo

Before the Expressiv Test the subjects were introduced and familiarized with the set of facial expressions, which can be detected by the Emotiv EPOC headset. The Emotiv EPOC Test Suite (see Chapter 3.4.6) was set to a demonstrative mode where only the avatar, representing the user's facial expressions, is displayed (see Figure 3.4.14). The investigator showed the subject a card with the name of an expression and the corresponding avatar face (see Figure 3.4.15). The subject was then asked to try to recreate the expression shown on the card. After three to four attempts to recreate the expression, the investigator drew the next card and the procedure was repeated until all of the 12 expressions (for a complete list see Table 3.4.2) were performed by the subject.

Training

In the next step of the Expressiv Test, the subjects were asked to try to recreate the facial expressions indicated by a randomly chosen cue. The subjects were aware that speed was relevant but not as important as accuracy. The results of [31, 55] indicate that at least 10 practice trials are necessary for healthy subjects to learn a movement procedure in simple electromyographic reaction time (ERT) studies. Based on these results, the Expressiv Test was divided into one training block and two testing blocks. Each block consisted of five trials per facial expression, making up a total of 60 trials for one block.
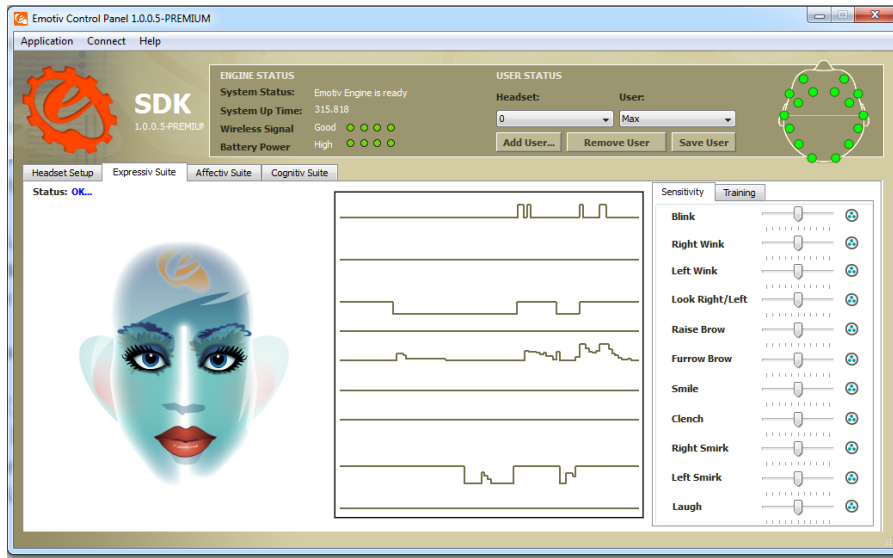
Figure 3.4.13.: The Emotiv Expressiv Suite showing the graphs for the detection and power of facial expressions over time. The sliders to the right adjust the sensitivity for the detections. In the user study the sensitivity sliders were set to their default position. To capture the detection accuracy with the default settings of the Emotiv EPOC Control Panel it is necessary to leave the sliders at the default settings. This also ensures that the results are comparable between subjects.

Figure 3.4.14.: The screen setup of the demonstration mode. The Test Suite shows only the avatar, which represents the subject's facial expressions currently detected by the Emotiv Expressiv Suite.

(a) furrow brows

(b) raise brows

(c) clench

(d) look left

(e) look right

(f) smile

(g) smirk left

(h) smirk right

(i) laugh

(j) wink left
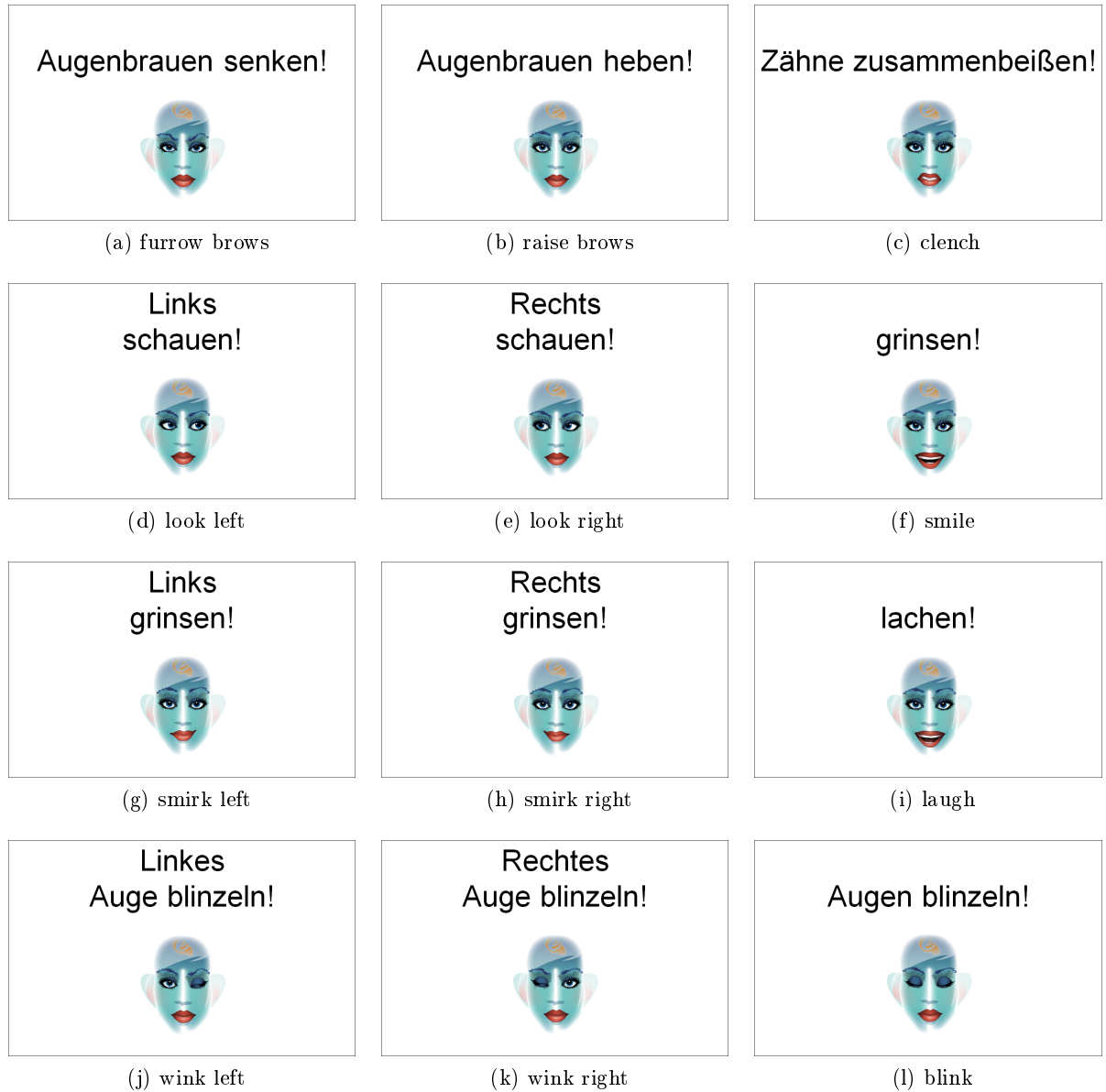
(k) wink right

(l) blink

Figure 3.4.15.: The cards used for familiarizing the subjects with the 12 different facial expressions (a–l).

eyes	upper face	lower face
blink	furrow brows	smile
wink left	raise brows	laugh
wink right		clench
look left		smirk left
look right		smirk right

Table 3.4.2.: List of facial expressions detectable by the Emotiv EPOC Expressiv Suite grouped by their API function.
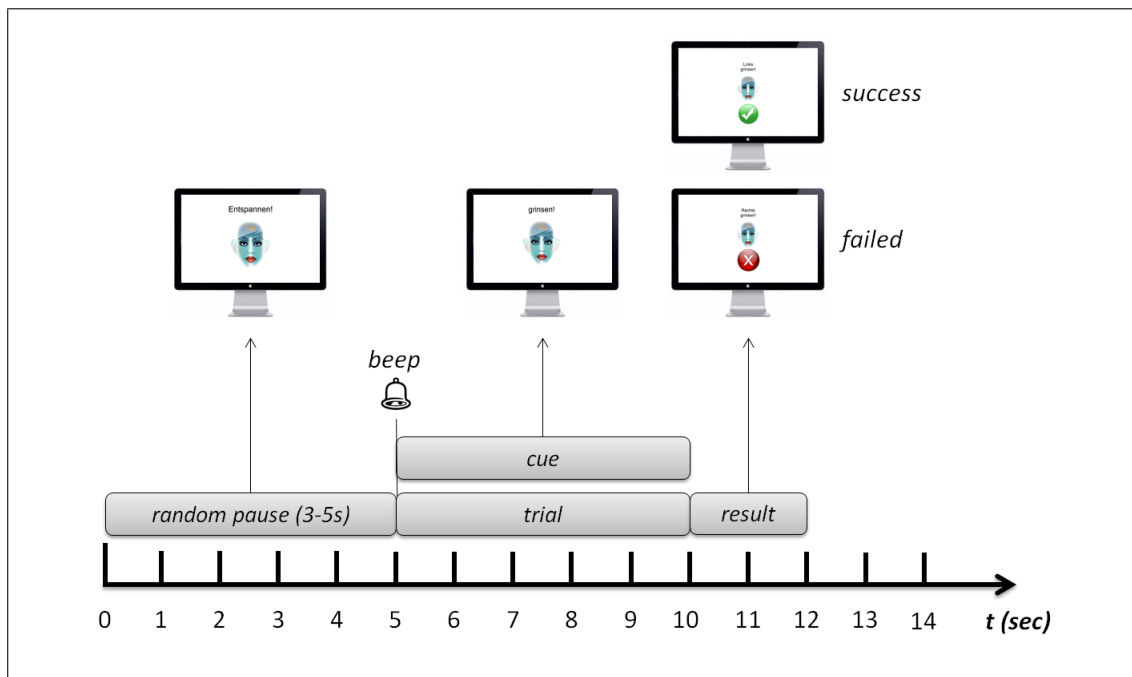
Figure 3.4.16.: The Expressiv Test training and test trial setup, showing the timings and screens of each trial phase.

Trial Setup

The training trial setup is shown in detail in Figure 3.4.16. At the beginning of each trial the subject was asked to relax the facial muscles for a random period of three to five seconds. The participants were advised to try to return to a neutral state with their avatar during this time. The timeout was randomized so that a subject could not prepare for the upcoming cue. The random pause was followed by a beep (700 Hz, 100 ms) and a cue indicating the name of a randomly chosen facial expression. During the trial time the subject could try to recreate the given facial expression. If the subject succeeded in creating the right signal during a five-second trial timeout, the recording of the motor time was started. The time between the trial start and the motor time was considered as premotor time. As long as the power of the signal for the requested facial expression was on the rise or equal to the previous sample, the time was considered as motor time. As soon as the signal power was lower than the previous sample, the recording of the motor time was stopped and a positive feedback was displayed on the screen. After a two-second result timeout (or post-recording time) the Expressiv trial was finished. A negative feedback was displayed if the subject was not able to perform the right facial expression or the headset was not able to detect it during the five-second trial time.

Minimum Power Levels

The values provided by the API of the Emotiv headset (see Listing 3.3) for the power level of the facial expressions are either binary (blink, wink left, wink right, look left, look right) or of floating point precision between 0.0 and 1.0 (clench, smile, laugh, smirk left, smirk right, brows furrow, brows raise). During the training procedure, the lowest maximum power level for each expression was determined. These minimum levels were used later on in the testing portion of the Expressiv Test to detect interferences of other signals. Table 3.4.4 and Table 3.4.3 show sample results of the expressive training.

trial no.	type	complete	premotor time (ms)	motor time (ms)	max. power
0	wink left	false	5000	0	0
1	blink	true	795	177	1
2	look left	true	1026	482	1
3	laugh	true	2553	148	0,698156
...	...	...	...	...	...

Table 3.4.3.: The data format of the recorded test results for each individual trial. The trial number indicates the order of the randomly chosen trial types. The premotor and motor times are recorded in milliseconds. The maximum power is the highest power level reached during the motor time.

```
//! Returns the detected upper face Expressiv action power of
    the user
/*!
    \param state - EmoStatehandle
    \return power value (0.0 to 1.0)
    \sa ES_ ExpressivGetUpperFaceAction
*/
EMOSTATE_DLL_API float ES_ExpressivGetUpperFaceActionPower(
    EmoStateHandle state);


//! Returns the detected lower face Expressiv action power of
    the user
/*!
    \param state - EmoStatehandle
    \return power value (0.0 to 1.0)
    \sa ES_ ExpressivGetLowerFaceAction
*/
EMOSTATE_DLL_API float ES_ExpressivGetLowerFaceActionPower(
    EmoStateHandle state);
```

Listing 3.3: The documentation of the ES_ExpressivGetLowerFaceActionPower and the ES_ExpressivGetUpperFaceActionPower API functions from the EmoStateDLL.h of the Emotiv EPOC SDK.

Test

In this part of the Expressiv Test, the subjects were again asked to recreate facial expressions chosen at random by the Emotiv EPOC Test Suite. This time, the subjects were informed that they should perform the requested expressions as fast as possible, but still focus on accuracy rather than speed. The trial setup was the same as the Expressiv Test training trial setup (see Figure 3.4.16). The test part included two blocks, each consisting of five test trials per expression, making up a total of 60 test trials per block.

expression	completed	min. power
blink	5	1
wink left	5	1
wink right	5	1
look left	5	1
look right	4	1
smile	1	0.123391
laugh	5	0.802884
clench	5	0.0862337
smirk left	5	0.766055
smirk right	5	0.435859
raise brow	5	1.0
furrow brow	5	0.258221

Table 3.4.4.: The data format of the recorded test results for all trials showing the number of successfully completed trials for each expression. Additionally, the lowest maximum power for each expression is determined. This minimum power is the lowest maximum power of all completed trials for one facial expression type. For example, the expression "smile" has a minimum power of 0.340529, which means that this was the lowest maximum power occurring during the five completed trials.

A short break between each block gave the subjects the opportunity to refresh and focus on the next task.

The results of the test consist of an individual file per trial showing all recorded input signals, a result table equal to Table 3.4.3 and an interference matrix for each block. The interference matrix is very much like a confusion matrix and shows how often another signal type interferes during a test trial. In case the power of a signal, other than the one currently requested by the cue, became greater than or equal to the minimum level (calculated during the training) of the requested expression, it was counted as interference and the counter in the matrix increased by one. These counters were stored in a 12 x 12 matrix, with each line and column representing one facial expression. The requested expressions are displayed in the lines of the matrix, and the expressions interfering the requested expressions are displayed in the columns of the matrix (see Table 3.4.5).

	blink	wink left	wink right	look left	look right	raise brow	fur. brow	smile	clench	laugh	smirk left	smirk right	Σ
blink	-	0	2	0	0	0	1	0	0	0	0	0	3
wink l.	2	-	0	0	0	0	1	0	0	0	0	0	3
wink r.	5	2	-	0	0	0	2	0	0	0	0	0	9
look l.	3	1	2	-	3	0	7	0	0	0	0	0	16
look r.	6	2	9	1	-	0	20	3	0	0	0	0	41
r. brow	1	0	0	0	0	-	0	0	0	0	0	0	1
f. brow	1	0	0	0	0	0	-	0	0	0	0	0	1
smile	6	0	0	0	0	0	0	-	0	6	6	1	19
clench	2	0	0	1	0	0	0	1	-	0	0	0	4
laugh	3	2	1	0	0	0	1	1	0	-	0	1	9
smirk l.	1	0	1	0	0	0	1	0	0	0	-	0	3
smirk r.	2	0	0	0	0	0	2	0	0	1	1	-	6
Σ	32	7	15	2	3	0	35	5	0	7	7	2	

Table 3.4.5.: The sample interference matrix of subject EE01F (block 2). It is a result of the test part in the Expressiv Test. It depicts the reliability of each facial expression and how they are influenced by other expressions. The summed-up values in the last line show how often the expressions interfered other expressions. A high value indicates that the expression was detected very often although its performance had not been requested. The summed-up values in the far-right column indicate how often an expression has been interfered by other expressions, even it was requested by the cue. A high value indicates that many other expressions were detected before the requested expression was recognized. In this example, look right received the most interference. Raise brow and furrow brow were interfered only once each. In contrary to raise brow, furrow brow interfered with many other expressions. Based on these results, raise brow is the most reliable expression for this particular subject.

3.4.11. Experience Test

The final portion investigated the possibility to play a modern game title hands–free by just using the Emotiv EPOC headset and the GBGC. This assessment was designed to answer the question whether performance can be increased by selecting the most reliable facial expressions identified by the interference matrix (see Chapter 3.4.10). User feedback was solicited regarding the usability of the gyro re-centering procedure that relied on the bordered mode of the GBGC and the visual feedback (described in Chapter 3.1.3).

World of Warcraft

In this part of the user study, the subjects had to control the popular MMORPG World of Warcraft (Blizzard, Inc., see Figure 3.4.17 and Figure 3.4.18) by using the gyro sensors and a selection of three facial expressions. The gyro sensors were used to control the movements of the avatar. By turning the head to the right, the subject could turn the avatar to the right and when turning the head to the left, the avatar also turned left. Depending on how far the subject rotated the head from a neutral position, the avatar rotated slowly or quickly. To run forward, the subject had to lift his head. There was no command for going backwards with the avatar since the same effect can be achieved by turning around.

(a)   (b)   (c)

Figure 3.4.17.: The logos of the successful MMORPG World of Warcraft (a) and the producer and publisher, Blizzard, Inc. (b). (c) Shows the box arts of the first version of WoW released on November 23, 2004.

WoW Add-ons

For user feedback, two WoW add-ons were created to extend the default UI of the game (see Figure 3.4.18). One of them displays the current position of the gyro sensors in the virtual 2D space (see Figure 3.4.19, described in detail in Chapter 3.1.3), and the second interface extension displays the facial expressions (see Figure 3.4.20) used to trigger three different in-game actions (target, attack, and loot).

Control Groups

To investigate if the interference matrix is capable of detecting the most reliable expressions, the subjects were divided into two groups: A and B. To perform three different

(a)

(b)

Figure 3.4.18.: The WoW user interface. (a) Shows the UI without any modifications and additional add-ons. (b) Shows the UI with the add-ons for the Emotiv EPOC headset loaded. The add-on below the avatar's feet displays the current position of the gyro sensors and the add-on to the right shows the facial expressions that trigger the in-game actions (target, attack and loot).
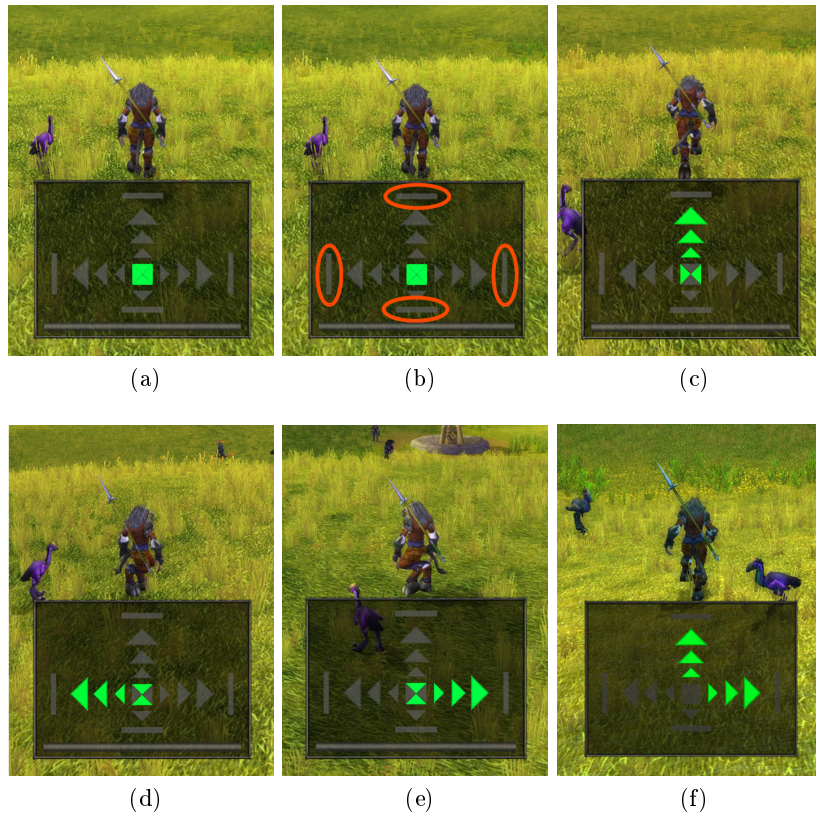
Figure 3.4.19.: The WoW add-on, displaying the current position of the gyro sensors. (a) Shows the gyro sensors in a centered position. (b) Shows the border markers (circled in red) that turn red in case the subject reaches the borders of the virtual gyro box (described in Chapter 3.1.3). These markers are helpful to re-center the virtual gyro position without an extra command. (c) Shows the add-on indicating that the users's head is lifted upwards and the avatar is moving forwards. (d–e) Show the add-on displaying that the avatar is rotating left/right. The subject can turn the character slowly by gently rotating the head. The further the head is rotated, the faster the character will turn and more arrows will turn green. (f) Represents a forward and right movement of the avatar. The rotations can be combined with a forward movement by turning and lifting the head at the same time.
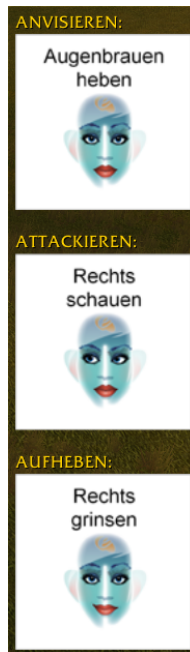
Figure 3.4.20.: The second WoW add-on, showing the names of the actions (target, attack, and loot) and the icons for the facial expression, which were selected individually for the subject to trigger the actions. In this example, the player could target an enemy by raising his eyebrows, he could attack his target by looking to the right, and when he moved his avatar close to the corpse he could loot the items by smirking right.

actions in the game (target, attack, and loot) three facial expressions were selected depending on the results of the Expressiv Test and the group the subject fell into. The expressions were chosen based on the results of the interference matrix resulting from the test block 2 of the Expressiv Test. For group A, three expressions were selected–those that were least interfered by other expressions. For group B, the expressions were selected with the highest interference count, but only if the subject was able to perform at least 60% of the trials successfully. Blink was selected for none of the groups as a controlling action since it is a naturally occurring involuntary expression.

Activity Score
To get a rough performance measure for the activity of a subject in the game, a scoring system was introduced. A subject received five points for killing an enemy and 10 points for looting an enemy corpse. The subjects were asked to collect as many points as possible.

To attack an enemy in WoW, the player has to run close to a creature and perform the target action (see Figure 3.4.21). Once the target was selected it could be attacked. In this user study, all the special attacks were triggered automatically by a GBGC input macro. Once the enemy was defeated, the user could collect loot from the corpse of the killed creature. To do this, the player had to move close to the dead body. Since the looting procedure is more tedious and requires more accurate movement than the killing they were awarded double the points.

The subjects had five minutes to get used to the game, the controls, and the re-centering procedure using the GBGC bordered mode. During this practice time no points were awarded. After the first five minutes each participant had 10 minutes to kill and loot as many enemies as possible. During this time each successful action was awarded with the corresponding points.
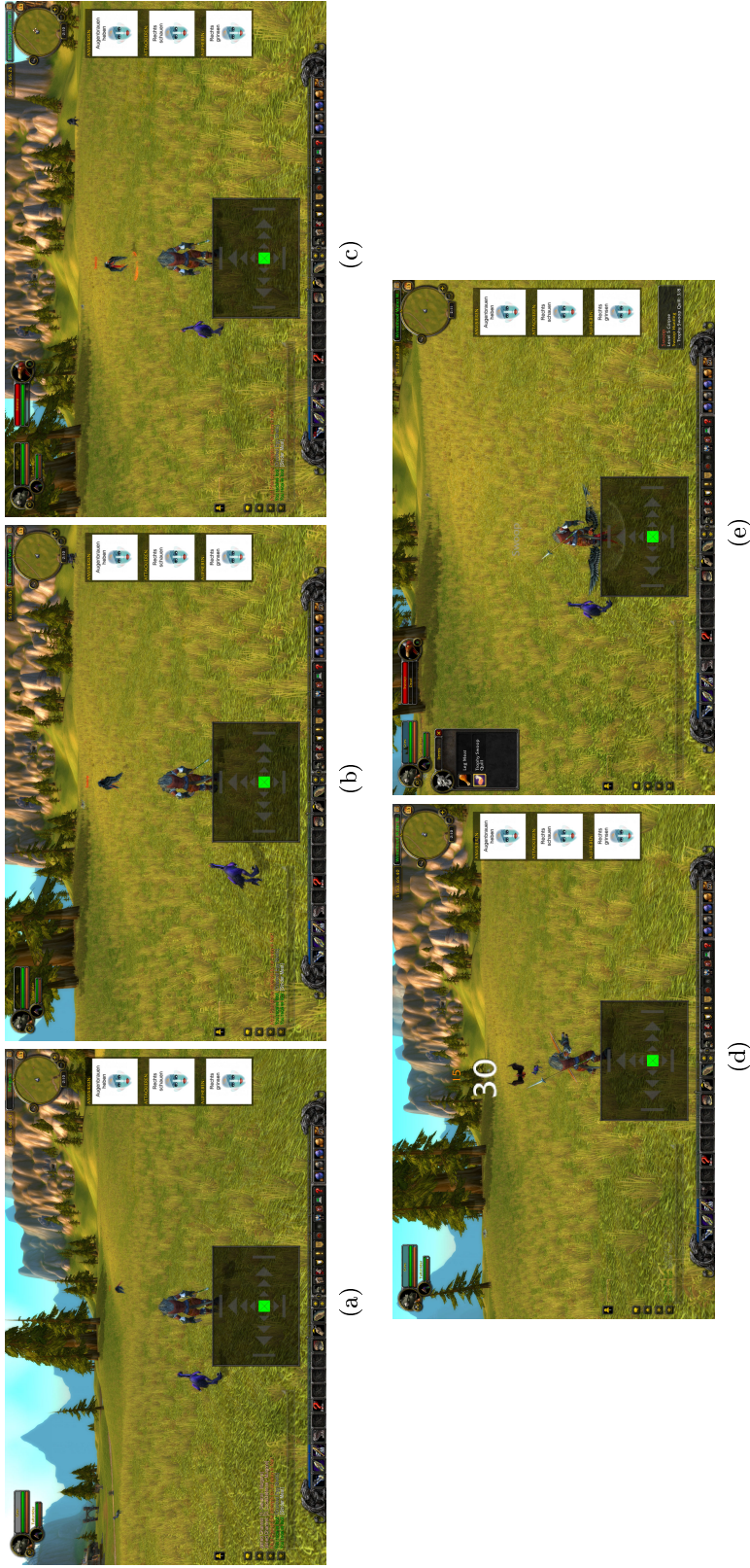
Figure 3.4.21.: WoW action score system. To score points, the subjects had to kill and loot creatures within the game WoW (a). To perform an attack, the player has to approach an enemy (b). Next, he has to target (select) the creature by performing the corresponding facial expression (c). Then the player can give the command to attack the creature (d). When the target is dead, he can move close to the corpse and collect the loot from the corpse of the recently killed opponent (e).

4. Results

The results from the IEE and EPOC SSVEP measurements are presented first in this chapter. In the second part, the results from the individual parts of the conducted user study are shown. The data recorded from the Test Suite is assessed and put into a meaningful context.

4.1. SSVEP Measurements

To suppress widespread noise in the EEG signal, the bipolar derivative formed from the 10–20 electrode positions O1 minus O2 was calculated. No other electrode positions were taken into account since they are not located near the visual cortex of the brain. The sampling rate of the EEG signal is 128 Hz.

A fast Fourier transform (FFT) was computed on a two-second window using 1024 points. The Hamming window and zero-padding were applied to the data prior to the FFT computation. The window was shifted by 0.1 seconds and the estimates were averaged. Although 60 seconds of data samples were recorded, the spectrum was estimated for only 20, 10, and 3 seconds of data (see Figure 4.1.1).

(a) 17 Hz 20 sec samples

(b) 17 Hz 10 sec samples

(c) 17 Hz 3 sec samples

(d) 20 Hz 20 sec samples

(e) 20 Hz 10 sec samples

(f) 20 Hz 3 sec samples
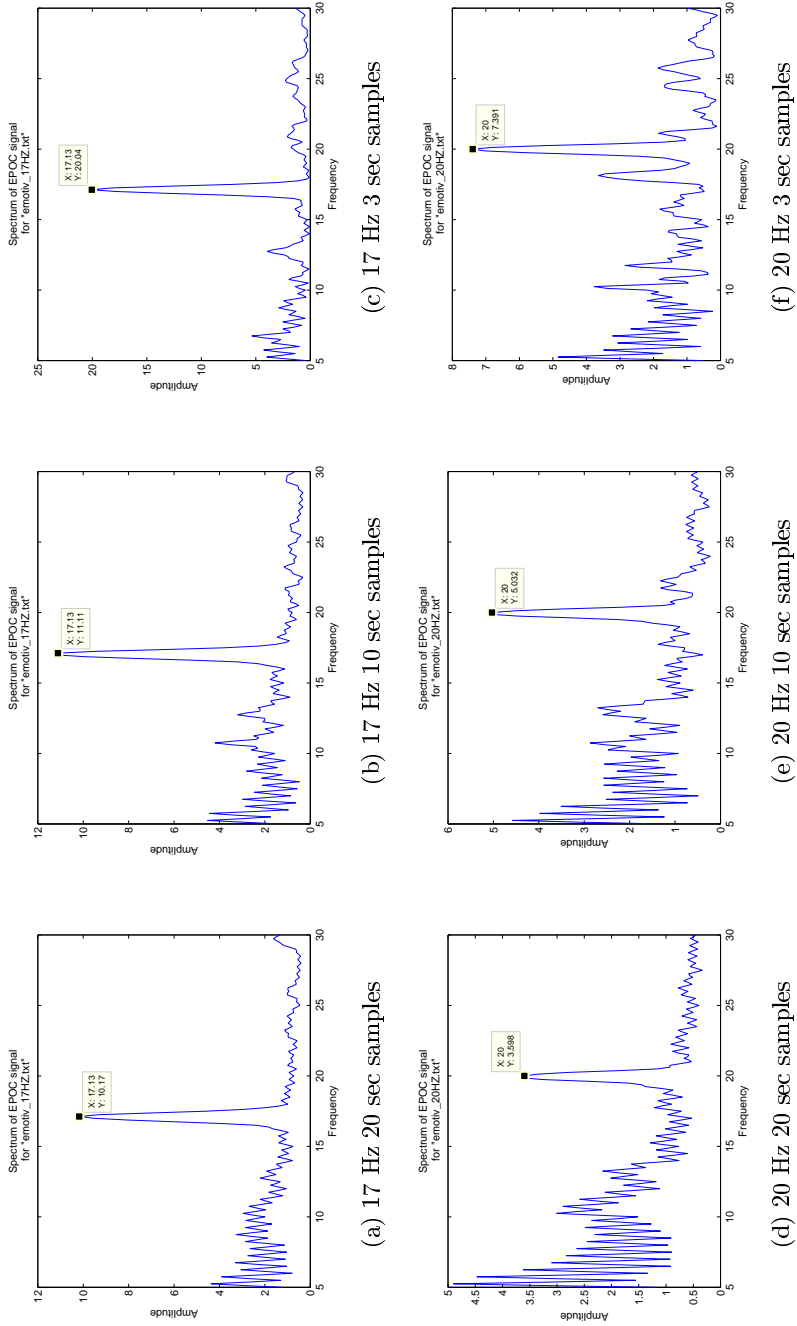
Figure 4.1.1.: The results of the SSVEP measurement from a single subject. The data was acquired using the GBGC IEE to present the flickering stimulus and the Emotiv EPOC to record the EEG signal. The stimulus was presented to the subject at 17.14 (a–c) and at 20 Hz (d–f) for 60 seconds. To calculate the FFT spectrum, only 20 (a, c), 10 (b, d), and 3 seconds (c, f) of data samples were used. All graphs (a–f) show a clear peak at the same frequency as the stimulus was presented.

4.2. User Study

This section describes the detailed results of the conducted user study. The VAS questionnaire results for the wearing comfort of the headset are assessed first, followed by the measurement and questionnaire results raised by the Cognitiv Test, Affectiv Test, and Expressiv Test. The results of the Experience Test conclude this chapter.

4.2.1. Wearing Comfort

The mean wearing times assessed by the questionnaires are 0, 34, 53, 90, and 113 minutes. Each part lasted about the same time for each subject due to the design of the user study. The clock was started immediately after the headset was mounted and all electrodes were adjusted to good contact. Figure 4.2.1(a) and Table 4.2.1 show the results of the questionnaires.

The relation between the head size and the mean comfort/pain VAS values is depicted in Figure 4.2.1(b). The head size was calculated by adding the nasion-inion distance and the head circumference of a subject. The means for comfort and pain were calculated using all scores marked by a subject during the whole study.

Wearing Time:	0 min	34 min	53 min	90 min	113 min
Mean Comf.:	7.45 (±2.00)	7.56 (±1.65)	6.82 (±3.38)	3.46 (±2.58)	2.73 (±2.31)
Mean Pain:	9.53 (±0.96)	9.15 (±1.48)	7.15 (±3.53)	3.58 (±3.03)	3.08 (±2.98)

Table 4.2.1.: The mean VAS values (±STD) for the wearing comfort and pain of the Emotiv EPOC. A value of 10 indicates that the subjects did not perceive the headset as disturbing or painful. Zero denotes that wearing the headset was considered disturbing or painful.

(a)   (b)
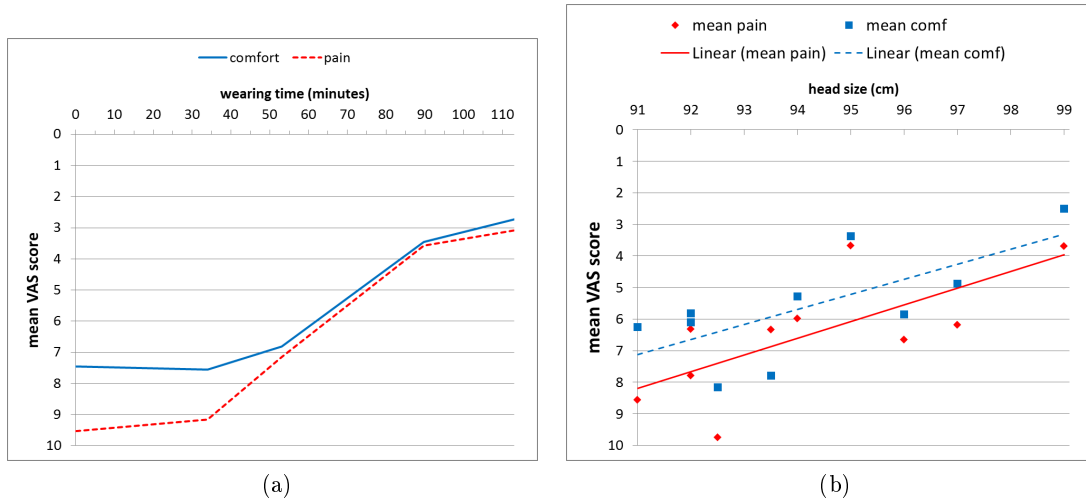
Figure 4.2.1.: The questionnaire results for the wearing comfort of the Emotiv EPOC. (a) Shows the mean values from the VAS, assessing wearing comfort and pain for all subjects over time. A value of 10 on the vertical axis indicates that the headset was not perceived as disturbing or painful at all, whereas 0 denotes that wearing the headset was very disturbing or painful. (b) Shows the relation between the mean comfort/pain VAS values and the head size of a subject. The head size was calculated by adding the nasion-inion distance and the head circumference. The vertical axis depicts the mean VAS values for comfort and pain which are calculated over all scores of the study for each single subject. The linear tendency lines show that subjects with a bigger head size generally perceived the headset more disturbing and painful than subjects with a smaller head size.

4.2.2. Cognitiv Test

This cue-paced experiment measured how long the subject lifted the cube during the trial time. If the cube was lifted during a neutral trial, the lift time was considered as a false positive (FP). Conversely, if the cube was lifted during a lift trial, the lift time was considered as a true positive (TP).

A comparison between the mean lift time during the neutral trials (MLTN) and the mean lift time during lift trials (MLTL) reveals if a subject was able to influence the position of the cube according to the given cue. The comparison between the MLTN (mean FP) and MLTN (mean TP) is shown in Figure 4.2.3 and Figure 4.2.4.

Accuracy

Accuracy is generally calculated as:

$$ACC = \frac{TP + TN}{P + N}$$

Where TP is the number of true positive and TN is the number of true negative (TN). P is the number of all positive instances of an experiment and N the number of all negative instances. To calculate the accuracy for each block of the Cognitiv Test, the formula for accuracy was adapted to:

$$ACC = \frac{MLTL + (TT - 1500 - MLTN)}{2(TT - 1500)}$$

Where MLTL is considered as TP and TT is the trial time (8000 ms). MLTN is considered as FP, therefore, TN can be calculated by (TT - MLTN).
1500 ms were subtracted from the overall trial time since the subjects were asked to start with their imagination as soon as the trial time started. The delay, which is needed for activation, is therefore not part of the accuracy calculation. 1.5 seconds were chosen based on the resulting graph from a time-based evaluation of the mean lift time energy (see Figure 4.2.5(d)). Additionally, [88](Chapter 10.4.3 BCI as Game Controller) confirms that all BCI types (SSVEP, ERD/ERS and P300) have a latency higher than 1.5 seconds. The resulting accuracies for each Cognitiv Test block are shown in Figure 4.2.5(a).
Another representation for investigating the lift and neutral behavior over time is shown in Figure 4.2.5(b–d). The mean lift energy was calculated once for all neutral trials and once for all lift trials (block 1, block 2 and all trials). The results of this evaluation for each individual subject are shown in Appendix E.

To assess if the subjects improved in accuracy using more training trials in advance to the test trials, the accuracy improvements were calculated using the following formula:

$$ACC\_IMPRV = ACC(block\,2) - ACC(block\,1)$$

A positive ACC_IMPRV value states that the subject's accuracy improved from block 1 to block 2. A negative ACC_IMPRV value indicates that the accuracy was lower in block 2 than in block 1. The results for the accuracy improvements are shown in Figure 4.2.5(e).

Receiver Operating Characteristic (ROC) Curves

The Receiver Operating Characteristic (ROC) curve plots the relation between the true positive rate (TPR) and the false positive rate (FPR) of a binary classified system. Whereas the TPR and FPR is calculated by:

$$TPR = TP/P$$

$$FPR = FP/N$$

A threshold value is used to divide the test trials of the Cognitiv Test into two classes (neutral and lift). All trials that have a lift time below the threshold level are considered as neutral, and all trials with a greater lift time are considered as lift trials. By comparing the estimated results to the trial type a number of TP and TN can be calculated. In both cases the total number of neutral and lift instances is 15 (P = N = 15). By shifting the threshold from 0 to TT (8000 ms) a set of TPR/FPR pairs can be calculated. Each pair represents a point in the 2D ROC space. The FPR is drawn on the horizontal (x) axis, and the TPR is shown on the vertical (y) axis. The values on the x and y axes range from 0.0 to 1.0.

A random system would be represented in a ROC curve as a diagonal line from the origin [0, 0] to the upper right corner [1, 1]. A ROC curve that runs above this random line (close to the upper left corner) states that the system performs better than random. A perfectly accurate system would be shown by two straight lines running from [0, 0] to [0, 1] to [1, 1]. The calculated ROC curves for all trials in block 1, block 2, and both are shown in Figure 4.2.2. The ROC curves for each subject are shown in Appendix D.

A performance indicator, which can be derived from a ROC curve, is the area under the curve (AUC). A random system has an AUC of 0.5, whereas a perfect system has an AUC of 1.0. The AUC for block 1 is 0.7 and for block 2 the AUC is 0.724, which results in a difference of +0.024 (+2.4%).

Perceived Cube Control

A VAS was included in the questionnaire after the Cognitiv Test, assessing the subjects' perceived control over the virtual cube. The results of the VASs are shown in Figure 4.2.6.

(a)　　　　　　　　　　　　　　(b)　　　　　　　　　　　　　　(c)
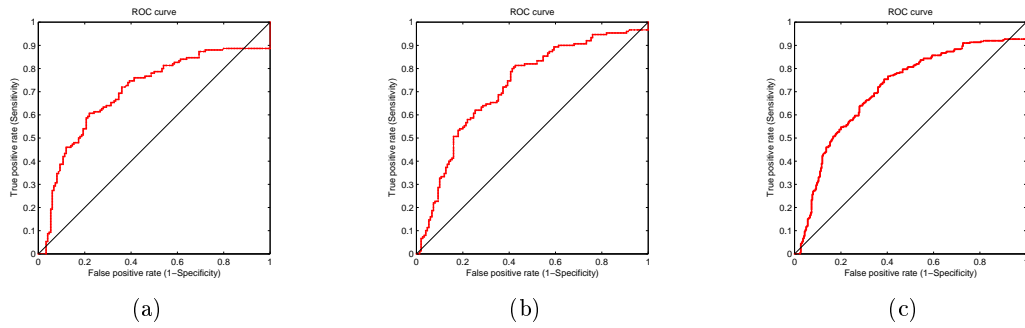
Figure 4.2.2.: The ROC curves for the Cognitiv Test. (a) Shows the ROC curve for all
test trials in block 1 with an AUC of 0.7. (b) Uses all samples from all
subjects of block 2 and has a AUC of 0.72. (c) Shows the ROC curves
resulting from all (block 1 + block 2) test trials of the Cognitiv Test with
an AUC of 0.71.
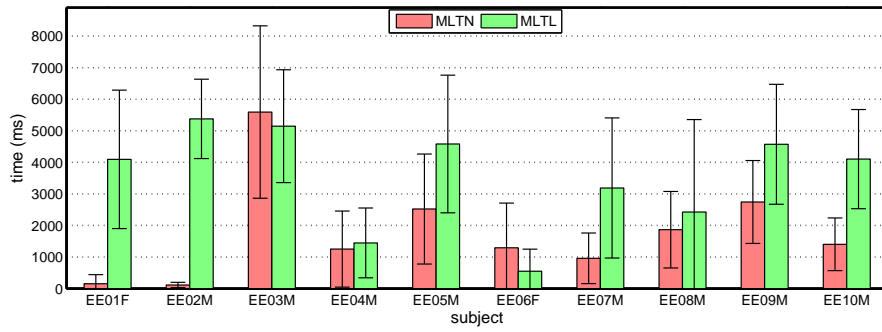
(a)
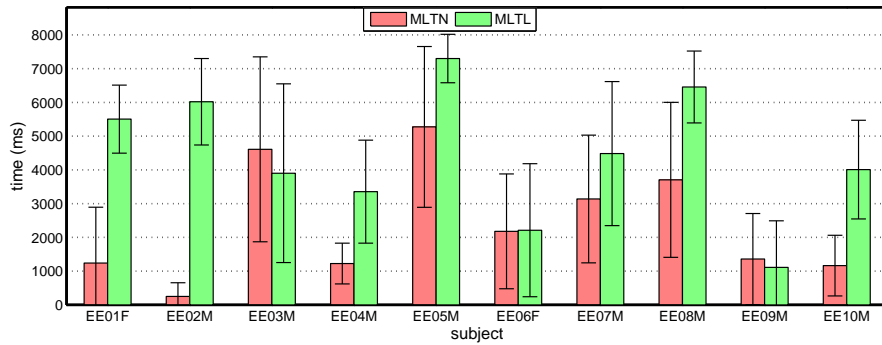
(b)
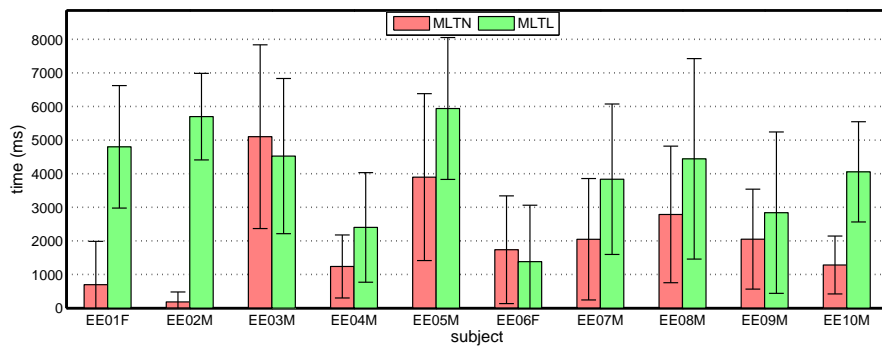
(c)

Figure 4.2.3.: The mean lift times (±STD) for each individual subject. The red bars show the MLTN (mean FP) and the green bars show the MLTL (mean TP). If the MLTL is significantly higher than the MLTN, it can be assumed that a subject had control over the cube. (a) Shows the MLTN and MLTL for the Cognitiv Test block 1 where five trials per state have been used in advance for training. (b) Shows the same values for Cognitiv Test block 2 where six trainings per state were performed prior to the test trials. (c) Shows the MLTN and MLTL for all test trials performed by a subject.
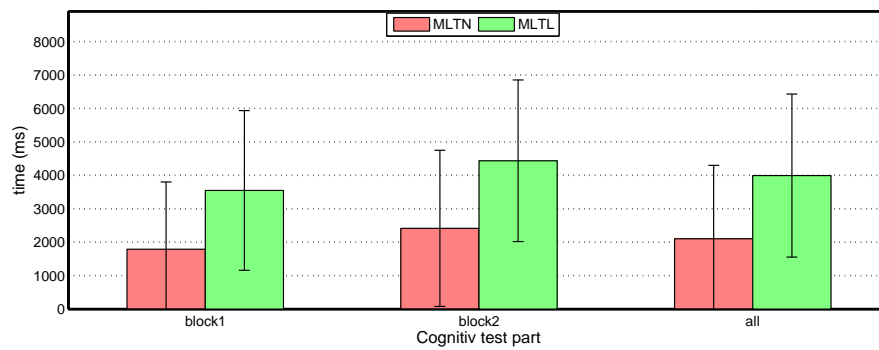
Figure 4.2.4.: The mean lift times (±STD) for all subjects combined. The red bars show the MLTN (mean FP) and the green bars show the MLTL (mean TP). The left group shows MLTN/MLTL for block 1, the middle bars represent the MLTN/MLTL for block 2, and the right bars show these values for both blocks combined.

(a)

(b)   (c)   (d)

(e)
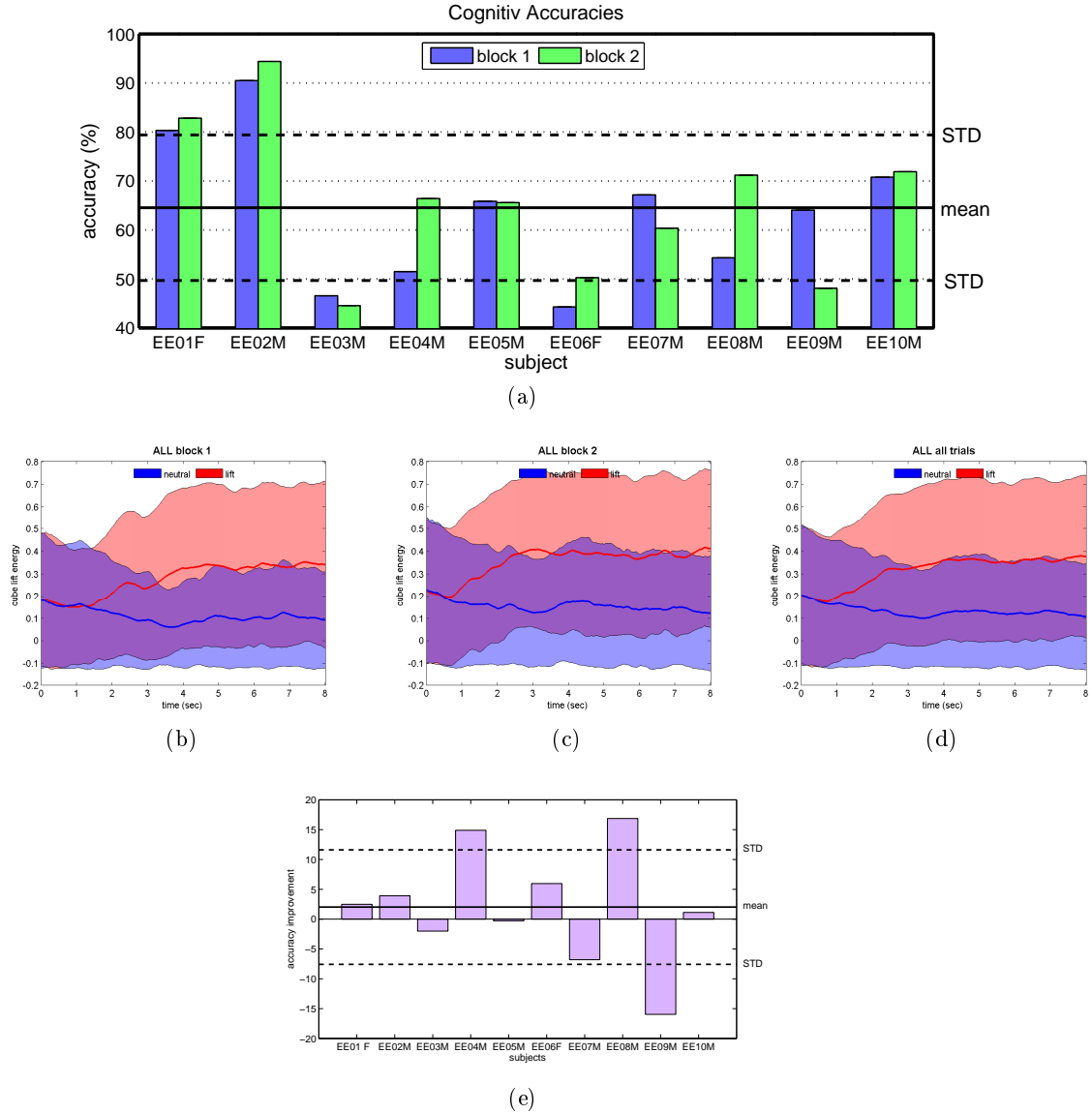
Figure 4.2.5.: The accuracies and their improvements for the Cognitiv Test. (a) Shows the accuracies for block 1 (blue) and block 2 (green) for each single subject. The mean accuracy, calculated over all subjects, is 64.53 ($\pm$14.86 STD). (b–d) Shows the mean lift energy ($\pm$STD) for all subjects over time. The means for the blue curve were calculated using all neutral trials and the red curve was calculated from all lift trials. The colored area represents the STD over time (blue = neutral, red = lift). (e) Represents the accuracy improvements for each subject between block 1 and block 2. A positive value indicates that the accuracy improved from block 1 to block 2. A negative value states that the accuracy is lower in block 2 than in block 1. The mean improvement for all subjects is +2.02% ($\pm$9.6 STD).
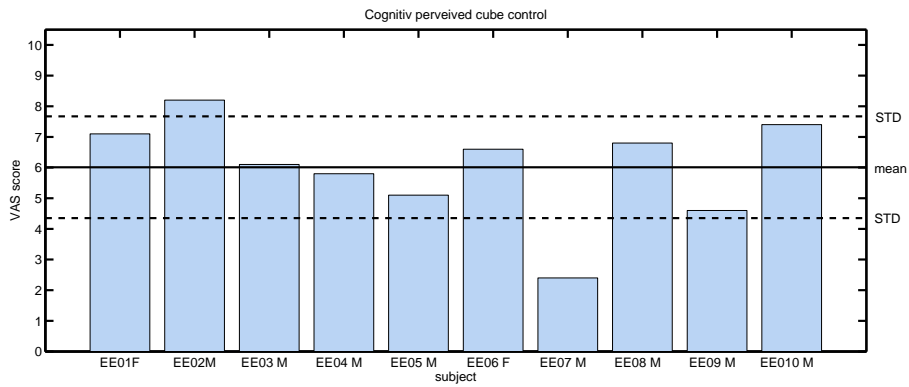
Figure 4.2.6.: The results from the VAS raising the perceived virtual cube control of each subject. A value of 10 on the vertical axis indicates that the subject felt like it had total control over the cube and a value of zero states that the subject felt like it had no control. The mean value of all VAS scores is 6,01 (±1,66 STD). The three subjects who marked the highest control VAS values also had the best accuracy (compare with Figure 4.2.5(a)).

4.2.3. Affectiv Test

The detailed results of the questionnaires are shown in Figure 4.2.7 and Table 4.2.2.

The values recorded by the Emotiv Affectiv Suite were re-sampled with 100 Hz to calculate the mean signal values (±STD) over all subjects. The signals for each emotion are shown in the following figures:

1. Frustration and instantaneous excitement, see Figure 4.2.8.

2. Engagement/boredom and meditation, see Figure 4.2.9.

The differences for the mean values during each phase of the trials are presented in Table 4.2.3.

(a)

(b)

(c)
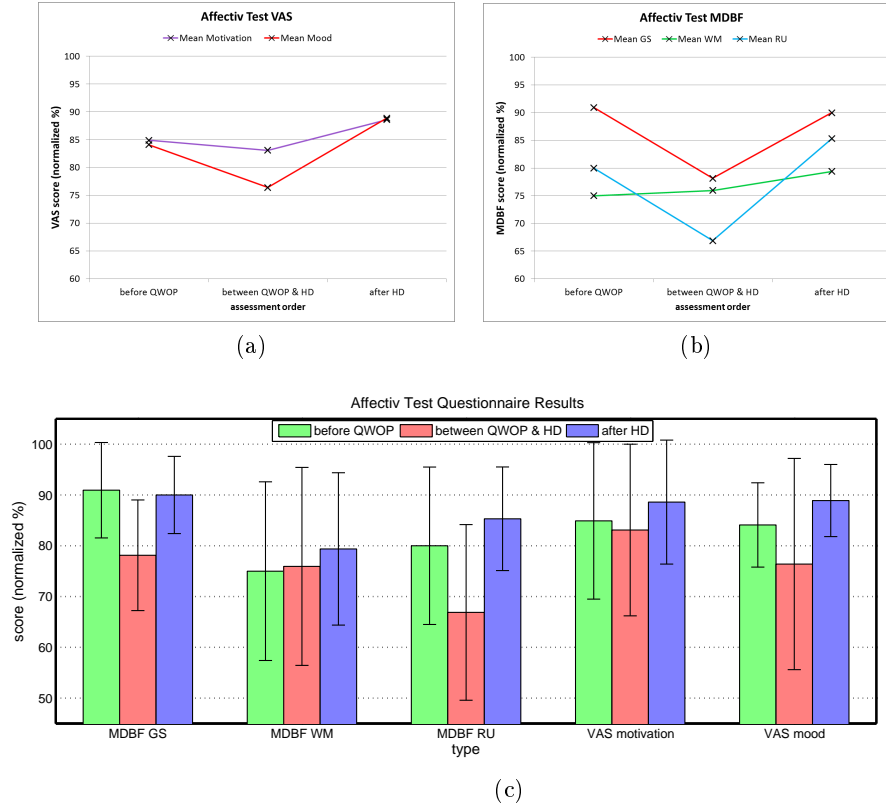
Figure 4.2.7.: The questionnaire results of the Affectiv Test. To get comparable results the values were normalized for the VAS and MDBF. (a) Shows the mean VAS scores of all subjects before playing QWOP, between playing QWOP & HD, and after playing HD. A higher score on the vertical axis states that the subjects had a better mood or more motivation. A lower value indicates that the subjects got more frustrated or less motivated. (b) Shows the mean MDBF dimensions GS, WM, and RU before playing QWOP, between playing QWOP & HD and after playing HD. A detailed description of these values can be found in Chapter 3.4.3. (c) Shows the mean values ($\pm$STD) for each assessed value of the questionnaires in the Affective Test.
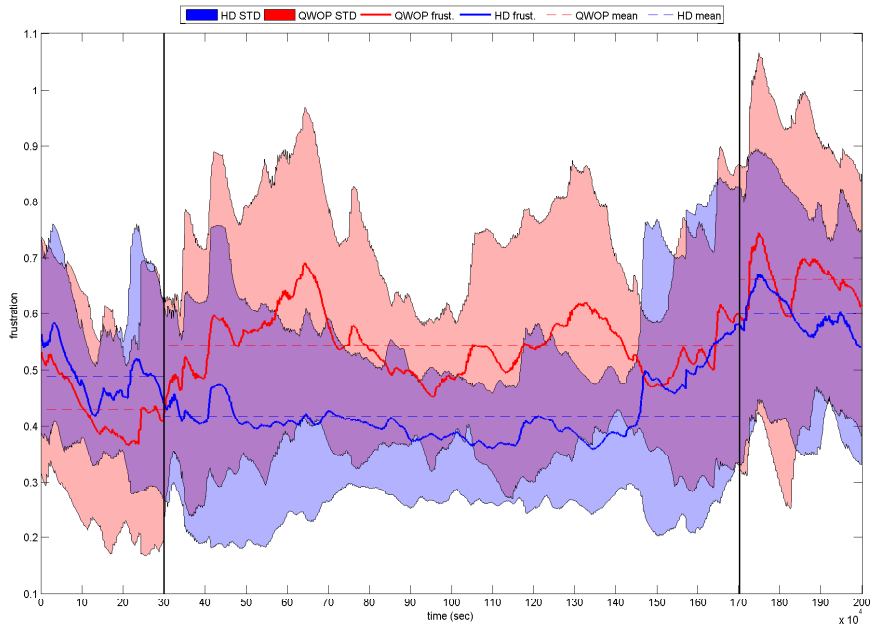
(a) Affectiv Suite frustration
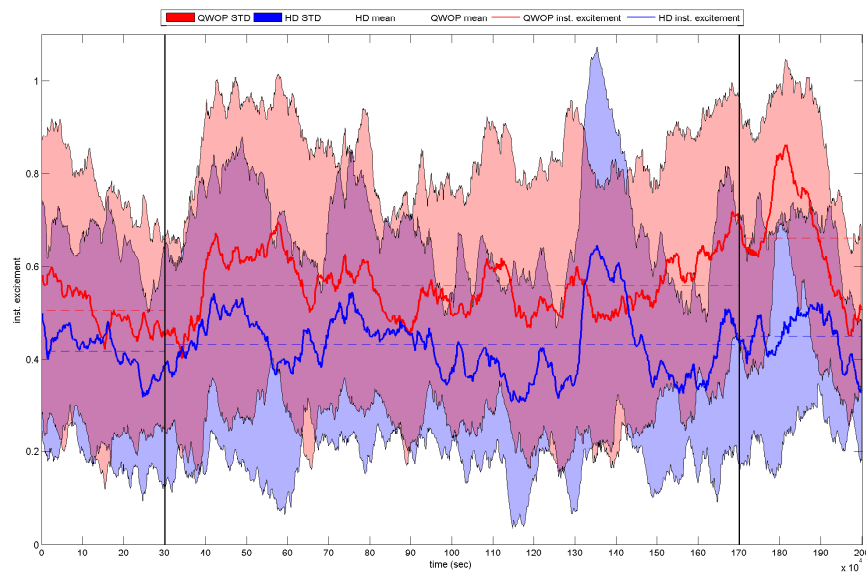
(b) Affective Suite instantaneous excitement

Figure 4.2.8.: Affectiv Suite measurements during the game tasks of QWOP (red) and
High Delivery (blue). The average values per trial phase are marked by
the dotted lines. (a) Shows the mean frustration of all subjects. (b) Shows
the mean instantaneous excitement of all subjects.
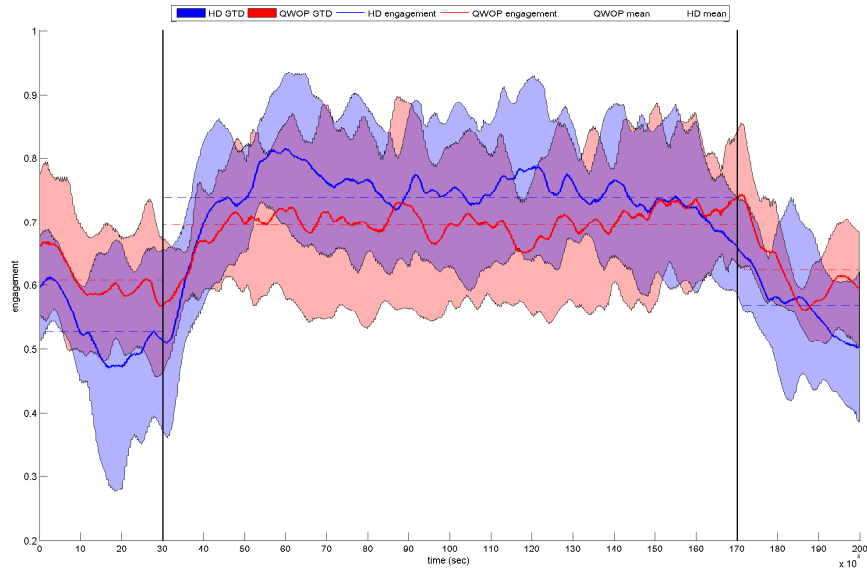
(a) Affective Suite engagement
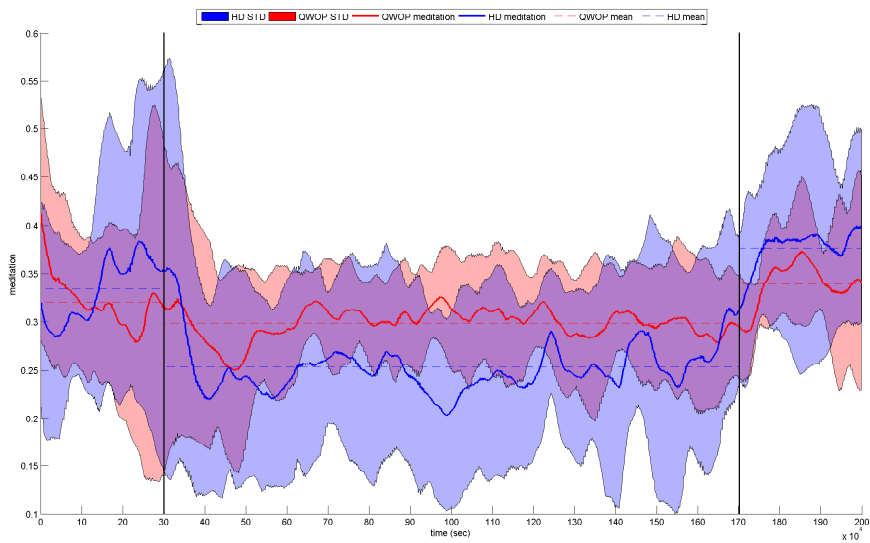
(b) Affective Suite meditation

Figure 4.2.9.: Affectiv Suite measurements during the game tasks of QWOP (red) and
High Delivery (blue). The average values per trial phase are marked by the
dotted lines. (a) Shows the mean engagement of all subjects. (b) Shows
the mean meditation of all subjects.

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Type	Score	Before QWOP	Between QWOP & HD	After HD
VAS	Mood	84.9 (±8.3)	83.1 (±20.8)	88.6 (±7.1)
VAS	Motivation	84.1 (±15.4)	76.4 (±16.9)	88.9 (±12.2)
MDBF	GS	90.9 (±9,4)	78.1 (±10.9)	90.0 (±7.6)
MDBF	WM	75.0 (±17.6)	75.9 (±19.5)	79.3 (±15.0)
MDBF	RU	80.0 (±15.5)	66.9 (±17.3)	85.3 (±10.2)

Table 4.2.2.: The normalized questionnaire results of the Affectiv Test in % (±STD).

	Relax phase 1	Play time	Relax phase 2
Frustration	-6%	+12%	+6%
Engagement	+8%	-4%	5%
Inst. excitement	+9%	+13%	21%
Meditation	-1%	+5%	-4%

Table 4.2.3.: Affectiv Suite measurement differences for the gaming tasks. The differences for the different phases of the trials are calculated by subtracting the mean value of the QWOP trial from the mean value of the HD trial. A positive value indicates that the mean value in the certain phase is higher in QWOP and vice versa.

4.2.4. Expressiv Test

The mean RTs for each expression are shown in the order of their occurrence in Figure 4.2.10. Table 4.2.4 shows the mean RTs (±STD) for all successful trials of the training, block 1 and block 2.

Accuracy

A trial is either considered successful or not depending on whether the subject was able to perform the right signal during the five-second trial time. All other classifications, apart from the one being requested by the cue, are ignored. As a result, there are only TP and FN samples. The accuracies for each facial expression are therefore determined by the TPR. The accuracies for each expression, calculated from a total of 150 samples (training + block1 + block2) per expression, are shown in Figure 4.2.11. The mean accuracy for all facial expressions is 89.6% (±11.5 STD).

	Training	Block 1	Block 2
Mean	1694 ms	1501 ms	1479 ms
STD	886 ms	825 ms	801 ms

Table 4.2.4.: The mean RTs and STD calculated out of all successful trials per block.
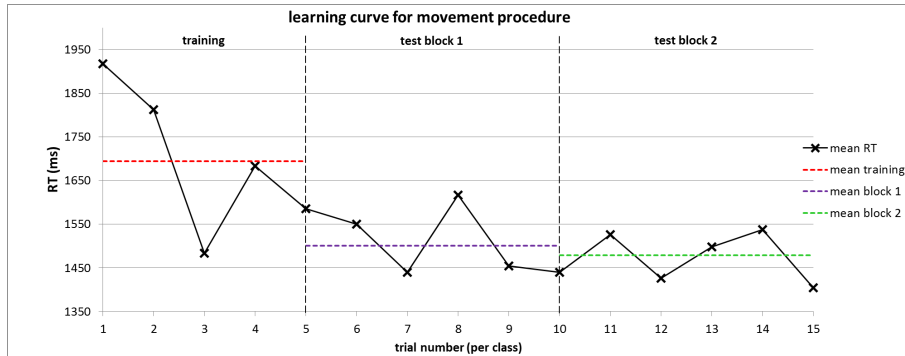
Figure 4.2.10.: The mean RTs in relation to the repetition count. Each expression was performed five times per block (15 in total). The means were calculated over all successfully performed expressions with the same repetition count. The graph shows that the subjects get faster as the repetition count rises. Also included are the mean RTs of all successful trials in the training, block 1, and block 2.
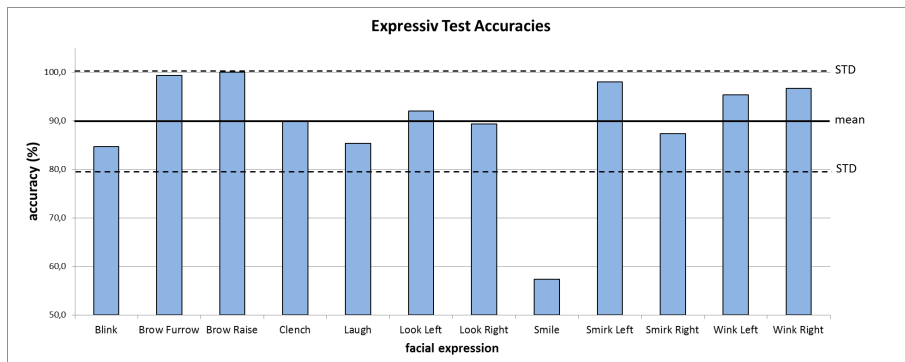
Figure 4.2.11.: The accuracies for each facial expression. A trial is considered successful if the subject was able to give the right signal during the five-second trial time. All other signals apart from the one being requested are ignored. In cases where the subject could not recreate the facial expression or the Emotiv EPOC was not able to detect it, the trial was unsuccessful. The mean accuracy for all facial expressions is 89.6% ($\pm$11.5 STD).

Expression	mu (μ)	sigma (δ)	tau (τ)	max. like. (ms)	max. power
blink	557,48	296,77	840,34	910	0,00066
brow furrow	721,78	432,75	519,36	1059	0,00068
brow raise	1032,59	144,51	267,35	1174	0,00170
clench	1321,98	253,83	7,64	1330	0,00160
laugh	1169,66	429,42	683,54	1560	0,00061
look left	812,86	136,13	272,51	951	0,00170
look right	833,15	15,02	438,59	867	0,00210
smile	877,13	415,89	1125,34	1362	0,00049
smirk left	1080,42	453,57	558,91	1439	0,00064
smirk right	1070,03	379,61	870,16	1482	0,00058
wink left	774,00	0,00	756,87	774	0,00130
wink right	837,05	45,67	671,89	927	0,00130
all	830,18	300,88	659,40	1150	0,00075

Table 4.2.5.: The estimated parameters (μ, δ, and τ) for the ex-Gaussian distributions from the DISTRIB toolbox for each single expression and all expressions. Additionally, the point of the maximum likelihood (maximum power) and the corresponding RT (maximum likelihood) was computed.

Premotor Times

To evaluate the premotor times of each facial expression the successfully completed trials from the Expressiv Test block 1 and block 2 were used to estimate probability distributions. Because of the findings of [92], the ex-Gaussian distribution was selected for evaluating the RTs. The curves were calculated from the samples using the DISTRIB matlab toolbox for characterizing RT (V2.3) distributions provided by [46]. The resulting estimated distributions for each single expression are shown in Figure 4.2.12 and Figure 4.2.13. The estimated ex-Gaussian distribution for all successfully detected facial expressions is shown in Figure 4.2.14. The detailed parameters for each distribution are listed in Table 4.2.5.

Interference Matrix

To investigate the influences between the detections of facial expressions, the interference matrices of each block and each subject were summed up (see Table 4.2.6). The structure of the interference matrix is explained in detail in Chapter 3.4.10.

Motor Times

Only the completed trials from the Expressiv Test were used to calculate the mean motor times for each facial expression. The results are shown in Figure 4.2.15.

(a) Brow Furrow

(b) Brow Raise

(c) Look Left

(d) Look Right

(e) Smirk Left

(f) Smirk Right
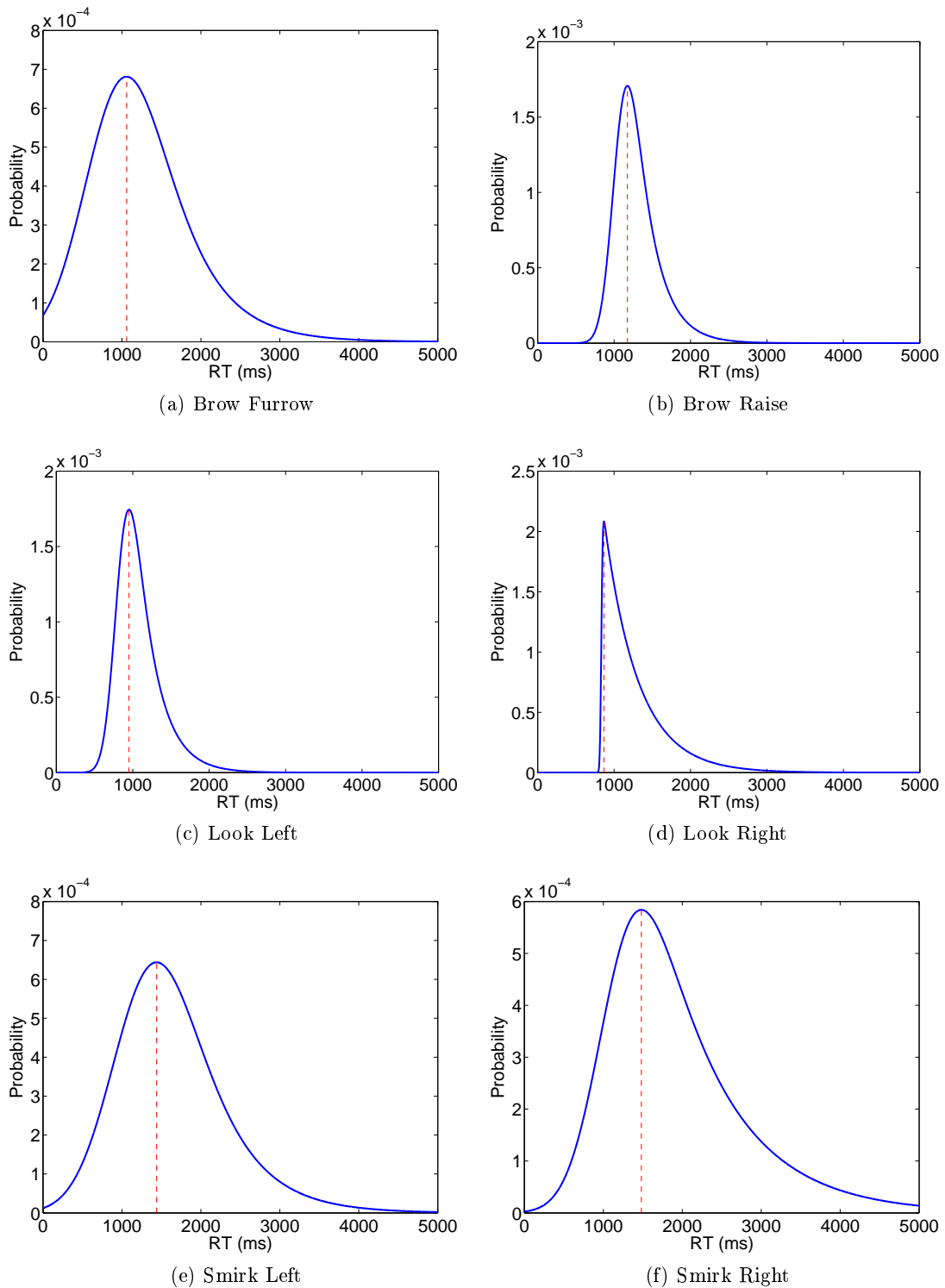
Figure 4.2.12.: The ex-Gaussian distributions (a–f) for each facial expression calculated from the successfully completed RT trials of the Expressiv Test (block 1 + block 2).

(a) Wink Left

(b) Wink Right

(c) Blink

(d) Clench

(e) Smile

(f) Laugh
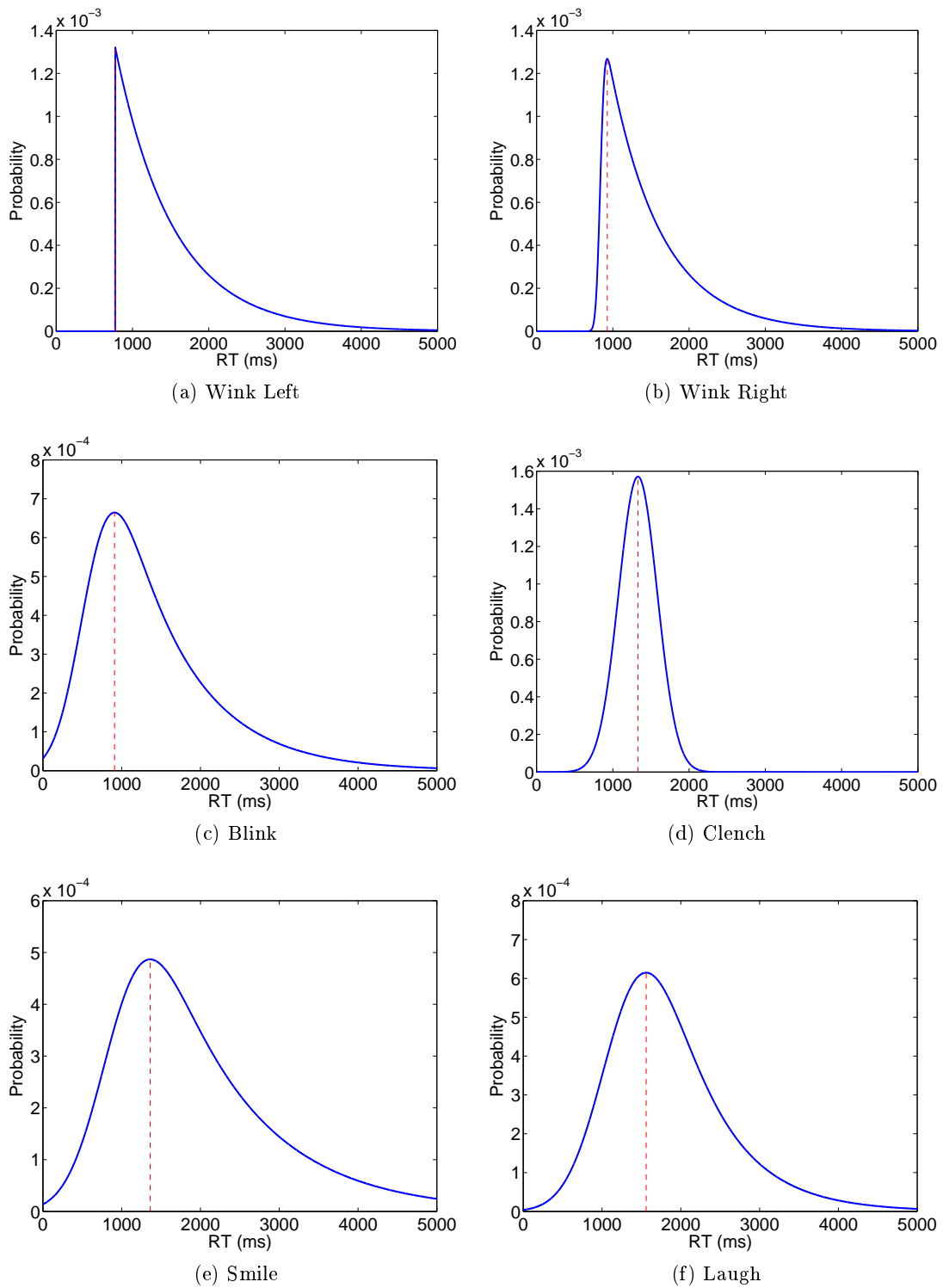
Figure 4.2.13.: The ex-Gaussian distributions (a–f) for each facial expression calculated from the successfully completed RT trials of the Expressiv Test (block 1 + block 2).
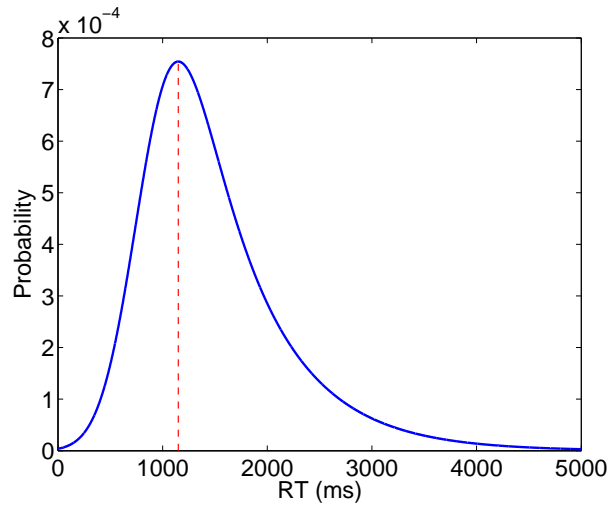
Figure 4.2.14.: The ex-Gaussian distribution calculated from all successful trials from the Expressiv Test (block 1 + block 2).
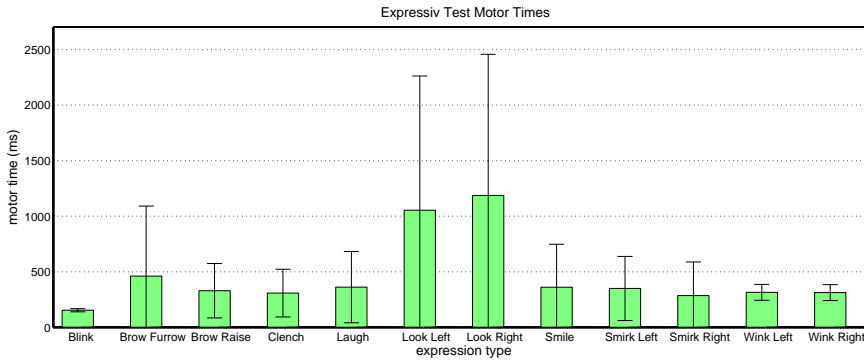
Figure 4.2.15.: The mean motor times (±STD) for each single facial expression. All successful trials from the Expressiv Test were considered in the calculation.

	blink	wink left	wink right	look left	look right	look right...							

	blink	wink left	wink right	look left	look right	raise brow	fur. brow	smile	clench	laugh	smirk left	smirk right	Σ
blink	-	46	32	2	3	2	68	2	0	5	3	3	166
wink l.	22	-	1	6	2	5	34	2	0	7	17	4	100
wink r.	33	2	-	2	0	13	33	3	0	0	10	2	98
look l.	17	2	4	-	21	6	29	8	1	0	8	4	100
look r.	30	7	20	27	-	2	48	12	0	3	4	2	155
r. brow	11	4	4	4	1	-	16	2	0	2	9	0	53
f. brow	7	5	4	2	2	9	-	1	2	4	5	2	43
smile	40	7	7	4	10	4	15	-	1	66	96	15	265
clench	15	8	6	4	5	1	19	17	-	10	10	15	110
laugh	26	10	16	6	7	33	32	34	5	-	19	17	205
smirk l.	12	8	3	12	0	0	15	12	1	8	-	1	72
smirk r.	15	2	14	4	6	0	24	9	0	13	30	-	117
Σ	228	101	111	73	57	75	333	102	10	118	211	65	

Table 4.2.6.: The interference matrix for all subjects and all test trials (block 1 + block 2), showing the reliability for each facial expression and how they are influenced by other expressions. The structure of the interference matrix is explained in detail in Chapter 3.4.10.

4.2.5. Experience Test

Figure 4.2.16 shows the results of the VASs capturing the user experience and the compared performance of group A and B.

The mean score (kills + loots) of group A was 383 (± 76 STD) and group B was able to score 303 (± 70 STD) points on average. Only two out of the ten subjects had some experience (less than 15 days play time) with the game WoW (one in group A, one in group B).
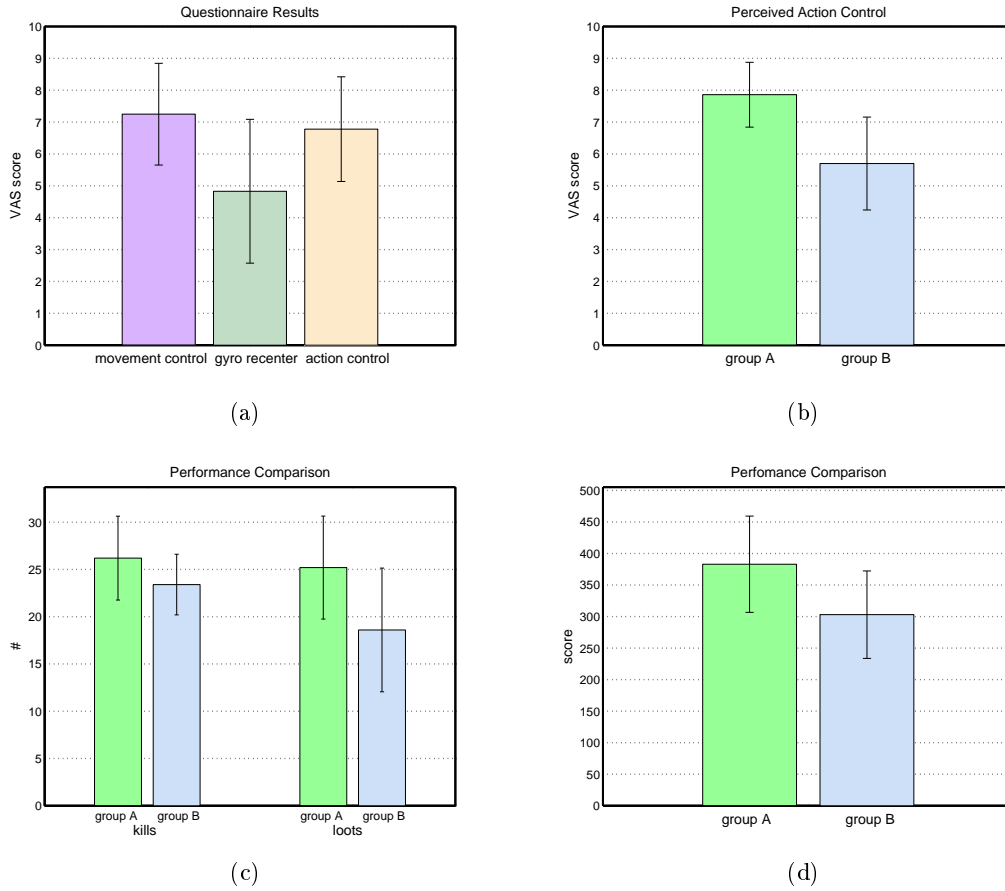
Figure 4.2.16.: (a) shows the mean scores of all subjects (group A + group B) for the three VASs given after the WoW experience test. The left bar represents how the participants perceived the movement control using gyro sensors (0 = no control, 10 = total control). The middle bar represents the mean score for the VAS which depicts how hard it is for the subject to re-center the gyro sensors using the GBGC bordered mode (0 = very hard, 10 = very easy). The right bar is the mean score for the control over the three in-game actions using facial expressions (0 = no control, 10 = total control). The Figures (b–d) compare various scores of the two control groups. Group A was given the three most reliable expressions to trigger in-game actions (target, attack, loot) and group B was given the least reliable, but performable, expressions. (b) Compares the mean VAS scores raising the perceived action control of group A and B. (c) Shows the kill and loot counts for group A and B. (d) Shows the comparison between the control groups using the introduced activity score (kill = 5 points and loot = 10 points).

5. Discussion and Conclusion

In this final chapter, the results of the presented work are discussed in detail. From this discussion a final conclusion is drawn which also outlines the success of the work at hand. Finally this chapter is concluded by a description of the future perspective and the challenges for future work.

5.1. GBGC for Controlling Proprietary Game Titles

With the presented game controller application it is possible to control proprietary game titles using non-standard input devices. The GBGC is a profound solution to make use of the variety of existing high-quality game titles. Instead of mapping one single key press to a device command, fast and easy configurable input macros are used to overcome the low ITRs of input devices. With the presented methods it is even possible to control complex game titles like WoW and Portal 2.

The GBGC IEE is a valuable extension to the GBGC. The possibility to adapt and customize interfaces is highly important to provide visual feedback for the user. The herein identified basic interface elements allow the creation of a variety of UIs. They are easily configured to fit nearly any application and set of input devices.

By integrating the Emotiv headset into the game controller, a method for incorporating head-mounted gyro sensors has been discovered. The proposed gyro mouse action allows camera and character rotations at various speeds similar to analog joysticks or mouse movements. The results of the Experience Test show that each subject was able to gain control over the character movements in the game WoW.

The challenge to re-center the gyro sensors has been addressed by the bordered mode of the GBGC. Yet, the user feedback from the VAS showed varied results. The subjects reported that they had medium control re-centering the gyro sensors using the GBGC bordered mode. This may result from an insufficient explanation of the mechanics prior to the experience test and there is still room for improvement of the visual representation of the gyro re-centering procedure.

5.2. Capability of the Emotiv EPOC

This work provides a good outline for the capability and potential of the Emotiv EPOC as an input device. A discussion of the results of the conducted measurement and user study is presented here.

5.2.1. EEG

Related work [22] and the conducted measurements indicate that the Emotiv EPOC can be used to measure actual EEG. The results of the IEE and EPOC SSVEP measurements show that even small samples of data (< 3 sec) are sufficient to detect the frequency of the stimulus in the frequency spectrum of the FFT on the EEG signal. Since these two frequencies are exactly equal, it can be proven that the IEE displays the icons accurately enough for SSVEP stimulation.

Since the measurements included only a single subject, it cannot be assumed that this will work equally well for other subjects. Yet, these findings show that EEG can be acquired with this device and that the GBGC IEE is capable of presenting a flickering stimulus accurate enough for SSVEP.

5.2.2. Wearing Comfort

Although the headset is not perceived as very disturbing or painful in the beginning, this drastically changes after 34 minutes of usage. At the end of the study all subjects reported that the pressure from the electrodes on the head is too intense for long-term use. Users with a larger head size are particularly affected as the headset is only available in one size. The relation between the head size and the mean comfort/pain VAS values reveals that subjects with a larger head size perceived the device as more disturbing and painful than subjects with a smaller head size.

In [9], a conducted user study led to approximately the same results. Although they did not collect evidentiary questionnaire data, their estimate for a comfortable wearing time of the EPOC headset is 30 minutes. These results are based on verbal statements collected from participants of the study.

If Emotiv claims that the EPOC is a gaming device, they need to address this issue in a possible future update. It is absolutely essential that the headset does not lead to discomfort or pain, even after several hours of use.

5.2.3. Cognitiv Test

The evaluation of the Cognitiv Test results show that all except one subject were able to get some sort of control over the virtual cube. The results depict that 16 out of 20 runs have more MLTL than MLTN. Yet, these differences are not substantial in all cases. Only two out of ten subjects (EE01F, EE02M) showed control accuracy far better than random ($> 80\%$). Overall, on average the subjects were able to lift the cube longer during the lift trials than during the neutral trials.

A comparison between of the AUC from the ROC curves reveals that the subjects improved slightly in block 2. Also the accuracies show the tendency for the mean to improve slightly. Although overall the subjects were able to improve their accuracy slightly there is no indication that six training trials perform consistently better than five training trials.

The results from the user questionnaire are just as, if not more, important than the actual accuracy values. It is noticeable that most participants felt like they were able to

control the position of the virtual cube (VAS score > 5.0). Only two out of ten subjects stated that they had little control (VAS score < 5.0). As long as a user perceives that he is in control of the actions, it is unlikely that he will get frustrated and that is very important in the context of gaming.

From these results it is not possible to prove that the headset uses brain-wave activity since the training and classification algorithms are not accessible to the public. Due to a lack of clear instructions for a user to train the headset's cognitive actions, it is not ensured that the results are as good as they could be. Certainly, the Emotiv Cognitiv Suite learns to detect activations based on the subjects' intent to lift the virtual cube from EEG or facial EMG signals. The assertion from Emotiv that users can easily gain (perceived) control over a virtual or real object can be supported by the results of the presented user study.

5.2.4. Affectiv Test

The results of the MDBF, VAS and the measurements from the Emotiv EPOC headset show the same influence of the two games on the affective state of the subjects.

VAS Results

The VAS results show that the mean motivation only decreased slightly after QWOP and increased again after the HD task. Compared to the motivation, the mood decreased noticeably after the subjects were confronted with the QWOP task. This behavior exactly matches the intent of this experiment to frustrate a subject on purpose. Also that the subjects could recover their initial affective state is shown in the VAS score results since the mean mood rose again after the subjects played HD.

MDBF

The WM value shows that overall the subjects were more awake after playing either of the two games. This behavior is to be expected since the gaming task was fun for the subjects and each subject was engaged in the process, although the games were fairly simple.

The RU graph shows that the subjects were less calm and more excited after playing the first game QWOP. It can be assumed that failing at the task provoked arousal and uncertainty in the subjects. Some of the subjects commented during the study that they were afraid of also failing at the following gaming task (they did not know that it was going to be much easier). This might be a reason why they got excited after the QWOP task.

The score for good-bad mood (GS) shows nearly the same tendency as the RU score. The subjects got frustrated by playing QWOP but regained their good mood after HD. This represents again the intended influence. For the subjects failing at the QWOP task led to being in a worse mood. Completing the HD task brought the subjects back to be in a better mood–even slightly better than before QWOP.

Affective Suite Frustration

The initial average frustration was higher in the first relax phase of the HD trial. This is to be expected since the subjects became frustrated in the QWOP task, which was followed by the HD task. The initial frustration of the HD task was therefore influenced by the previous QWOP gaming task.

Although the initial average frustration was lower before the subjects played QWOP, this immediately turned around once the play times began. It is noticeable that the mean frustration rises continuously in the first 30 seconds of the QWOP play time. The difference between the mean curves peaks after about 35 seconds of play time. This might be the point where the subjects realized that QWOP is not an easy task for them. At the end of the play time for HD the mean frustration also began to rise. This might be caused by the game mechanics, since the number of flowers dropping down at the end of the game is that large that it becomes impossible for the player to catch them all. Up to this point, a player can easily catch all of the dropping flowers.

As expected, in the second relaxation phase, where the subjects were asked to think about their performance, the mean frustration is higher in the QWOP trials. Of course, the subjects are less satisfied with their performance after they failed in a task. What is noticeable, though, is that frustration also rose in the second relaxation phase with HD, but not as much as it did in QWOP.

Affectiv Suite Engagement/Boredom

Although the subjects' engagement was not evaluated using a questionnaire, the engagement/boredom graphs measured by the Affectiv Suite show expected results. The mean values of both games are fairly equal and show the same behavior. The average engagement of the subjects increased vastly as soon as the play time started and fell again as soon as the subjects stopped playing.

Affectiv Suite Instantaneous Excitement

Although the instantaneous excitement signal is very volatile, the mean levels increase constantly from the relax phase 1 to the play time to the relax phase 2. It is also noticeable that the increase is much higher during the QWOP trials than during the HD trials. There is a peak in the HD mean curve at the 140-second mark, which might be caused by the increased amount of flowers dropping in the game. From this point on, the player cannot catch them all.

The lower RU score of the MDBF backs up the higher excitement level measured by the Emotiv headset.

Affectiv Suite Meditation

The resulting graphs show that the meditation levels are nearly equal during the QWOP and HD trials. The expectation that the meditation is higher in HD is not shown by the results. The mean meditation values are even slightly lower in HD compared to QWOP. Since this value should represent a measure for relaxation, it was expected that this value would be higher while playing HD. There is not an increase in meditation even in the beginning of the HD game. At this point in the game there are hardly any flowers to catch, which is why a player should be more relaxed. This issue may result from either

one of the following reasons:

1. The games QWOP and HD are not suited to show differences in the meditation level provided by the Affectiv Suite.

2. The order in which the games were played affected the results of the meditation assessment.

3. The Affective Suite estimation is too rough or the duration of the games too short to evaluate this affective user state.

Results

The higher frustration measured by the Affectiv Suite after playing QWOP corresponds to the lower mood score of the VAS and the lower GS score of the MDBF. By comparing the results from the questionnaires and the measured values from the Emotiv Affectiv Suite it is possible to show two findings:

1. QWOP is a game which is capable of inducing frustration in a player.

2. The Affectiv Suite can estimate the state of a player when it comes to frustration in a gaming scenario.

5.2.5. Expressiv Test

Optimal Repetition Number

To verify the findings of [31, 55] for the optimal repetition count of a movement procedure in ERT studies, the mean RTs for each expression in order of their occurrence were evaluated. The results show that subjects got faster by performing each expression several times. After the subjects performed each expression about seven times, the mean RTs stopped decreasing significantly. Including the three to four attempts from the preceding Expressiv Demo (see Chapter 3.4.10) it can be verified that a movement procedure needs to be trained at least 10 times to evaluate reaction times in an ERT study.

Premotor Times

The assessed premotor times show that the eye-related expressions (blink, wink l., wink r., look l., look r.) are on average much faster than other expressions, including mouth, jaw, or brow movement. Laugh has the greatest reaction time with 1560 ms on average. For most subjects it was very hard to get this expression right (compare with interference matrix) so that the Emotiv Expressiv Suite classifies the correct expression.

An overall reaction time of 1150 ms does not qualify facial expressions as an input modality for high-speed FPS games. For non-timing based games or strategy games it is sufficient to give a command with a delay of about one second.

Motor Times

The results of the motor times show that look left and look right have significantly longer motor times than other facial expressions. This is certainly due to flaws in the study

design. A subject is not able to tell if the expression was successfully detected when looking to the left or right. This uncertainty led to a chance in behavior where the subjects held on to the expression longer to ensure that the detection was successful. This issue can easily be avoided by including an audible cue in case of a successful classification during the trial time. Otherwise, the results show that the motor times are fairly equal, except for blink.

Interference Matrix
A closer look at the overall interference matrix shows that the standard classifier provided by Emotiv is too sensitive for certain facial expressions (furrow brow, smirk left). The matrix also reveals relations between the miss-classifications of various expressions. The expressions wink left, wink right, and blink are very often mixed-up, which might be caused by the motor abilities of the subjects. Laugh often seems to be accompanied by a preceding brow raise. The expressions smile and laugh interfere each other quite noticeably. It is also remarkable that smile is very often interfered by smirk left, but this does not hold for smirk right as one would expect.

To get meaningful accuracy for the detection of the facial expressions, the interference matrix can be used to perform one of the following actions:

1. Adjust the sensitivity sliders in the Emotiv Expressiv Suite to lower the interferences of certain expressions.

2. Combine multiple expressions into one, if they get easily mixed-up, like smile and laugh.

3. Drop expressions that are classified too often.

5.2.6. Experience Test

Interference Matrix
The resulting differences between group A and group B (size N = 5) verify that group B not only perceived that they had less control than group A, but also that the achieved score was on average 80 points lower than in group A. By selecting the best or worst (but performable) three actions from the interference matrix it was possible to influence the performance by 21% (383 points being 100%). These differences between the control groups (A, B) indicate that the interference matrix is a good evaluation method to identify the most reliable inputs in terms of facial expressions.

Experience & Performance
In general the Experience Test showed that all subjects were able to perform the basic game play tasks within the MMORPG WoW. The user feedback depicts that the users had good control over the movement and the actions (excluding group B).

A highly proficient player was able to collect 3420 points (57 kills + 57 loots) in the same experiment setup using mouse and keyboard. To get a better feeling for the performance of the control groups, the scores of the control groups were compared with the high score of the proficient player. Group A reached 11.2% and group B achieved

8.8% of the high score player. These results show that with the GBGC the Emotiv headset can be used to control a popular high-quality game title to a reasonable extent.

5.3. Future Perspective and Work

This thesis demonstrates a profound solution for how BCI research can profit from a wide range of already existing game titles. This thesis should encourage future work to use high-quality game titles for proof of concepts or research studies. If there is no game that fully satisfies given study conditions, it may be an option to use the content creation tools shipped with game titles to get the desired controlled behavior.

To make BCIs applicable for gaming and home use, it is necessary to consider mobile low-cost EEG solutions. Although the lack of high-quality signal acquisition might not be acceptable in foundational neuroscience research, it is definitely necessary to explore the possibilities for these low-cost EEG devices.

A big advantage of the Emotiv EPOC is that the headset can be mounted with little preparation effort and in less time compared to a high-quality EEG system. Not everyone is eligible to use an SSVEP based BCI (see Chapter: "Could anyone use a BCI?", in [88]). In a clinical setting, the headset can be easily used to screen subjects if they are capable of operating an SSVEP based BCI. This could prevent patients from a tedious mounting procedure of gel-based electrodes before it is evident if SSVEP will produce desired results.

A. Informed Consent (German)

The informed consent is adopted from a template form of the Laboratory of Brain-Computer Interfaces, Institute for Knowledge Discovery, Graz, Austria.

Einwilligungserklärung

Name des/der ProbandIn in Druckbuchstaben: ……..

Geb. Datum: ....

Ich erkläre mich bereit, an der Studie

„emotiv EPOC Experience Test"

teilzunehmen.

Ich bin über Sinn, Bedeutung und Verlauf der Studie sowie über mögliche Belastungen und Risiken, mittels erhaltener schriftlicher ProbandInnen-Information, und durch Herrn Markus Pröll aufgeklärt worden. In diesem Zusammenhang sind mir alle meine Fragen vollständig beantwortet worden. Ich hatte überdies ausreichend Zeit mich für bzw. gegen eine Teilnahme zu entscheiden.

Ich werde den Anordnungen, die für die Durchführung der Studie erforderlich sind, Folge leisten, behalte mir jedoch das Recht vor, meine freiwillige Mitwirkung jederzeit zu beenden, ohne dass mir daraus Nachteile entstehen.

Ich wurde darüber aufgeklärt und stimme zu, dass die im Rahmen dieser Studie erhobenen Daten in anonymisierter Form dokumentiert und ggf. weitergegeben werden.

Beim Umgang mit den Daten werden die Bestimmungen des Datenschutzgesetzes beachtet.

Eine Kopie dieser ProbandInnen-Information und der Einwilligungserklärung habe ich erhalten. Das Original verbleibt bei der Studienleitung.

....
(Datum und Unterschrift des Probanden bzw. der Probandin)

....
(Datum, Name und Unterschrift des/der verantwortlichen StudienleiterIn

B. Questionnaires (German)

The questionnaires used in the conducted user study.

Datum: _____   **Uhrzeit: _____**

Supervisor:

Name: Markus Pröll

Subject Code (ID):   _____ (bitte nicht ausfüllen!)

Kopfgröße:

Nasion-Inion Distanz: _____ cm

Umfang: _____ cm

GRAZ BCI

Pers. Daten:

Vorname: _____   Nachname: _____

Geschlecht: □ männlich   □ weiblich

Alter: Geb. Monat: _____   Geb. Jahr: _____

Händigkeit: □ rechts   □ links

Normalsichtig: □ ja   □ nein

Falls nein:
    Ist ihre Fehlsichtigkeit mit einer Sehhilfe auf normal korrigiert: □ ja   □ nein

Haben Sie schon an einer BCI
Studie teilgenommen: □ ja   □ nein

Spielen Sie regelmäßig Computerspiele: □ ja   □ nein

Falls ja:
    Wie viele Studen/Woche spielen Sie: □ <5h   □ 10-20h   □ 30-40h   □ >40h

Haben Sie eine Vorgeschichte von Epilepsie?   □ ja   □ nein

Nehmen Sie zurzeit Medikamente?   □ ja   □ nein

Rauchen Sie: □ ja   □ nein

Haben Sie innerhalb der letzten 24 Stunden
Alkohol zu sich genommen?   □ ja   □ nein

Wie viele Stunden haben Sie letzte Nacht geschlafen?   _____ Stunden

Ist diese Stundenzahl typisch für Sie?
        □ weniger als sonst   □ übliche Menge   □ Mehr als sonst
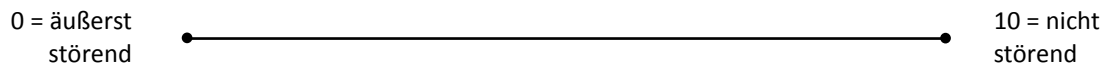
GRAZ BCI

Zwischenbefragung (nach Montage)

Tragezeit: _____ (bitte nicht ausfüllen!)

Bitte beurteilen Sie die unten angeführten Fragen auf einer 10-er Skala. Machen Sie als Markierung bitte einen senkrechten Strich an der Stelle, von der Sie denken, dass Sie ihre Antwort am besten repräsentiert.

Gemütszustand:

Fühlen Sie sich entspannt?

0 = sehr aufgeregt •————————————————————————————• 10 = sehr entspannt

Fühlen Sie sich aufmerksam?

0 = sehr schläfrig •————————————————————————————• 10 = sehr aufmerksam

Wie ist ihre Motivation?

0 = überhaupt nicht motiviert •————————————————————————————• 10 = außerordentlich motiviert

Wie ist ihre Stimmung?

0 = sehr schlechte Stimmung •————————————————————————————• 10 = außerordentlich gute Stimmung

Headset Tragekomfort:

Wie empfinden Sie das Headset auf ihrem Kopf?

0 = äußerst störend •————————————————————————————• 10 = nicht störend

Verursacht das Tragen des Headsets Schmerzen?

0 = äußerst schmerzhaft •————————————————————————————• 10 = nicht schmerzhaft
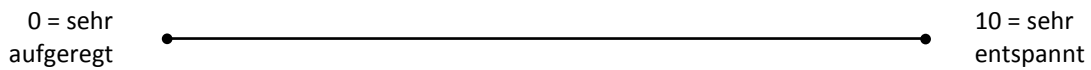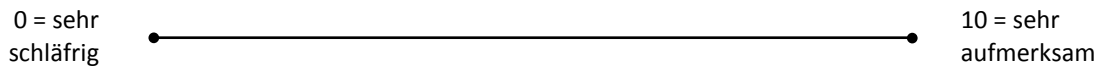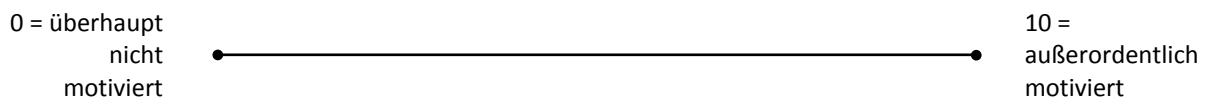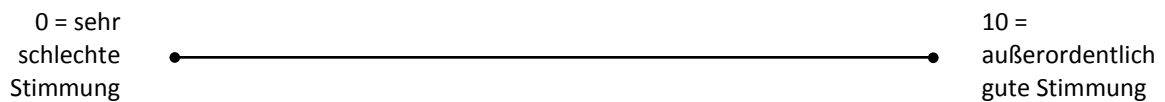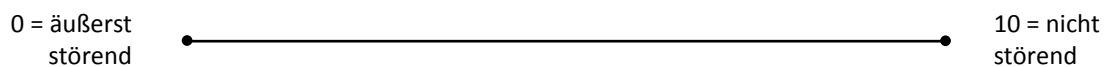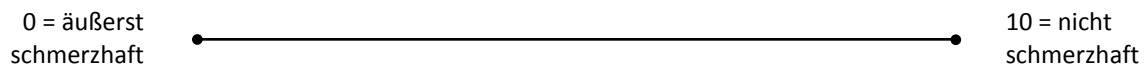
Zwischenbefragung (nach Cognitiv)

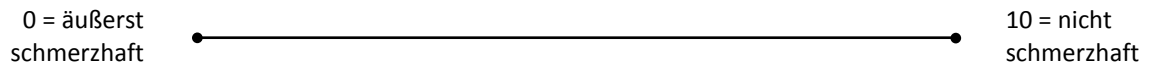Tragezeit: _____ (bitte nicht ausfüllen!)

Bitte beurteilen Sie die unten angeführten Fragen auf einer 10-er Skala. Machen Sie als Markierung bitte einen senkrechten Strich an der Stelle, von der Sie denken, dass Sie ihre Antwort am besten repräsentiert.

Headset Tragekomfort:
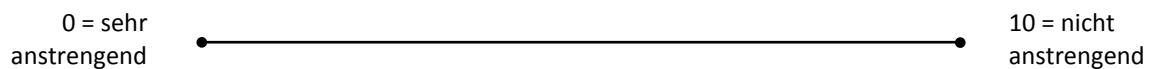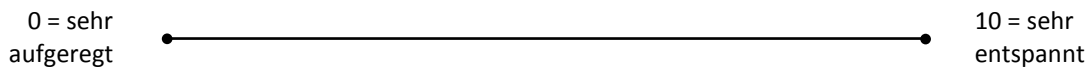
Wie empfinden Sie das Headset auf ihrem Kopf?

| 0 = äußerst störend | •————————————————————————————• | 10 = nicht störend |

Verursacht das Tragen des Headsets Schmerzen?

| 0 = äußerst schmerzhaft | •————————————————————————————• | 10 = nicht schmerzhaft |
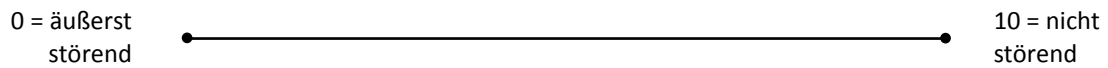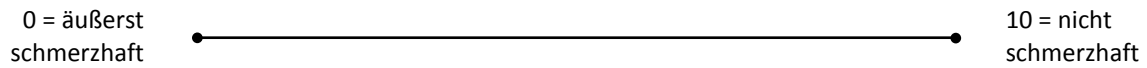
Aufgabenstellung:

Hatten Sie das Gefühl den Würfel kontrollieren zu können?

| 0 = keine Kontrolle | •————————————————————————————• | 10 = totale Kontrolle |

Empfanden Sie die ihnen gestellte Aufgabe als anstrengend?

| 0 = sehr anstrengend | •————————————————————————————• | 10 = nicht anstrengend |
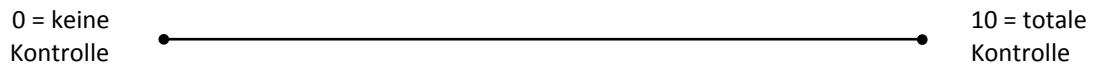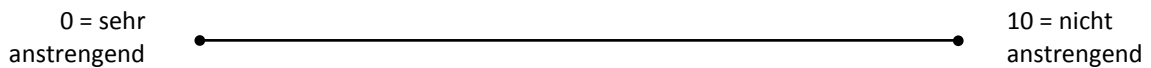
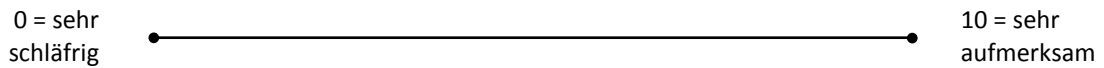**Zwischenbefragung (vor QWOP)**

Bitte beurteilen Sie die unten angeführten Fragen auf einer 10-er Skala. Machen Sie als Markierung bitte einen senkrechten Strich an der Stelle, von der Sie denken, dass Sie ihre Antwort am besten repräsentiert.
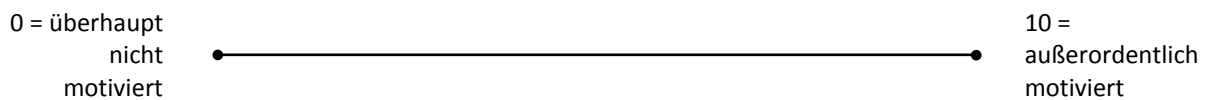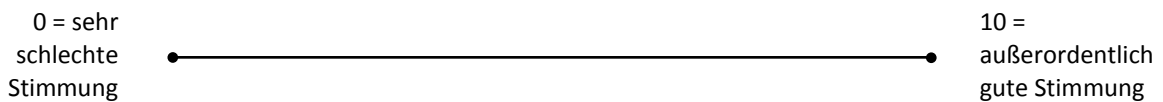
Gemütszustand:

Fühlen Sie sich entspannt?

0 = sehr aufgeregt ●————————————————————● 10 = sehr entspannt

Fühlen Sie sich aufmerksam?

0 = sehr schläfrig ●————————————————————● 10 = sehr aufmerksam

Wie ist ihre Motivation?

0 = überhaupt nicht motiviert ●————————————————————● 10 = außerordentlich motiviert

Wie ist ihre Stimmung?

0 = sehr schlechte Stimmung ●————————————————————● 10 = außerordentlich gute Stimmung

GRAZ BCI
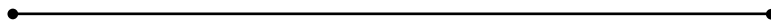
Zwischenbefragung (vor QWOP)

Im Moment fühle ich mich	überhaupt nicht				sehr
1.zufrieden	○	○	○	○	○
2. ausgeruht	○	○	○	○	○
3. ruhelos	○	○	○	○	○
4. schlecht	○	○	○	○	○
5. schlapp	○	○	○	○	○
6. gelassen	○	○	○	○	○
7. müde	○	○	○	○	○
8. gut	○	○	○	○	○
9. unruhig	○	○	○	○	○
10. munter	○	○	○	○	○
11. unwohl	○	○	○	○	○
12. entspannt	○	○	○	○	○

Im Moment fühle ich mich	überhaupt nicht				sehr
13.schläfrig	○	○	○	○	
14. wohl	○	○	○	○	○
15. ausgeglichen	○	○	○	○	○
16. unglücklich	○	○	○	○	
17. wach	○	○	○	○	○
18. unzufrieden	○	○	○	○	
19. angespannt	○	○	○	○	
20. frisch	○	○	○	○	
21. glücklich	○	○	○	○	
22. nervös	○	○	○	○	○
23. ermattet	○	○	○	○	○
24. ruhig	○	○	○	○	○

überhaupt nicht   sehr

überhaupt nicht   sehr

GRAZ BCI

Zwischenbefragung (nach QWOP, vor HD)

Bitte beurteilen Sie die unten angeführten Fragen auf einer 10-er Skala. Machen Sie als Markierung bitte einen senkrechten Strich an der Stelle, von der Sie denken, dass Sie ihre Antwort am besten repräsentiert.

Gemütszustand:

Fühlen Sie sich entspannt?

0 = sehr aufgeregt •————————————————————• 10 = sehr entspannt

Fühlen Sie sich aufmerksam?

0 = sehr schläfrig •————————————————————• 10 = sehr aufmerksam

Wie ist ihre Motivation?

0 = überhaupt nicht motiviert •————————————————————• 10 = außerordentlich motiviert

Wie ist ihre Stimmung?

0 = sehr schlechte Stimmung •————————————————————• 10 = außerordentlich gute Stimmung

GRAZ BCI

Zwischenbefragung (nach QWOP, vor HD)

Im Moment fühle ich mich	überhaupt nicht				sehr
1.zufrieden	○	○	○	○	○
2. ausgeruht	○	○	○	○	○
3. ruhelos	○	○	○	○	○
4. schlecht	○	○	○	○	○
5. schlapp	○	○	○	○	○
6. gelassen	○	○	○	○	○
7. müde	○	○	○	○	○
8. gut	○	○	○	○	○
9. unruhig	○	○	○	○	○
10. munter	○	○	○	○	○
11. unwohl	○	○	○	○	○
12. entspannt	○	○	○	○	○

überhaupt nicht   sehr

Im Moment fühle ich mich	überhaupt nicht				sehr
13.schläfrig	○	○	○	○	
14. wohl	○	○	○	○	○
15. ausgeglichen	○	○	○	○	○
16. unglücklich	○	○	○	○	○
17. wach	○	○	○	○	○
18. unzufrieden	○	○	○	○	○
19. angespannt	○	○	○	○	○
20. frisch	○	○	○	○	○
21. glücklich	○	○	○	○	○
22. nervös	○	○	○	○	○
23. ermattet	○	○	○	○	○
24. ruhig	○	○	○	○	○

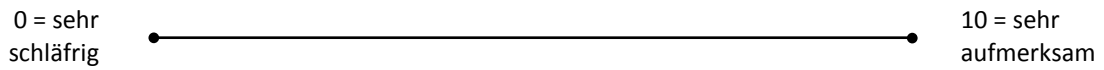überhaupt nicht   sehr

Zwischenbefragung (nach HD)

Bitte beurteilen Sie die unten angeführten Fragen auf einer 10-er Skala. Machen Sie als Markierung bitte einen senkrechten Strich an der Stelle, von der Sie denken, dass Sie ihre Antwort am besten repräsentiert.
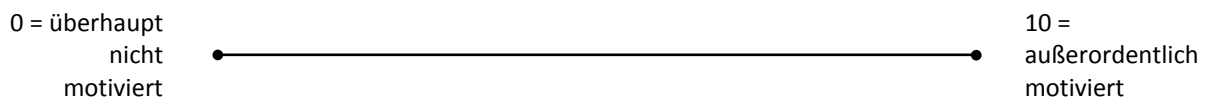
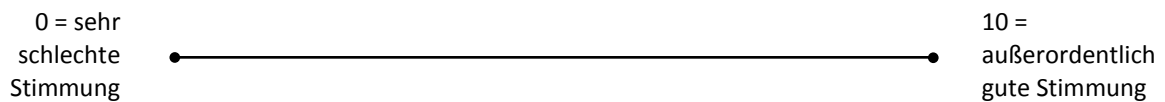**Gemütszustand:**

Fühlen Sie sich entspannt?

0 = sehr
aufgeregt ●————————————————————————————● 10 = sehr
entspannt

Fühlen Sie sich aufmerksam?

0 = sehr
schläfrig ●————————————————————————————● 10 = sehr
aufmerksam

Wie ist ihre Motivation?

0 = überhaupt
nicht ●————————————————————————————● 10 =
außerordentlich
motiviert motiviert

Wie ist ihre Stimmung?

0 = sehr
schlechte ●————————————————————————————● 10 =
außerordentlich
Stimmung gute Stimmung

Zwischenbefragung (nach HD)

Im Moment fühle ich mich	überhaupt nicht				sehr
1.zufrieden	○	○	○	○	○
2. ausgeruht	○	○	○	○	○
3. ruhelos	○	○	○	○	○
4. schlecht	○	○	○	○	○
5. schlapp	○	○	○	○	○
6. gelassen	○	○	○	○	○
7. müde	○	○	○	○	○
8. gut	○	○	○	○	○
9. unruhig	○	○	○	○	○
10. munter	○	○	○	○	○
11. unwohl	○	○	○	○	○
12. entspannt	○	○	○	○	○

überhaupt nicht   sehr

Im Moment fühle ich mich	überhaupt nicht				sehr
13.schläfrig	○	○	○	○	○
14. wohl	○	○	○	○	○
15. ausgeglichen	○	○	○	○	○
16. unglücklich	○	○	○	○	○
17. wach	○	○	○	○	○
18. unzufrieden	○	○	○	○	○
19. angespannt	○	○	○	○	○
20. frisch	○	○	○	○	○
21. glücklich	○	○	○	○	○
22. nervös	○	○	○	○	○
23. ermattet	○	○	○	○	○
24. ruhig	○	○	○	○	○

überhaupt nicht   sehr

Zwischenbefragung (nach Affectiv)

Tragezeit: _____ (bitte nicht ausfüllen!)

Bitte beurteilen Sie die unten angeführten Fragen auf einer 10-er Skala. Machen Sie als Markierung bitte einen senkrechten Strich an der Stelle, von der Sie denken, dass Sie ihre Antwort am besten repräsentiert.

Headset Tragekomfort:

Wie empfinden Sie das Headset auf ihrem Kopf?

0 = äußerst störend ●————————————————● 10 = nicht störend

Verursacht das Tragen des Headsets Schmerzen?

0 = äußerst schmerzhaft ●————————————————● 10 = nicht schmerzhaft

Aufgabenstellung:

Empfanden Sie die ihnen gestellte Aufgabe als anstrengend?

0 = sehr anstrengend ●————————————————● 10 = nicht anstrengend

Zwischenbefragung (nach Expressiv)

Tragezeit: _____ (bitte nicht ausfüllen!)

Bitte beurteilen Sie die unten angeführten Fragen auf einer 10-er Skala. Machen Sie als Markierung bitte einen senkrechten Strich an der Stelle, von der Sie denken, dass Sie ihre Antwort am besten repräsentiert.

Gemützustand:

Fühlen Sie sich entspannt?

0 = sehr aufgeregt ———————————————————————— 10 = sehr entspannt

Fühlen Sie sich aufmerksam?

0 = sehr schläfrig ———————————————————————— 10 = sehr aufmerksam

Wie ist ihre Motivation?

0 = überhaupt nicht motiviert ———————————————————————— 10 = außerordentlich motiviert

Wie ist ihre Stimmung?

0 = sehr schlechte Stimmung ———————————————————————— 10 = außerordentlich gute Stimmung

Headset Tragekomfort:

Wie empfinden Sie das Headset auf ihrem Kopf?

0 = äußerst störend ———————————————————————— 10 = nicht störend

Verursacht das Tragen des Headsets Schmerzen?

0 = äußerst schmerzhaft ———————————————————————— 10 = nicht schmerzhaft

Aufgabenstellung:

Empfanden Sie die ihnen gestellte Aufgabe als anstrengend?
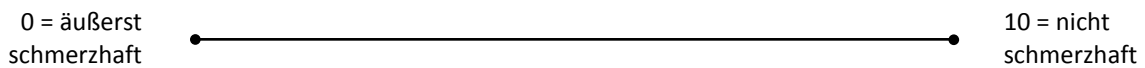
0 = sehr anstrengend ———————————————————————— 10 = nicht anstrengend
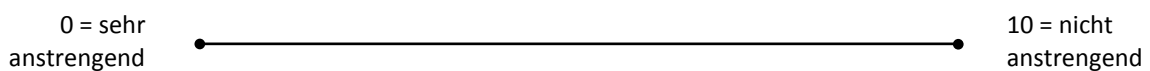
World of Warcraft Experience

Haben Sie bereits Erfahrungen mit dem
Spiel „World of Warcraft":   □ ja   □ nein

Falls ja:
  Wie viele oft haben Sie
  bereits gespielt: □ <1 Tag   □ 1 – 15 Tage   □ 15-30 Tage
                                       □ 1-3 Monate   □ 3-6 Monate   □ 6+ Monate

Aufgabenstellung:

  Empfanden Sie die ihnen gestellte Aufgabe als anstrengend?

  0 = sehr   10 = nicht
  anstrengend •────────────────────────────────────• anstrengend
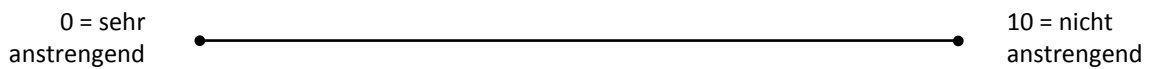
  Empfanden Sie die ihnen gestellte Aufgabe als schwierig?

  0 = sehr   10 = sehr
  schwierig   •────────────────────────────────────• einfach
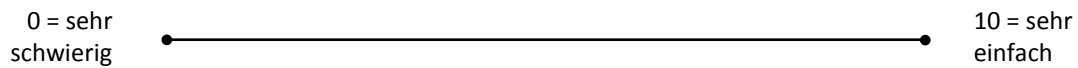
  Wie empfanden Sie die **Bewegungskontrolle** über ihren Avatar?

  0 = keine   10 = totale
  Kontrolle   •────────────────────────────────────• Kontrolle
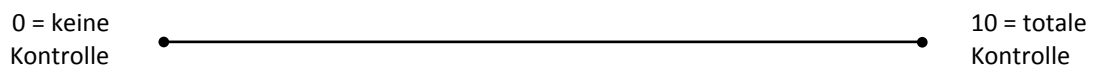
  Wie schwierig war es für Sie die Gyrosensoren mit Hilfe der Begrenzungsmarkierungen neu
  zu zentrieren?
  0 = sehr   10 = sehr
  schwer   •────────────────────────────────────• leicht
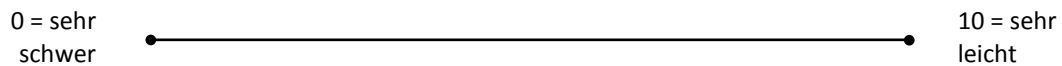
  Wie empfanden Sie die **Kontrolle über die Aktionen** (Anvisieren, Attackieren &
  Aufheben)?
  0 = keine   10 = totale
  Kontrolle   •────────────────────────────────────• Kontrolle
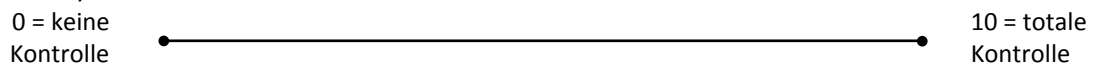
Zwischenbefragung (nach WoW)

Tragezeit: _____ (bitte nicht ausfüllen!)

Bitte beurteilen Sie die unten angeführten Fragen auf einer 10-er Skala. Machen Sie als Markierung bitte einen senkrechten Strich an der Stelle, von der Sie denken, dass Sie ihre Antwort am besten repräsentiert.

Gemütszustand:

Fühlen Sie sich entspannt?

0 = sehr aufgeregt •————————————————————————————————• 10 = sehr entspannt

Fühlen Sie sich aufmerksam?

0 = sehr schläfrig •————————————————————————————————• 10 = sehr aufmerksam

Wie ist ihre Motivation?

0 = überhaupt nicht motiviert •————————————————————————————————• 10 = außerordentlich motiviert

Wie ist ihre Stimmung?

0 = sehr schlechte Stimmung •————————————————————————————————• 10 = außerordentlich gute Stimmung

Headset Tragekomfort:

Wie empfinden Sie das Headset auf ihrem Kopf?

0 = äußerst störend •————————————————————————————————• 10 = nicht störend

Verursacht das Tragen des Headsets Schmerzen?

0 = äußerst schmerzhaft •————————————————————————————————• 10 = nicht schmerzhaft
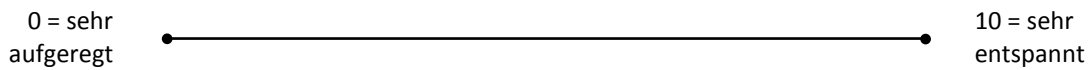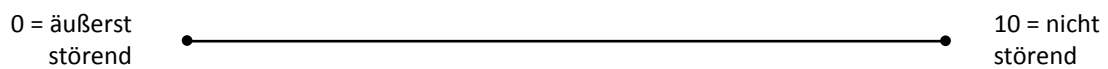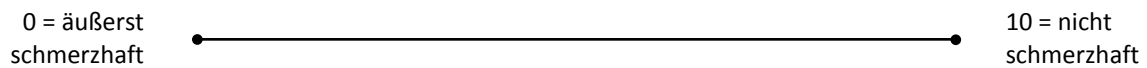
World of Warcraft Experience

TEST GRUPPE: □ A   □ B

Action 1: _____

Action 2: _____

Action 3: _____

Kills:	Loots:
Ges:	**Ges:**
Punkte:	**Punkte:**
Punkte Ges.:	

C. IEE XML DTD

```
<?xml version="1.0" encoding="utf-8" standalone="yes"?>
<!DOCTYPE SystemConfig [


        <!ELEMENT SystemConfig (Display, Network?, Interface, Commands?, SelectionSets?)>
        <!ELEMENT Display EMPTY>
        <!ATTLIST Display width CDATA #REQUIRED>
        <!ATTLIST Display height CDATA #REQUIRED>
        <!ATTLIST Display fullscreen CDATA #REQUIRED>
        <!ATTLIST Display refresh_rate CDATA #REQUIRED>
        <!ELEMENT Network (Server?, BciClient?)>
        <!ELEMENT Server EMPTY>
        <!ATTLIST Server local_ip CDATA #REQUIRED>
        <!ATTLIST Server local_port CDATA #REQUIRED>
        <!ATTLIST Server protocol CDATA #REQUIRED>
        <!ATTLIST Server timeout CDATA #REQUIRED> <!--timeout in seconds-->
        <!ELEMENT BciClient EMPTY>
        <!ATTLIST BciClient local_ip CDATA #REQUIRED>
        <!ATTLIST BciClient local_port CDATA #REQUIRED>
        <!ATTLIST BciClient remote_ip CDATA #REQUIRED>
        <!ATTLIST BciClient remote_port CDATA #REQUIRED>
        <!ATTLIST BciClient protocol CDATA #REQUIRED>
        <!ELEMENT Interface (Icons, Masks+)>
        <!ELEMENT Icons (CheckerIcon*, BitmapIcon*, TextureIcon*, BarIcon*)>
        <!ELEMENT Masks (Mask*)>
        <!ELEMENT Mask (Icon*)> <!ATTLIST Mask id ID #REQUIRED>
        <!ELEMENT Icon EMPTY> <!ATTLIST Icon id IDREF #REQUIRED>
        <!ELEMENT CheckerIcon (DefaultFrame?, SelectionFrame?, Animation?)>
        <!ATTLIST CheckerIcon id ID #REQUIRED>
        <!ATTLIST CheckerIcon pos_x CDATA #REQUIRED>
        <!ATTLIST CheckerIcon pos_y CDATA #REQUIRED>
        <!ATTLIST CheckerIcon height CDATA #REQUIRED>
        <!ATTLIST CheckerIcon width CDATA #REQUIRED>
        <!ATTLIST CheckerIcon color CDATA #REQUIRED>
        <!ATTLIST CheckerIcon lines CDATA #REQUIRED>
        <!ATTLIST CheckerIcon columns CDATA #REQUIRED>
        <!ELEMENT BitmapIcon (DefaultFrame?, SelectionFrame?, Animation?)>
        <!ATTLIST BitmapIcon id ID #REQUIRED>
        <!ATTLIST BitmapIcon pos_x CDATA #REQUIRED>
        <!ATTLIST BitmapIcon pos_y CDATA #REQUIRED>
        <!ATTLIST BitmapIcon texture CDATA #REQUIRED>
        <!ATTLIST BitmapIcon color CDATA #IMPLIED>
        <!ELEMENT TextureIcon (DefaultFrame?, SelectionFrame?, Animation?)>
        <!ATTLIST TextureIcon id ID #REQUIRED>
        <!ATTLIST TextureIcon pos_x CDATA #REQUIRED>
        <!ATTLIST TextureIcon pos_y CDATA #REQUIRED>
```
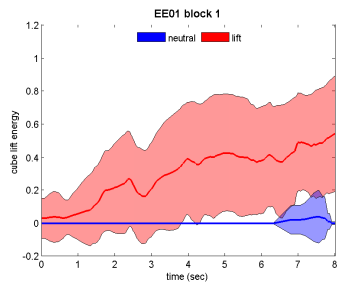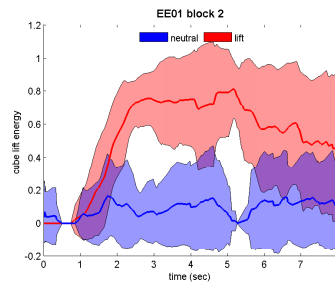
```
<!ATTLIST TextureIcon texture CDATA #REQUIRED>
<!ATTLIST TextureIcon scale CDATA #IMPLIED>
<!ELEMENT BarIcon (DefaultFrame?)>
<!ATTLIST BarIcon id ID #REQUIRED>
<!ATTLIST BarIcon pos_x CDATA #REQUIRED>
<!ATTLIST BarIcon pos_y CDATA #REQUIRED>
<!ATTLIST BarIcon width CDATA #REQUIRED>
<!ATTLIST BarIcon height CDATA #REQUIRED>
<!ATTLIST BarIcon animation_id IDREF #REQUIRED>
<!ATTLIST BarIcon color CDATA #REQUIRED>
<!ELEMENT Animation EMPTY>
<!ATTLIST Animation type (ONOFF|INVERT) #REQUIRED>
<!ATTLIST Animation active_frames CDATA #REQUIRED>
<!ATTLIST Animation inactive_frames CDATA #REQUIRED>
<!ATTLIST Animation offset CDATA #REQUIRED>
<!ELEMENT SelectionFrame EMPTY>
<!ATTLIST SelectionFrame width CDATA #REQUIRED>
<!ATTLIST SelectionFrame color CDATA #REQUIRED>
<!ELEMENT DefaultFrame EMPTY>
<!ATTLIST DefaultFrame width CDATA #REQUIRED>
<!ATTLIST DefaultFrame color CDATA #REQUIRED>
<!ELEMENT Commands (Command*)>
<!ELEMENT Command (Action*) >
<!ATTLIST Command id ID #REQUIRED>
<!ELEMENT Action EMPTY>
<!ATTLIST Action type (LoadSelectionSet|LoadMask|SelectIcon|DeselectIcon|
HideIcon|ShowIcon|PlaySound|ActivateCommand|Selection|SendMessage) #REQUIRED>
<!ATTLIST Action parameter CDATA #REQUIRED>
<!ATTLIST Action trigger (ACTIVATE|DEACTIVATE) #REQUIRED>
<!ELEMENT SelectionSets (SelectionSet*)>
<!ELEMENT SelectionSet (Selection*)>
<!ATTLIST SelectionSet id ID #REQUIRED>
<!ELEMENT Selection EMPTY>
<!ATTLIST Selection id CDATA #REQUIRED>
<!ATTLIST Selection type (EEG|EMG) #REQUIRED>
<!ATTLIST Selection command_id IDREF #REQUIRED>
<!ATTLIST Selection delay CDATA #IMPLIED>
<!ATTLIST Selection animation_id ID #IMPLIED>

]>
```

D. Cognitiv Test Results ROC Curves
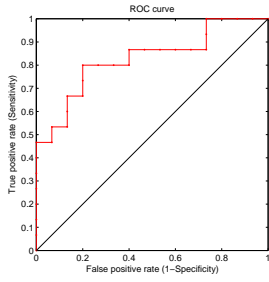
(a) EE01F block1
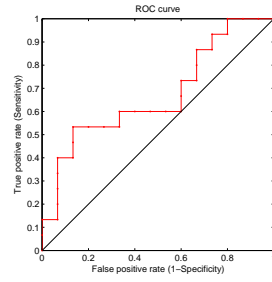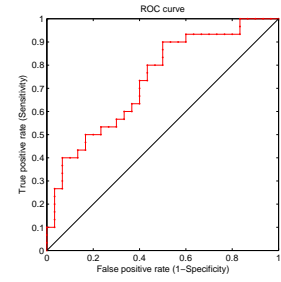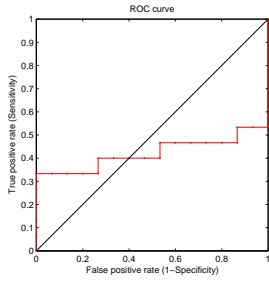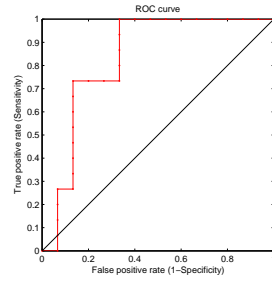
(b) EE01F block2

(c) EE01F all

(d) EE02M block1

(e) EE02M block2

(f) EE02M all

(g) EE03M block1

(h) EE03M block2
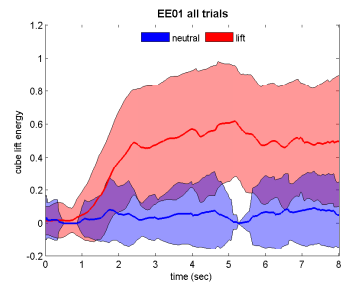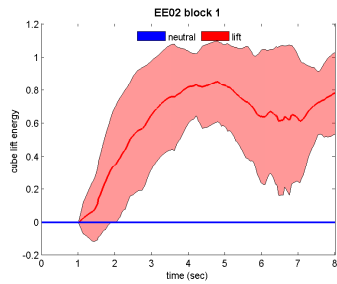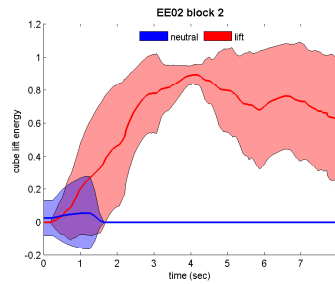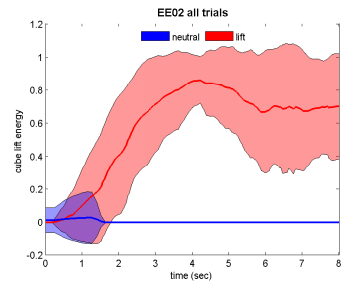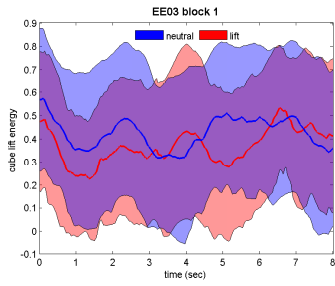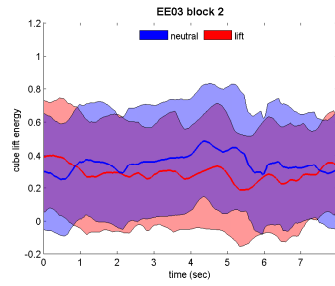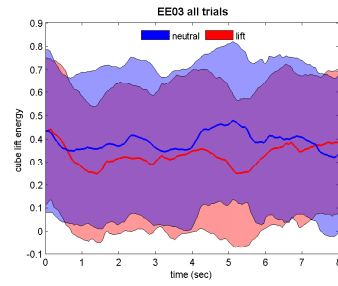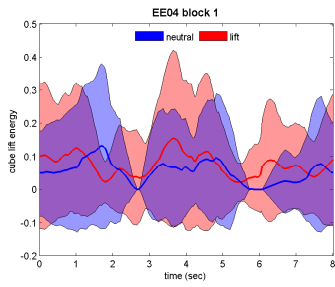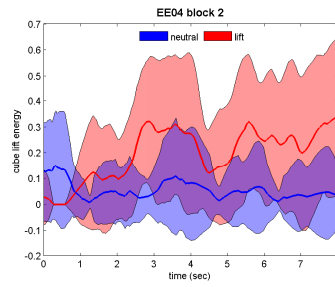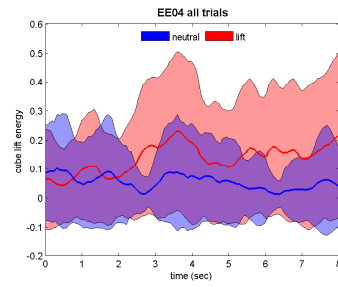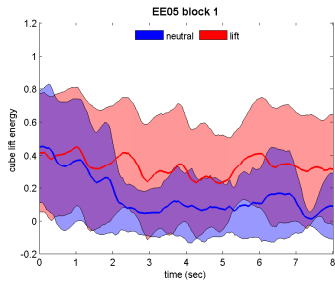

(i) EE03M all

(j) EE04M block1

(k) EE04M block2

(l) EE04M all

(m) EE05M block1

(n) EE05M block2

(o) EE05M all

(p) EE06F block1

(q) EE06F block2

(r) EE06F all

(a) EE07M block1

(b) EE07M block2

(c) EE07M all

(d) EE08M block1
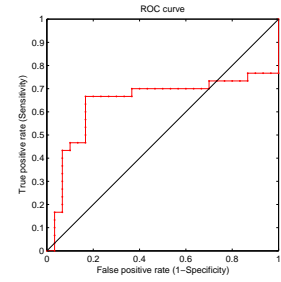
(e) EE08M block2

(f) EE08M all
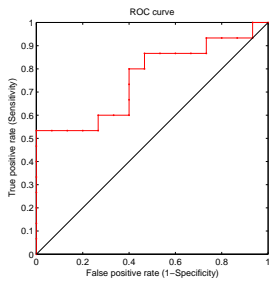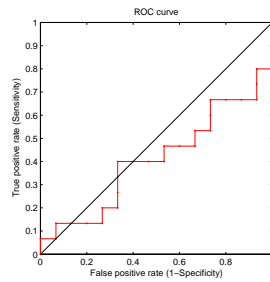
(g) EE09M block1
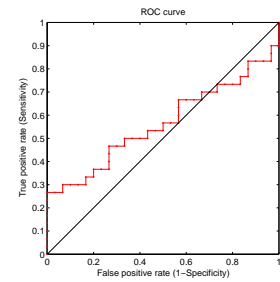
(h) EE09M block2

(i) EE09M all
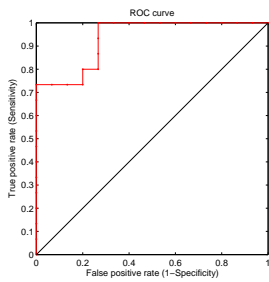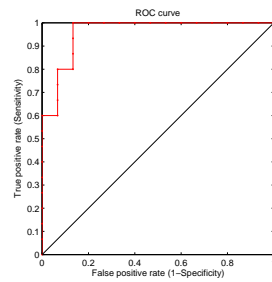
(j) EE10M block1
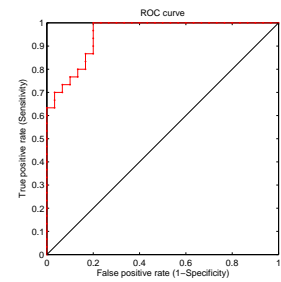
(k) EE10M block2

(l) EE10M all

E. Cognitiv Test Results Lift over Time

(a) EE01F block 1

(b) EE01F block 2

(c) EE01F all

(d) EE02M block 1

(e) EE02M block 2

(f) EE02M all

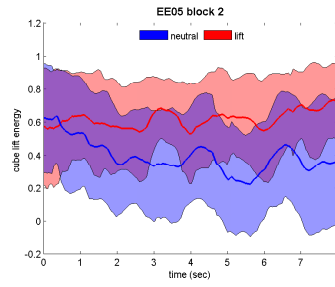(g) EE03M block 1

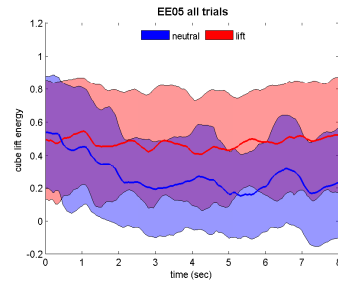(h) EE03M block 2

(i) EE03M all
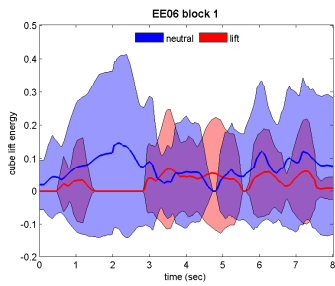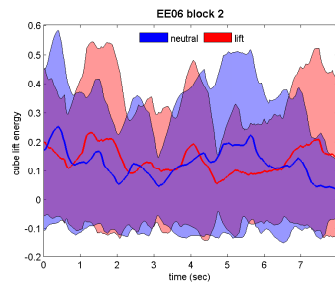
(j) EE04M block 1

(k) EE04M block 2
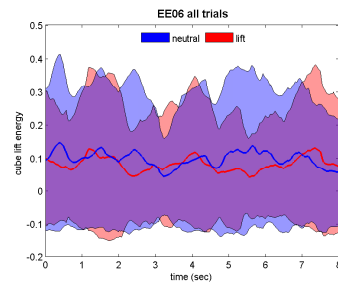
(l) EE04M all

(m) EE05M block 1

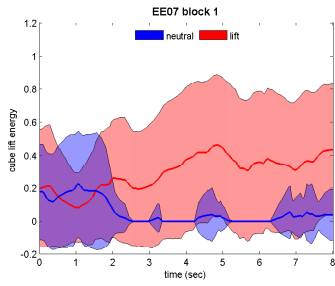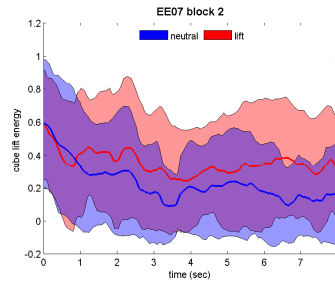(n) EE05M block 2

(o) EE05M all

(p) EE06F block 1

(q) EE06F block 2

(r) EE06F all

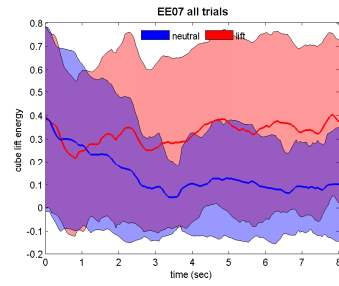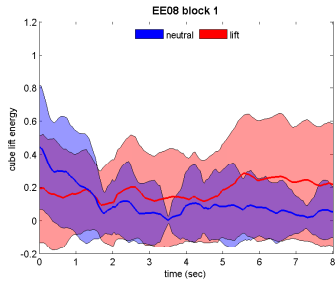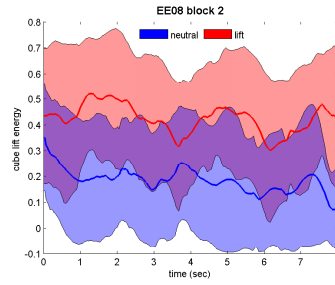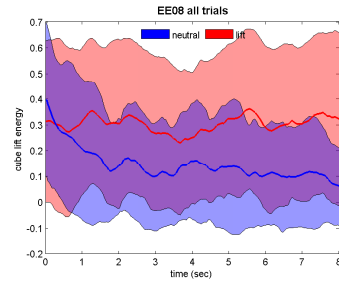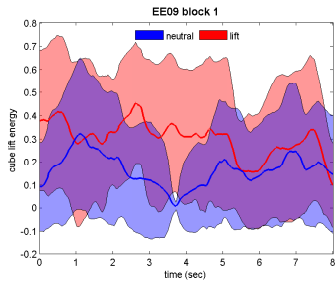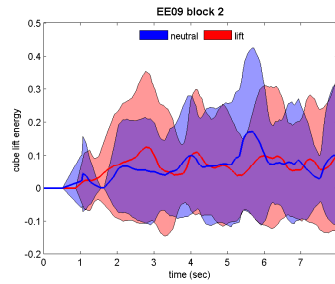(a) EE07M block 1   (b) EE07M block 2   (c) EE07M all
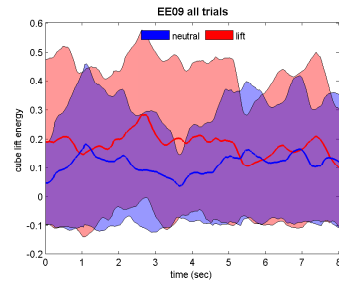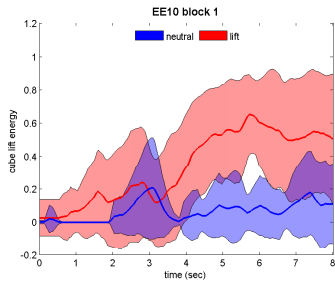
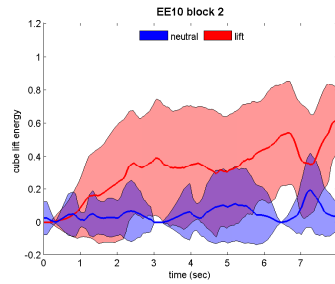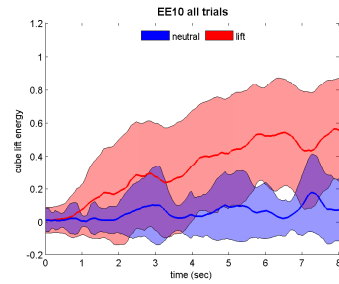(d) EE08M block 1   (e) EE08M block 2   (f) EE08M all

(g) EE09M block 1   (h) EE09M block 2   (i) EE09M all

(j) EE10M block 1   (k) EE10M block 2   (l) EE10M all

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