Comparison of Theta/Beta, Slow Cortical Potential, and Adaptive Neurofeedback Training in Adults: Training Effects on Attentional Processes, Motor System, and Mood

Dissertation
der Mathematisch-Naturwissenschaftlichen Fakultät
der Eberhard Karls Universität Tübingen
zur Erlangung des Grades eines
Doktors der Naturwissenschaften
(Dr. rer. nat.)

vorgelegt von
M.Sc. Petra Studer
aus Stuttgart

Tübingen
2011

Tag der mündlichen Qualifikation: 24.10.2011

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Acknowledgements

I would like to thank Professor Dr. Martin Hautzinger for his continuous support during my project and for his exceptionally clear style of dealing with upcoming questions, which was just perfect. I am also very grateful to Professor Dr. Niels Birbaumer for offering me his time to be my second supervisor.

Furthermore, I owe my gratitude to Professor Dr. Gunther H. Moll for providing me with the great opportunity of doing my PhD project in his department in cooperation with the University of Tübingen. Dr. Oliver Kratz deserves my thanks for all his support in the course of the study, especially for his support around the screening interviews to which I owe a larger number of participants. My very special thanks go to PD Dr. Hartmut Heinrich for his never-ending support ranging from the design of the study, via complex data analysis methods to fruitful discussions of results. I am also very thankful for the support, discussions, and feedback of my colleagues of the “AG Neurophysio”.

Moreover, I would like to give many thanks to Martin Deinzer who spent uncountably many long days in the lab in order to perform the pre- and post-assessments which form the heart of the present study, solving occurring technical problems on the fly, and for creating a good atmosphere during assessments for the participants. I am very grateful to my student assistants Jacqueline Gänßbauer, Anne Birlauf, Iris Hartmann and Jelena Siebert for greatly supporting me in the course of the study, for contributing their ideas, and beyond all for being great colleagues during long working days. I would also like to thank all colleagues in the “research wing” for their good company and for their patience with my many “please be quite” requests during assessments – let’s shout out!

In addition, all assistant doctors deserve my gratitude for again and again moving to my office and spending their time in the “research wing” during TMS assessments at all possible times. I would like to give many thanks to the medical secretaries and to Martin Deinzer for screening EEG and ECG assessments and especially for enabling quite some assessments at short notice. My special thanks go to Dr. Mona Pfaffenberger and all assistant doctors who performed the screening EEG and ECG analyses. For spending some nightly hours on the analyses I am grateful to Dr. Christa Wichmann and Susanne Wangler, in particular. Moreover, all participants of the present study deserve my thanks for their contribution and for taking so much time and effort to comply with

the tight time schedule of the study. My thanks also go to Dr. Martin Schmucker for taking his time to answer my special questions on statistics.

I would also like to thank the cooperation partner from the Child & Adolescent Psychiatry at the University of Göttingen (Professor Dr. Aribert Rothenberger) and in particular Holger Gevensleben.

Furthermore, I owe my gratitude to Dörte Klein for introducing me to the fascinating field of neurofeedback, for giving me the opportunity to observe her training sessions, and assist in her workshops, as well as for getting to know the adaptive neurofeedback approach.

Beyond the many people who have directly supported me with conducting the study, there are some more persons that merit a lot of thanks. I would like to pronounce many thanks to my friend Debbie for offering me some time of her holidays for the English proof-reading of major parts of my thesis – and I hope that my last-minute changes have not affected her great corrections. In addition, I would like to thank my mother for her help with the final checking. I am also very grateful to Antje and especially to Tobias for the crash course in graphics and layout, which saved me a lot of trouble in the end.

Moreover, I would like to thank all my friends, my sisters, and my brothers for their support along the way, and beyond that: It’s great that you are there! My special thanks go to Lu for being with me for countless hours on the phone. I am very happy that we stay so well connected despite the long distance – and I am looking forward to seeing you again soon! Furthermore, I also want to express my very special gratitude to Tobias for supporting me in all imaginable (and unimaginable) ways – I am very happy to have you at my side!

Last but not least, I would like to thank my parents from my heart for their love and support all along until the present day.

This study was partially financed by the German Research Foundation (MO 726/2, HE 4536/2, RO 698/4).

Abstract

Objective: Neurofeedback (NF) training is being applied in an increasing number of clinical and peak performance fields. Better controlled NF studies with larger sample sizes are being conducted, aiming at gaining insights into the specific effects of particular NF protocols together with the underlying mechanisms mediating a successful training. The aim of the present investigation was three-fold. It set out to examine the effects of different NF protocols on well-being / mood, to evaluate the effects of an adaptive type of NF training, as well as to shed further light on the neuronal mechanisms underlying different NF protocols with respect to attentional processes and motor system excitability.

Methods: ‘Healthy’ adults (*n* = 73) were randomly allocated to one of four groups: a theta/beta neurofeedback, a slow cortical potential (SCP) neurofeedback, an adaptive neurofeedack (ANF), or a control training group. Neurofeedback training consisted of 10 double sessions. Pre- and post-training assessments encompassed both self-report and performance measures in addition to resting EEG and event-related potential (ERP) recordings as well as measurements based on transcranial magnetic stimulation (TMS). Self-report measures comprised the domains attention, well-being / mood, and personality characteristics. Performance measures assessed working memory, motor skills, as well as attentional skills during the Attention Network Test (ANT). ERPs recorded during the ANT were analyzed focusing on the contingent negative variation (CNV), reflecting anticipation and preparation, as well as on cue- and target-P3 amplitudes which are thought to be related to attentional resource allocation. TMS measurement was based on a double pulse paradigm applied during a resting state to assess short-interval intracortical inhibition (SICI) and intracortical facilitation (ICF). In addition, self-regulation skills acquired during theta/beta and SCP training were analyzed and associated with behavioral and ERP measures.

Results: Overall, pre-post improvements were observed independent of type of group in the domains action-orientation, self-access, and in tendency for attention, while an overall decrease in vigor was observed. Participants showed faster and less variable responses during the ANT, improved working memory, and improved darts performance. Resting EEG measures revealed an increase in theta and alpha activity, and a tendency for increased beta activity. No general training effects on ERP measures

(cue-P3, target-P3, and CNV amplitudes) during the ANT were obtained. TMS measures indicated a tendency for decreased intracortical inhibition.

With respect to specific results related to the NF protocols, the following pattern of results was obtained, mainly based on effect size measures. While only a slight advantage of NF on self-ratings of attention was observed, somewhat more positive effects were obtained for well-being / mood and perceived stress, which were slightly more pronounced in the SCP and ANF groups. Theta/beta training was associated with faster responding in the ANT. ERPs assessed during the ANT revealed increased CNV amplitudes after NF training. Self-regulation analyses suggested a slight hint for increased CNV amplitudes being associated with successful negativity regulation during SCP training, and for decreased target-P3 amplitudes being associated with successful theta/beta regulation. An increase in alpha activity (at Pz) was observed after ANF training, and an increase in both SICI and ICF was observed after theta/beta training.

Discussion: Some effects of NF training protocols on well-being / mood were observed, but the results were smaller than expected, especially with respect to effects on attention. All three NF protocols were associated with improved resource allocation during cognitive preparation (as indicated by increased CNV amplitudes), which may have been specifically targeted by regulation abilities during negativity trials of SCP training. The association of reduced target-P3 amplitudes with successful theta/beta regulation may indicate less attentional resources needed for target stimulus evaluation. Motor system excitability changes after theta/beta training mimicked the results observed after a single dose of methylphenidate in healthy adults. The results obtained for the ANF group were comparable to those of the other NF groups, although the expected advantage on well-being / mood became only slightly visible. The effects of relaxation training in the ANF group may have been reflected in increased alpha activity observed after ANF training in a resting state. Future studies including larger sample sizes are needed to further determine the specificity of the effects related to particular NF protocols as well as the latter’s effects on well-being / mood.

Zusammenfassung

Zielsetzung: Neurofeedback (NF) wird in einer immer größer werdenden Zahl von klinischen Studien und Peak-Performance Studien eingesetzt. Besser kontrollierte NF-Studien mit größeren Stichproben werden durchgeführt, die darauf abzielen, Einsichten über die spezifischen Effekte bestimmter NF-Protokolle, sowie über die Wirkmechanismen, die einem erfolgreichen Training zugrunde liegen, zu bekommen. Die vorliegende Untersuchung hatte drei Ziele. Es sollten sowohl die Effekte verschiedener NF-Protokolle auf Wohlbefinden / Stimmung untersucht werden, als auch die Effekte eines adaptiven NF-Trainings evaluiert werden, sowie weitere Einsichten über die neuronalen Wirkmechanismen der verschiedenen NF-Protokolle in Bezug auf Aufmerksamkeitsprozesse und die Exzitabilität des motorischen Systems gewonnen werden.

Methoden: ‚Gesunde' Erwachsene (*n* = 73) wurden randomisiert einer von vier Gruppen zugeteilt, wobei Probanden eines der folgenden Trainings absolvierten: ein Theta-/Beta-NF-Training, ein Training langsamer kortikaler Potentiale (Engl. slow cortical potentials, SCPs), ein adaptives NF-Training (ANF) oder ein Kontrolltraining. Die NF-Trainings bestanden aus 10 Doppelsitzungen. Prä- und Postmessungen umfassten sowohl Selbstbeurteilungs- als auch Performancemaße zusätzlich zu Ruhe-EEG-Messungen, Ableitungen von ereignisbezogenen Potentialen (EPs) und Messungen mit transkranieller Magnetstimulation (TMS). Selbstbeurteilungsmaße bezogen sich auf die Bereiche Aufmerksamkeit, Wohlbefinden / Stimmung und Persönlichkeitsmerkmale. Performancemaße erfassten Arbeitsgedächtnis, motorische Fähigkeiten und Aufmerksamkeitsleistung während des Attention Network Tests (ANT). EPs, die während des ANT aufgezeichnet wurden, wurden im Hinblick auf die kontingente negative Variation (Engl. contingent negative variation, CNV), die Vorbereitungsprozesse widerspiegelt, als auch auf die P3-Amplituden (während Warnreiz- und Zielreizverarbeitung), die mit der Bereitstellung von Aufmerksamkeitsressourcen in Verbindung gebracht werden, untersucht. Die TMS-Messung, die basierend auf dem Doppelpulsparadigma während eines Ruhezustandes durchgeführt wurde, erfasste intrakortikale Inhibition (Engl. short-interval intracortical inhibition, SICI) und Fazilitation (Engl. Intracortical facilitation, ICF). Darüber hinaus wurde die Selbstregulationsfähigkeit, die während des Theta-/Beta und des SCP-

Trainings erlernt wurde, ausgewertet und mit Verhaltens- und EP-Maßen in Zusammenhang gebracht.

Ergebnisse: Insgesamt wurden unabhängig von der Gruppe Prä-Post-Verbesserungen in den Bereichen Handlungsorientierung, Selbstzugang und tendenziell für Aufmerksamkeit beobachtet, während der Tatendrang abnahm. Studienteilnehmer zeigten schnellere und weniger variable Antworten während des ANT sowie verbesserte Arbeitsgedächtnis- und Dartleistung. Ruhe-EEG-Messungen ließen eine Zunahme der Theta- und Alphaaktivität und eine Tendenz für eine Zunahme der Betaaktivität erkennen. Es ergaben sich keine allgemeinen Effekte auf EP-Maße (P3-Amplituden während Warn- und Zielreizverarbeitung und CNV-Amplituden) während des ANT. TMS-Maße zeigten eine Tendenz für eine Abnahme der intrakortikalen Inhibition.

Bezüglich spezifischer Ergebnisse für die NF-Protokolle ergab sich, vor allem basierend auf Effektstärkenmaßen, das folgende Ergebnismuster. Während für die NF-Gruppen nur ein sehr geringer Vorteil für die Selbsteinschätzung der Aufmerksamkeit beobachtet wurde, zeigten sich etwas positivere Effekte für Wohlbefinden / Stimmung und erlebten Stress, die in der SCP- und ANF-Gruppe etwas größer ausfielen. Theta-/Beta-Training stand im Zusammenhang mit schnelleren Antworten im ANT. EPs, die während des ANT erhoben wurden, zeigten höhere CNV-Amplituden nach den NF-Trainings. Die Selbstregulationsanalysen ergaben einen sehr kleinen Hinweis dafür, dass höhere CNV-Amplituden mit einer erfolgreichen Regulation während der Negativierungsdurchgänge im SCP-Training und niedrigere P3-Amplituden (nach Zielreizen) mit einer erfolgreichen Theta-/Beta-Regulation verbunden sind. Nach dem adaptiven Training wurde eine Zunahme der Alpha-Aktivität (Pz) beobachtet und nach dem Theta-/Beta-Training eine Zunahme von SICI und ICF.

Diskussion: Für die NF-Protokolle zeigten sich einige Effekte auf Wohlbefinden / Stimmung, aber die Effekte waren kleiner als erwartet, besonders in Bezug auf die Aufmerksamkeit. Alle drei NF-Protokolle waren mit einer verbesserten Ressourcenaktivierung (angezeigt durch erhöhte CNV-Amplituden) während der kognitiven Vorbereitung verbunden, die möglicherweise speziell durch Regulationsfähigkeit während den Negativierungsdurchgängen begünstigt wurde. Der Zusammenhang zwischen einer Reduzierung der P3-Amplituden (während Zielreizverarbeitung) und erfolgreicher Theta-/Beta-Regulation könnte darauf hindeuten, dass weniger Aufmerksamkeitsressourcen für die Verarbeitung des

Zielreizes benötigt wurden. Veränderungen der Exzitabilität des motorischen Systems in der Theta-/Beta-Gruppe entsprachen den Ergebnissen einer Einmalgabe von Methylphenidat bei gesunden Erwachsenen. Die Ergebnisse, die für die ANF-Gruppe erzielt wurden, waren vergleichbar mit den anderen NF-Gruppen, obwohl der erwartete Vorteil bezüglich Wohlbefinden / Stimmung nur sehr minimal sichtbar wurde. Effekte des Entspannungstrainings in der ANF-Gruppe könnten sich in der erhöhten Alphaaktivität widergespiegelt haben, die in der ANF-Gruppe im Ruhezustand beobachtet wurde. Zukünftige Studien, die größere Stichproben umfassen, sind nötig um spezifische Effekte von bestimmten NF-Protokollen sowie ihre Auswirkungen auf Wohlbefinden / Stimmung weiter bestimmen zu können.

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List of Abbreviations

ACC	*anterior cingulate cortex*
ADHD	*attention-deficit hyperactivity disorder*
ANF	*adaptive neurofeedback training*
ANOVA	*analysis of variance*
ANT	*Attention Network Test*
AOF	*action orientation after failure*
AOP	*prospective action orientation*
BOLD	*blood oxygen level dependent response*
CNV	*contingent negative variation*
CPT-OX	*continuous performance test version OX*
ECG	*electrocardiogram*
EEG	*electroencephalogram*
EMG	*electromyogram*
EOG	*electrooculogram*
ERPs	*event-related potentials*
EWL-N	*self-report measure: adjective checklist (Eigenschaftswörterliste-N)*
fMRI	*functional magnetic resonance imaging*
FQ	*theta/beta frequency band training*
H	*hypothesis*
HAKEMP	*self-report measure: action orientation after failure and prospective*
IAPS	*International Affective Picture System*
ICF	*intracortical facilitation*
LORETA	*low resolution brain electromagnetic tomography*
MEP	*motor evoked potential*
MIDI	*Musical Instrument Digital Interface*
ms	*millisecond*
NF	*neurofeedback*
NIRS	*near-infrared-spectroscopy*
POMS	*Profile of Mood States*
PRI	*perceptual reasoning index*

PSS	*Perceived Stress Scale*
QEEG	*quantitative electroencephalogram*
RMT	*resting motor threshold*
RT	*reaction time*
rtfMRI	*real-time functional magnetic resonance imaging*
RTV	*variability of reaction time*
s	*second*
SCL-90-R	*Symptom Checklist-90-R*
SCP	*slow cortical potential*
SICI	*short-interval intracortical inhibition*
sLORETA	*standardized low resolution brain electromagnetic tomography*
SMA	*supplementary motor area*
SMR	*sensorimotor rhythm*
TMS	*transcranial magnetic stimulation*
VCI	*verbal comprehension index*
WIE	*Wechsler Adult Intelligence Scale*
μV	*microvolt*

1 Introduction and theoretical background

Since its invention in the 1960s, electroencephalogram (EEG) biofeedback training, also known as neurofeedback (NF), has become increasingly popular. During NF, individuals learn to acquire self-regulation skills of particular brain activity patterns. To date, NF is being applied in both clinical as well as peak performance domains. Regarding the clinical field, NF in both children with attention deficit/hyperactivity disorder and patients with epilepsy are the two applications for which treatment outcome has been most intensively studied (Heinrich, Gevensleben, & Strehl, 2007). With respect to peak performance training in healthy adults, the applications of NF training range from cognitive to artistic performance and creativity. But despite the ever growing diversity of NF applications, mechanisms mediating a successful NF training are still not fully understood. A better understanding of these mechanisms may allow for the improvement of NF training protocols and thereby for increasing the effectiveness of treatment outcome. In this respect, the better designed NF studies which have been emerging, especially in recent years, are taking an important step in this direction.

The first chapter (1.1 Relation of brain activity and mental states / behavior), sets out to establish the methodological basis on which NF training is grounded, by briefly outlining the relation between brain activity and mental states / behavior. In addition, neurophysiological methods are introduced which play a relevant role in the evaluation of the effects of NF. In the next chapter (1.2 Neurofeedback training: definition, rationales, protocols), besides providing some additional information on the purpose of NF training, the rationales underlying its application and different types of NF protocols will be outlined. In a third chapter (1.3 Neurofeedback: applications and scientific evidence), an overview of NF studies in both the clinical and peak performance field will be provided. Moreover, an overview of studies which have analyzed neuronal mechanisms related to particular NF protocols will be provided in the following chapter (1.4 Neuronal mechanisms underlying neurofeedback and the specificity of training effects), focusing on findings in children with ADHD and the peak performance field. Moreover, in this context, the importance of a control training to gain insights into the specificity of NF training protocols will also be discussed.

1.1 Relation of brain activity and mental states / behavior

1.1.1 Electroencephalogram (EEG) and mental states / behavior

The EEG was invented in the late 1920s by Hans Berger in order to non-invasively measure electrical activity of the cerebral cortex. EEG activity was observed to differ during different mental states. While low-voltage fast electrical activity is characteristic for alert wakefulness, deep sleep is characterized by high-voltage slow activity (Saper, 2000).

EEG activity is composed of different rhythms which can be described by means of the following frequency bands (among others): delta (.5-4 Hz), theta (4-7 Hz), alpha (8-13 Hz), and beta (13-30 Hz). Pronounced activity in each of these frequency bands has a functional correlate. Theta and delta waves are dominant during drowsiness and early slow-wave sleep while slow delta waves (.5-2Hz) dominate during stage-3 sleep. A state of relaxed wakefulness is related to prominent alpha activity while during mental activity, beta waves are more pronounced. An example of EEG changes related to a change in mental state is the following: when a relaxed person is alerted, a reduction in alpha activity together with an increase in beta activity can be observed (Rechtschaffen & Siegel, 2000; Westbrook, 2000).

Furthermore, regarding the theta/beta ratio, in a test on sustained attention performed in healthy adults, a correlation between the theta/beta ratio and the number of correct responses as well as between the theta/beta ratio and reaction time has been observed (Wiegand & Keller, 2009). The authors of this study concluded that the theta/beta ratio appeared to be a good indicator of attention in healthy subjects. In addition, the theta/beta ratio was observed to be inversely related to mental effort during a go/no-go and cued target detection task (Howells, Stein, & Russell, 2010).

Two further functional correlates of specific EEG activity are to be mentioned here. Slow cortical potentials (SCPs) – negative or positive polarizations of the EEG (< 1 Hz) – can be functionally related to a threshold regulation mechanism of cortical networks as well as preparatory activity of the cortex (Birbaumer, 1999; Strehl, Leins, & Heinrich, 2011). Sterman discovered that the sensorimotor rhythm (SMR, 12-15 Hz) is suppressed by motor activity and that the presence of this rhythm is a marker for motor inhibition (for a review see Sterman, 2010).

Based on such associations between particular EEG activity patterns and specific states, the rationale underlying NF training was established (Vernon, 2005; see also 1.2.2 Rationales for neurofeedback).

1.1.2 Event-related potentials (ERPs) and mental states / behavior

ERPs can be extracted from the ongoing EEG by signal averaging. ERPs represent changes in the EEG that are time-locked and phase-locked to a specific event and thus are related to processes such as perception, cognition as well as motor function. These ERP components can be divided into early components, which mainly reflect the processing of the physical properties of the corresponding stimulus, and late components, which are more related to cognitive stimulus processing stages (Banaschewski & Brandeis, 2007).

Exemplarily, two late ERP components and their functional significance will be mentioned here. One established component is the P3, measured after target processing which is thought to reflect attentional resource allocation, stimulus evaluation as well as context updating processes of the working memory (Banaschewski & Brandeis, 2007; Polich, 2007). A further component is the contingent negative variation (CNV), a negative polarization of a slow cortical potential occurring between a warning and a target stimulus which reflects attentional processes related to anticipation and preparation (Birbaumer, 1999; Birbaumer, Elbert, Canavan, & Rockstroh, 1990; Wangler et al., 2011). A higher CNV is related to reduced excitation thresholds and reflects the tuning of attentional processes as a preparation for efficient performance; inattentive behavior might then be related to the deficient regulation of cortical excitability (Rockstroh, Elbert, Lutzenberger, & Birbaumer, 1990).

ERP measures are applied to unveil covert processing mechanisms (Banaschewski & Brandeis, 2007), e.g. P3 amplitude as an indicator of resource allocation, that cannot be grasped by overt performance measures. ERPs allow further insights into the mental state of a person during the performance of tasks involving perception, cognition and/or motor responses.

1.1.3 Transcranial magnetic stimulation (TMS) and mental states / behavior

TMS allows investigating the excitatory mechanisms of the motor system which are based on a complex interaction of excitatory and inhibitory processes (Reis et al., 2008). One established TMS measure is the double-pulse paradigm (Kujirai et al., 1993) where two TMS stimuli are applied consecutively, with the first one below and the second one above motor threshold (for an overview see Wahl & Ziemann, 2007). Depending on the inter-stimulus interval, the motor evoked potential (MEP) amplitude measured at the target muscle is either reduced or increased compared to a single pulse reflecting short-interval intracortical inhibition (SICI) and intracortical facilitation (ICF), respectively. Thus, these MEP amplitude measurements allow drawing conclusions about the degree of inhibitory and excitatory processes in the motor cortex (Moll, Heinrich, & Rothenberger, 2002).

For example, in children with attention-deficit hyperactivity disorder (ADHD), a decreased SICI was observed compared to typically developing children (Moll et al., 2002). This decrease probably reflects “a neurophysiological correlate of motor hyperactivity and an inhibitory deficit in these children” (Kratz et al., 2009, p. 2). In addition, stimulant medication (methylphenidate) – the most effective treatment in children with ADHD (Banaschewski & Rothenberger, 2009) – was reported to increase SICI in these children and was accompanied by clinical improvements of motor hyperactivity (Moll et al., 2002).

These findings exemplify the possible relation between the excitability of the motor system as measured by the TMS double-pulse paradigm and behavior.

1.2 Neurofeedback training: definition, rationales, protocols

1.2.1 What is neurofeedback?

Neurofeedback is also known as EEG-biofeedback. The idea behind biofeedback is to receive real-time feedback about one’s own body functions that normally are not perceived consciously, e.g. heart rate or skin temperature. These body functions are recorded with appropriate sensors and translated into real-time visual or acoustic feedback signals. The aim is to learn to modulate these body functions in a desired direction, for example to increase one’s skin temperature in order to change one’s own state and become more relaxed (Nestoriuc, Rief, & Heuser, 2011). For a more comprehensive introduction to biofeedback, please refer to Rief and Birbaumer (2011).

In the case of NF, the body function measured is brain electrical activity. EEG electrodes that are attached to the scalp are used as sensors. In other words, NF is a neurobehavioral training which aims at acquiring self-control over certain brain activity patters related to a specific state of mind. Self-regulation ability is learned on the one hand by receiving continuous feedback from modulations of this brain activity pattern and on the other hand by a positive reinforcement of modulations in the desired direction. In order to generate a motivating setting, NF training is often realized as a kind of computer game (see Figure 1). Positive reinforcement can therefore be realized in various ways: collecting points in a game, an animation that moves on, a DVD movie becoming clearly visible. Furthermore, as NF is a neurobehavioral training which is often applied in clinical contexts, it can be embedded in multi-modal treatment programs including e.g. behavior therapy. In addition, and also for its application in non-therapeutic contexts, the trainer-trainee interaction is an important factor influencing motivation and learning (Rief & Birbaumer, 2011).

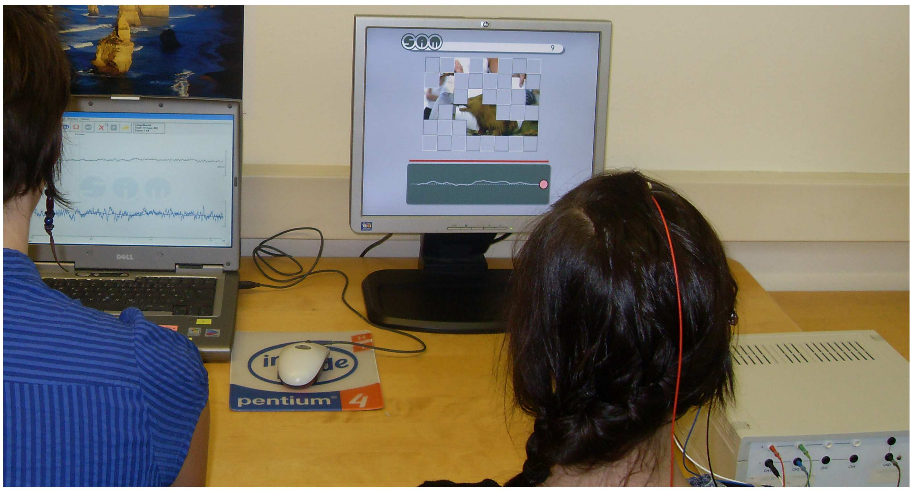

Figure 1. Neurofeedback training setting.

On the right hand side the participant is depicted with electrodes hooked up and connected to the EEG amplifier. In the presented animation, feedback of the EEG parameter to be trained is provided by the time course and color of a ball which is moving from left to right as well as by a puzzle game. On the left hand side the trainer monitors the time course of the EEG signals and controls for artifacts.

Moreover, in some NF settings, individual cognitive strategies may be developed to support the acquisition of self-regulation abilities (Strehl et al., 2011). Finally, the goal is to be able to transfer these self-regulation abilities to daily life situations (in which no feedback of brain electrical activity is provided). To support this transfer to daily life situations, some NF protocols provide so-called “transfer trials” in which self-regulation is trained without receiving continuous feedback on one’s brain electrical activity. Also, practicing transfer to daily life situations within a training session can be helpful. All in all, the successful application of self-regulation abilities in daily life situations requires continuous practice in exactly these situations.

Besides NF based on EEG signals, newer approaches also comprise real-time magnetoencephalography (Mellinger et al., 2007) as well as the blood-flow based measures of real-time functional magnetic resonance imaging (rtfMRI) and near-infrared-spectroscopy (NIRS)-based neurofeedback training. As these approaches are a topic of their own, they will not be outlined further in the thesis at hand and the reader is referred to review articles (e.g. Birbaumer, Murguialday, Weber, & Montoya, 2009; Caria, Sitaram, & Birbaumer, 2011; Sitaram, Caria, & Birbaumer, 2009).

1.2.2 Rationales for neurofeedback

Neurofeedback trainings can be applied based on the rationale of targeting deviant brain activity or based on the rationale of peak performance training. These different rationales will be described in the following.

1.2.2.1 Rationale: Targeting of deviant brain activity

One rationale is to apply NF in order to target deviant brain activity patterns. Such deviations can be observed in statistical analysis comparing the EEG and/or ERP parameters of a specific patient group to a control group. Based on such findings, specific NF training protocols were developed aimed at training this deviant brain activity in a desired direction. This kind of training is related to the assumption that the symptomatology of a patient will thereby be improved.

In order to make this rationale clearer, NF in children with attention deficit/hyperactivity disorder will be provided as an example. ADHD can be described as a symptomatology of inattention, impulsiveness and hyperactivity which is developmentally inappropriate (Biederman & Faraone, 2005). Among others, the comparison of resting EEG activity of children with ADHD and typically developing children has revealed increased theta activity as well as reduced alpha and beta activity in children with ADHD (for a review, see Barry, Clarke, & Johnstone, 2003; for a brief summary, see Gevensleben, Holl, Albrecht, Vogel, et al., 2009). E.g. theta/beta NF training is applied as a neurofeeback protocol in children with ADHD with the aim of targeting this deviant EEG activity and thereby improving the ADHD symptomatology. However, these deviations in EEG activity in ADHD could not be replicated by the working group around Professor Brandeis in Zürich (Liechti, Drechsler, et al., 2010). In addition, Lansbergen and colleagues (Lansbergen, Arns, van Dongen-Boomsma, Spronk, & Buitelaar, 2011) pointed out that group differences in theta/beta ratio observed in children with ADHD vs. controls no longer remained significant when analysis was based on individualized frequency bands. Thus, so far findings remain contradictory (Gevensleben, Holl, Albrecht, Vogel, et al., 2009) which may also be related to different assessment as well as analysis methods used. Nevertheless, due to the peak performance concept as the other rationale behind NF, the application of theta/beta training in ADHD is still reasonable (see 1.2.2.2 Rationale: Peak performance training).

Another approach revolving around deviations in the EEG is to compare the specific EEG parameters of a person to an EEG normative database and train these parameters towards normal (Lansbergen, van Dongen-Boomsma, Buitelaar, & Slaats-Willemse, 2011), a method which is currently also performed as a z-scores training (e.g. Hammer, Colbert, Brown, & Ilioi, 2011). However, these databases are controversial, and NF based on these databases is a topic of its own and hence beyond the scope of this thesis.

1.2.2.2 Rationale: Peak performance training

The other rationale behind NF is independent of any deviations in the EEG or rather any neurophysiological dysfunction. It is based on the concept of peak performance training which has as a goal the enhancement of a specific cognitive or attentional state in order to improve performance in a certain situation. Based on this NF rationale, e.g. theta/beta training in ADHD aims at improving self-regulation abilities related to achieving and maintaining a state of sustained attention and applying it to relevant real life situations. I.e. the application of theta/beta training in ADHD is seen as useful irrespective of any possible underlying deviations in the EEG. Learning to increase beta and decrease theta activity is related to attaining a state of sustained attention which is a useful ability to learn for children with ADHD that have difficulties in staying focused. This rationale of peak performance training, i.e. learning to enhance a desired mental state, is also the basis for NF training in adults as applied in the present thesis.

1.2.3 Neurofeedback protocols

Neurofeedback protocols were developed to address neurophysiological dysfunction observed in certain patient groups (e.g. ADHD) as well as to train specific states of mind based on the concept of peak performance training (e.g. relaxation, attention). For this reason, NF protocols differ in the electrode positions used to measure brain electrical activity as well as in the EEG pattern used as feedback parameter.

Principally, two basic kinds of NF protocol types can be distinguished: the so-called frequency band training in which a decrease or increase in the amplitudes of a specific frequency band of the EEG is trained, and the so-called training of slow cortical potentials which is related to the level of excitability of the underlying cortical areas (Birbaumer, 1999; Heinrich et al., 2007).

In addition, an adaptive NF protocol will be described in a separate section below – although strictly speaking, this protocol also belongs to the category of frequency band training – as it differs from the above described protocols in various ways.

1.2.3.1 Frequency band training with a focus on theta/beta training

The principle of NF was observed by Sterman, Wyrwicka and Roth (1969, as cited in Sterman & Egner, 2006) who used an operant conditioning paradigm to train the sensorimotor rhythm (SMR, 12-14Hz) in cats in the context of sleep research. This study demonstrated that the self-regulation of a distinct EEG frequency band could be learned, and training to increase SMR became the first NF protocol. Furthermore, Sterman and colleagues observed that SMR training increased the epileptic seizure threshold in these trained cats compared to non-trained ones and thereby demonstrated that the self-regulation of a specific frequency band of the EEG had an impact on behavior. Further studies demonstrated that both the self-regulation ability of the SMR and its impact on decreasing epileptic seizure incidence could also be observed in humans (for a review see Sterman & Egner, 2006).

Subsequently, a variety of frequency band-based NF training protocols were developed (e.g. alpha/theta training, theta/beta training) targeting different states of mind (e.g. relaxation, sustained attention). They differ in the frequency bands trained (e.g. alpha/theta, theta/beta) as well as in the electrode positions at which brain activity is recorded (e.g. Pz for alpha/theta training, Cz for theta/beta training, with one mastoid as reference).

For example, theta/beta training addresses the tonic regulation of cortical arousal and aims at training a state of sustained attention in which the subject remains alert and focused for a certain period of time. This can be achieved by subjects learning to decrease their theta (4-8 Hz) activity and at the same time increase their beta (13-20 Hz) activity (Gevensleben, Holl, Albrecht, Vogel, et al., 2009).

1.2.3.2 Training of slow cortical potentials (SCP training)

Slow cortical potentials originate in the apical dendritic layers of the neocortex and last from several hundred milliseconds to several seconds (Birbaumer et al., 1990; Heinrich et al., 2007). SCPs reflect levels of cortical excitability and are recorded as surface-positive and surface-negative potentials. Positive potentials are related to reduced excitability of underlying cortical networks and thereby involved in behavioral inhibition. In contrast, negative potentials correspond to excitation of these networks and are related among others to cognitive and behavioral preparatory processes.

SCP neurofeedback training addresses the phasic regulation of cortical excitability. During SCP training both negativity (increased surface-negative potentials) and positivity (increased surface-positive potentials) trials are trained. The aim is to gain self-control over these SCPs recorded over sensorimotor cortex at electrode position Cz (mostly relative to a mastoid reference) and to transfer these self-regulation abilities to relevant daily life situations. Studies have shown that the self-regulation of these potentials can be learned (Rockstroh et al., 1990).

As SCP training aims at learning the self-regulation of cortical excitability, its application might be conceivable in patients with neuropsychiatric disorders related to deficits in cortical self-regulation. One of the first applications of this protocol was in patients with epilepsy, with the aim of increasing the seizure threshold by means of training positive potential shifts that are related to lower cortical excitability (Kotchoubey et al., 1999; Rockstroh et al., 1993).

SCP neurofeedback training has also become an important protocol in the treatment of ADHD (see 1.3.1.2. Clinical studies: NF in children with ADHD). ADHD is characterized by reduced self-regulation abilities which are thought to be related to suboptimal energetic state regulation (Sergeant, 2000, 2005) as well as to deficits in behavioral inhibition (Barkley, 1997). These deficits in turn are assumed to be linked to deficits in attentional abilities as well as to developmentally inappropriate levels of hyperactivity and impulsivity observed in children with ADHD. SCP training in children with ADHD aims at increasing their self-regulation abilities (Heinrich, Gevensleben, Freisleder, Moll, & Rothenberger, 2004; Rockstroh et al., 1993).

1.2.3.3 Adaptive neurofeedback training

The adaptive NF training[1] in fact belongs to the category of frequency band training (see 1.2.3.1 Frequency band training with a focus on theta/beta training), as also in this training protocol, feedback is given based on specific frequency bands. One main characteristic of the adaptive NF training is that training is based on bipolar electrode placements – which is also the case with some frequency band training protocols – with the aim of increasing inter- or intra-hemispheric difference within a reward frequency band, thereby mainly targeting phase differences[2]. The main difference to “classical” frequency band training protocols is that instead of training a fixed frequency band, the frequency band trained is tailored to the client on the basis of symptom response (Othmer & Othmer, 2009). Furthermore, the training is not based on predefined electrode positions from which the feedback signal is derived, but rather, training sites are chosen and changed in the course of the training based on the symptomatology to be targeted.

This kind of adaptive NF training was developed by Siegfried and Susan Othmer (Othmer & Othmer, 2007; Patrick & Friel, 2007), who founded the EEG Institute where they provide clinical NF training. Their type of NF training is applied more and more in psychological practices all over the world as a treatment for a wide range of psychiatric, neurologic and psychosomatic disorders, and is receiving appreciation within the field of clinical NF practitioners. However, scientifically, this type of NF protocol is not well established (see 1.3.1.3 Clinical studies: adaptive neurofeedback training).

Othmer and Othmer’s rationale for applying NF in patients with various psychopathologies is based on viewing these disorders as failures of brain internal

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[1] Adaptive neurofeedback training is the name chosen to refer to this type of training protocol.

[2] “In EEG training with a bipolar montage, the net reward signal is a strong function of the relative phase.” Othmer, S., Neuromodulation Technologies: An Attempt at Classification (p. 10). Retrieved August 5, 2011, from http://www.eeginfo.com/research/researchpapers/Neuromodulation_Technologies.pdf

communication based on a model of thalamocortical dysrhythmias (McCormick, 1999). Based on such a disregulation model, failures of self-regulatory mechanisms of the brain are seen as either setpoint errors or instabilities (Othmer, Othmer, & Kaiser, 1999a; Othmer, Othmer, & Othmer, 1998). NF appeals to the self-regulatory abilities of the brain – which is viewed as a self-organizing nonlinear dynamical system – in the continuum between activation and relaxation of the regulatory networks of the brain. By this means, NF targets arousal mechanisms, attentional networks and further cognitive functions as well as the regulation of mood and sensitivity/reactivity to the sensory world (Othmer, Othmer, & Kaiser, 1999b). These effects are achieved via operant conditioning (Othmer, 2001) by rewarding the brain for changes in the direction of the improved performance. In this kind of NF training, no cognitive strategies are involved, as training aims at changing the brain state towards a more stable and desirable state and relies on the self-regulatory abilities of the brain to maintain this state in daily life situations. The main idea behind this training is to approach these disregulations by re-establishing self-regulation (Othmer, 2001) which is achieved through an individualized and adaptive NF training as described above.

1.2.3.4 Control of artifacts

For the technical realization of all NF protocols, the control of artifacts that superpose EEG measurements is of vital importance (Heinrich et al., 2007). The main sources of artifacts are eye and head movements as well as muscular activity, especially of facial muscles. To ensure that brain and not muscle activity is trained, artifacts have to be recognized and ideally corrected online.

For this purpose, some NF protocols use two additional electrodes placed above and below one eye for the recording of eye movements (electrooculogram: EOG) as well as for the online correction of eye movement artifacts. Further artifacts are registered by means of preset artifact thresholds; if the signals recorded exceed this threshold, continuous feedback is interrupted for a moment to prevent the subjects from using muscle activity to mimic self-regulation abilities.

In addition, implementing NF with a two-screen setting is recommended to allow the trainer to monitor the time course of the EEG signals (and EOG signals if recorded) and provide feedback to the subject if artifacts occur that are not detected by the NF software. SCP training is especially susceptible for artifacts (Birbaumer et al., 1990; Heinrich et al., 2007), as a very low high pass filter (≤ 0.01 Hz) is required for recording, which also allows artifacts that especially affect this low frequency range to be recorded. Good NF equipment as well as good knowledge about artifacts are a prerequisite for realizing a high quality NF training.

1.3 Neurofeedback: applications and scientific evidence

At present, NF is applied both in a variety of clinical fields and for peak performance training in healthy subjects.

1.3.1 Clinical studies of neurofeedback

1.3.1.1 Clinical studies: an overview

Epilepsy and ADHD (in children) are the two clinical applications of NF that are scientifically best established. For both disorders, treatment outcome has been examined in a variety of studies which have shown positive effects of different NF protocols (ADHD in children: e.g. Drechsler et al., 2007; Gevensleben, Holl, Albrecht, Vogel, et al., 2009; Leins et al., 2007; Monastra, Monastra, & George, 2002; Strehl, Leins, & Heinrich, 2011; epilepsy: e.g. Strehl, Kotchoubey, & Birbaumer, 2011; Tan et al., 2009).

Different NF protocols have also been applied in a variety of other psychiatric, psychosomatic or neurological disorders (for a comprehensive list of studies please refer to Hammond's Comprehensive Neurofeedback Bibliography) like for example: insomnia (e.g. Cortoos, De Valck, Arns, Breteler, & Cluydts, 2010), depression (e.g. Choi et al., 2011), learning disabilities, anxiety, tinnitus (e.g. Crocetti, Forti, & Del Bo, 2011; Dohrmann, Weisz, Schlee, Hartmann, & Elbert, 2007), alcohol or drug abuse, schizophrenia, obsessive-compulsive disorder, tourette’s syndrome, autism (for a review see Holtmann et al., 2011). However, for most of these applications, only few and partly also methodologically limited studies have examined effects of NF.

1.3.1.2 Clinical studies: NF in children with ADHD

As the present thesis is strongly motivated by the application of NF in children with ADHD, an overview over studies will be given with a focus on those studies employing the same or similar NF protocols as those applied in the thesis (theta/beta training and SCP training). Reasons for research on NF in ADHD are the following (see Gevensleben, Holl, Albrecht, Vogel, et al., 2009; Nash, 2000). With a prevalence of about 5% (Polanczyk, de Lima, Horta, Biederman, & Rohde, 2007; for an overview see

Steinhausen, 2009), ADHD is one of the most frequent psychiatric disorders in children and adolescents. Up to now, medication is the most common and most effective treatment (Banaschewski & Rothenberger, 2009). However, due to side-effects, non-responders, and parents disapproving of medicinal treatments for their children, this is not always the best treatment option. Moreover, in responders as well as for other treatments like behavior therapy, improvements could go further and beyond the core ADHD symptomatology in addition to targeting long-term effects. Neurofeedback studies aim at filling this gap by providing a potentially additional module to a multi-model treatment for ADHD as recommended by the European guidelines.

Based on the two rationales for NF (see 1.2.2 Rationales for neurofeedback), a variety of NF studies have been conducted in the field of ADHD. A comprehensive review of research on NF including NF in children with ADHD (until 2007) is provided by Heinrich et al. (2007). Recently, a German review article was published (Drechsler, 2011), outlining the current state of research related to the question of how efficacious NF is as a treatment for children with ADHD.

As outlined by Heinrich et al. (2007), the application of NF in children with ADHD is not a new idea. The first study reporting on a frequency-band NF training in children with ADHD was published in 1976 by Lubar and Shouse. Since then, a variety of studies have provided evidence for positive effects of frequency band as well as SCP NF training in children with ADHD regarding clinical symptomatology as well as cognitive performance (Drechsler et al., 2007; Fuchs, Birbaumer, Lutzenberger, Gruzelier, & Kaiser, 2003; Heinrich et al., 2004; Monastra et al., 2002; Strehl et al., 2006). However, some methodological limitations have to be considered when interpreting the reported effects: e.g. mostly small sample sizes; missing control group or control group that does not control for unspecific training effects (waiting list control group, medication); no randomized group assignment; mix-up of multiple interventions which does not allow to disentangle effects of NF from effects of other interventions; no evaluation of long-term effects; and no comprehensive analysis of the neurophysiological effects underlying NF.

In more recent years, several studies have addressed these limitations more comprehensively than previous ones (e.g. Doehnert, Brandeis, Straub, Steinhausen, & Drechsler, 2008; Drechsler et al., 2007; Gevensleben, Holl, et al., 2010; Gevensleben, Holl, Albrecht, Schlamp, et al., 2009; Gevensleben, Holl, Albrecht, Vogel, et al., 2009; Gevensleben, Moll, & Heinrich, 2010; Wangler et al., 2011).

A meta-analysis on the efficacy of NF in children with ADHD was conducted by Arns and colleagues (Arns, de Ridder, Strehl, Breteler, & Coenen, 2009). The authors concluded that NF training was efficacious and specific and reported large effect sizes for inattention and impulsivity and medium effect sizes for hyperactivity. However, as noted by Gevensleben and colleagues (Gevensleben, Moll, et. al., 2010), this promising conclusion has to be considered with some care due to methodological limitations of the studies included in the meta-analysis, as mentioned above.

Further studies targeting improved methodological design are still ongoing. For example, the working group around Professor Brandeis in Zürich is studying effects of surface theta/beta and SCP training, low resolution brain electromagnetic tomography (LORETA) based NF training, and electromyogram (EMG) biofeedback training in children with ADHD (Drechsler, 2009; Liechti, Maurizio, et al., 2010). In Germany, a large multi-center study (Holtmann, 2009) aiming at including about 150 patients is comparing SCP training to EMG biofeedback training in children with ADHD in combination with analyzing medication washout and the stability of effects at six months follow-up.

Drechsler (2011) concluded in her review of the application of NF training in children with ADHD[3]: Neurofeedback training is effective in the treatment of clinical symptoms of ADHD and can result in specific changes in some participants. However, if and to which degree learned cortical regulation causally influences clinical improvements remains to be shown by future studies.

The findings of a selection of these studies on NF in children with ADHD that have analyzed regulation skills or neurophysiological parameters related to NF training will be described in more detail in chapter 1.4.1 (Neuronal mechanisms underlying neurofeedback in ADHD).

1.3.1.3 Clinical studies: adaptive neurofeedback training

Since another focus of the present thesis is to analyze the effects of adaptive NF training, an overview of studies applying this paradigm in various clinical contexts will

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[3] The following two sentences are citations from Drechsler (2011) which I translated as accurately as possible from German into English.

be provided. The adaptive NF training has been developed by Siegfried and Susan Othmer and has been applied by them in a variety of clinical fields.

When Othmer and Othmer started out with NF, they applied ‘classical’ frequency band training protocols, like SMR and beta training. Their application of NF focused on the field of attention, learning and behavioral problems in children. Over the years, Othmer and Othmer moved towards more individualized NF protocols and extended their application of NF to a variety of clinical fields.

Lubar (1991) observed that in hyperkinetic children SMR training (with theta inhibition) led to a reduction of hyperactive symptoms, while beta training (with theta inhibition) was able to reduce inattention. This observation of distinct effects of training specific frequency bands formed a basis for the development of more individualized NF protocols.

Othmer and Othmer also applied SMR (12-15 Hz) and beta (15-18 Hz) training and individualized the training protocol by changing the training site to C3, Cz, or C4 based on the symptomatology. The idea of combining SMR and beta enhancement training with inhibit bands was adopted from Lubar (1991). Othmer and Othmer first used protocols in which they inhibited excessive amplitudes in the 4-7 Hz and 22-30 Hz, which they later expanded to include two wideband inhibits ranging across the whole EEG spectrum (while in more recent years multiple inhibits are used instead).

The above described protocol was applied in 15 children with attentional deficits and learning disabilities, and significant improvements in cognitive skills, academic performance, and behavior were reported in combination with improvements in IQ (Othmer, Othmer, & Marks, 1992). An analysis of the clinical application of 20 sessions of the described protocol in patients with ADHD and ADHD-type symptoms ($n = 239$) revealed improved inattention scores, impulsivity scores as well as a reduced variability of response time as measured by the TOVA, the test of variables of attention (Othmer, Kaiser, & Othmer, 1995).

The efficacy of NF training in ADHD is in their view related to the remediation of the disregulation of arousal manifested variously in inattention or behavioral disinhibition (Othmer et al., 1995). In a larger clinical sample of 1089 patients, improvements in one or more of these measures were observed in 85% of those patients with moderate pre-training deficits, and it was concluded that NF can effectively improve attentional dysfunction (Kaiser & Othmer, 2000). However, the interpretation of these findings is limited due to methodological shortcomings such as a missing control group and the heterogeneity of the sample.

In the following years, the Othmers' training protocols evolved (Othmer, 2005, 2007, 2008; Othmer, Othmer, & Putman, 2008; Legarda, McMahon, Othmer, & Othmer, 2011) towards bipolar training at various sites and more and more individual protocols, in which the reward frequency band was adapted throughout a training session based on the unique experience of the patient trained. These adaptive types of training protocols with a wide range of optimal reward frequencies were applied especially at T3-T4, Fp1-Fp2, F3-F4, C3-C4, and P3-P4 in a wide variety of patients (Putman, Othmer, Othmer, & Pollock, 2005). TOVA results of 44 patients showed a clear trend of improvement on the impulsivity, inattention, and variability of responding scales after NF training, indicating that this type of training protocol had positive effects on attentional regulation.

Othmer, Othmer, and Putman (2005) compared the efficacy of their earlier training protocols in which they used lateralized training optimized to each hemisphere to their newer approach of bipolar inter-hemispheric training on homologous sites ($n > 100$). The main bipolar training sites comprised T3-T4, Fp1-Fp2, and P3-P4. Based on the clinical response, the reward band was adjusted individually and broad band inhibits were used. Success rates in achieving a normalization of TOVA scores had improved for the new types of training protocols even though patients with more severe deficits like autism were treated with the newer protocols. However, this conclusion has to be considered with some care, as TOVA measures might be sensible for evaluating improvements in children with ADHD (which was the main patient group for NF applications with earlier training protocols), as here attentional problems were the focus of the treatment. For the patient group with a broader spectrum of deficits for which the newer protocols were used, improvements in TOVA scores might also be related to practice effects while not displaying the effectiveness of the training related to the core symptomatology.

The adaptive NF training has been applied to a broad range of neurologic and psychiatric conditions while only few and merely case studies reported on the training effects, which will be described below.

The adaptive NF training was applied in a case study by Jacobs (2005) who treated two boys with learning, attention, mood, social, and developmental deficits. The training was conducted for six months in semi-weekly 20-minute training sessions and comprised individualized protocols that were adapted individually based on the symptomatology. Bipolar training sites for one or both boys included among others T3-T4, Fp1-Fp2, C3-C4, and P3-P4 (sites that were also targeted by the adaptive training in the present thesis). Bipolar temporal lobe training was used with the aim of improving emotional stability; prefrontal lobe training was included to improve inhibition and executive functions; and parietal training was implemented for physical calming and sleep regulation. According to a parent rating scale on which target problems were monitored over the course of the trainings, each boy improved in all tracked symptoms. Improvements in e.g. control of emotions and behavior, social interactions, and performance at school were observed.

There are two reports on the application of adaptive NF training in treating pain. In a case study by Sime (2004), a patient with trigeminal neuralgia experiencing episodes of extreme facial pain received 29 sessions of adaptive NF training within a multimodal treatment setting. The author concluded that the T3-T4 placement seemed to be most effective for tackling pain. After nine months of treatment, the patient experienced a substantial reduction in pain and was able to avoided surgery of the trigeminal nerve.

A study by Jensen and colleagues (Jensen et al., 2007) included 18 patients with complex regional pain syndrome taking part in a multidisciplinary treatment. They rated pain intensity before and after a single 30 minute session of NF at T3-T4. A significant reduction in pain was observed after NF, indicating that NF can induce short-term reductions in patients' experience of pain. In addition, a single patient with multiple sclerosis received several sessions of NF at T3-T4, P3-P4, and Cz-Fz and reported prolonging times of pain reduction after NF sessions with progressing treatment (Jensen et al., 2006).

In a stroke patient participating in a multimodal treatment, specific improvements were reported to be related to specific adaptive NF training sites, e.g. intrahemispheric training on the sensorimotor strip on the right side was related to relaxing overtensed body parts of the left side, and frontal/prefrontal training increased motivation (Klein, 2006). In addition, cognitive methods to anchor these experiences during training were indicated to be important.

These described reports sound promising, however neither of them allows for the effects of adaptive NF training protocols to be discerned. From a therapeutical perspective, a multimodal treatment is desirable. But especially for single case reports, multimodal treatments do not allow to draw conclusions on the effectiveness of the NF treatment, as the other interventions and/or the patient-trainer interaction possibly combined with therapeutic interventions might as well account for the positive effects observed.

A further development in the Othmers’ training protocols was that they moved reward frequencies down to what they call “infra-low frequencies” of below 1 Hz (Othmer, 2011). However, from a technical perspective, especially the question of whether an appropriate artifact control was implemented to guarantee good signal quality remains to be discussed, which is why this issue will not be addressed further here.

All in all, the above-described findings regarding adaptive NF training are not very convincing from a scientific perspective. Studies with a control group in order to control for unspecific training effects as well as with larger samples of patients with a specific type of psychiatric disorder are needed to evaluate the efficacy of this approach. In addition, pure effects of adaptive NF training without being embedded in a multimodal treatment setting are needed to discern any specific effects of this intervention.

1.3.2 Peak performance studies of neurofeedback

So far, NF as peak performance training in healthy adults has mainly been applied for improving cognitive abilities as well as in the field of arts. Only few studies have reported on the effects of NF on mood / well-being or in sports.

Vernon (2005) provides an overview of studies until 2005, evaluating NF protocols in peak performance applications as well as some background on the underlying rationales – associations of specific EEG measures with expert performance. Vernon (2005) concluded his review stating that “the findings […] are suggestive, a clear connection between NF training and enhanced performance has yet to be established” (p. 362).

A much less critical overview of NF applications for optimizing performance was provided by Gruzelier, Egner and Vernon (2006) who report mainly on their own research. The authors concluded that "with SMR, beta1 and alpha/theta training protocols, the principle strategy was accomplished of revealing a possible causal link between NF training and dependent measure changes" (Gruzelier et al., 2006, p. 428). The working group around Professor Gruzelier in London has conducted a variety of NF studies in healthy adults. Earlier studies aimed mainly at differentiating the effects of different NF protocols on improving cognitive abilities. Within the last years, the focus of such studies has shifted more towards examining the effects of NF on arts performance, with a focus on alpha/theta training (for a review on alpha/theta NF, see Gruzelier, 2009).

In addition, in the review on the clinical applications of NF training by Heinrich et al. (2007), a good overview of NF studies in the field of peak performance training until 2007 is included. The authors conclude that despite small sample sizes, these peak performance studies were able to show specific effects for distinct NF protocols at the cognitive and neurophysiological level.

In the following, a comprehensive overview of NF studies addressing peak performance training will be provided for the fields of cognitive abilities, arts, mood / well-being, and sports.

1.3.2.1 Peak performance and cognitive abilities

In a study by Vernon et al. (2003), healthy individuals ($n = 30$) either participated in eight sessions of a theta enhancement training (while inhibiting delta and alpha activity), in eight sessions of an SMR enhancement training (while inhibiting theta and beta activity), or were part of a non-NF control group. Only the SMR group learned the desired neuroregulation and in addition showed improved performance in a semantic working memory task as well as to some extent improved accuracy of focused attentional processing in a continuous performance task. However, the latter result was only revealed by planned comparisons and not by a significant TIME x GROUP interaction and was also not observed in a more difficult version of the same task. Vernon (2005) argued that for the interpretation of these results, it has to be taken into account that the described changes in SMR activity were only observed during training sessions but not across training sessions. They therefore represent short-term changes of SMR activity rather than permanent effects.

Egner and Gruzelier (2004) compared the effects of SMR neurofeedback (12-15 Hz), beta neurofeedback (15-18 Hz), and Alexander technique training in students (*n* = 25) with respect to performance on tests of sustained attention as well as target P3 amplitudes in an oddball task. While no changes were observed in the control group, protocol-specific effects were evident for the two NF groups. SMR training was related to increased perceptual sensitivity, reduced omission errors and reduced reaction time variability in a sustained attention task which may be interpreted as an attention-enhancing effect. Faster reaction times in a sustained attention task and increased target P3 amplitudes in an oddball task were associated with beta training, which may be linked to increased arousal. However, these faster reaction times came along with a slight but non-significant increase in commission errors and might therefore be interpreted as a speed-accuracy trade-off (Vernon, 2005). In addition, effects were not as robust as suggested by the abstract of the paper: reported group-specific performance effects were in most cases not revealed by a respective group interaction factor of the ANOVA and the described group-specific performance patterns were not observed in a similar way in both sustained attention tasks, which is not mentioned in the abstract.

Ros et al. (2009) allocated 20 trainee microsurgeons to an SMR-theta or an alpha-theta training group which both received eight 30-minute sessions of NF. A subset of each group participated in a waiting-list control group (*n* = 8) beforehand. SMR-theta training was significantly related to improved surgical technique, reduced time on task and decreased everyday anxiety, while these advantages were not observed in the control group. The decrease in surgical task time was associated with desired EEG changes observed during SMR training. For the alpha-theta training group, only marginal improvements in technique and overall performance time were observed while successful theta-alpha ratio increases were positively correlated with improvements in overall technique. Ros et al. (2009) concluded that these findings provide encouraging evidence of optimized learning of complex surgical tasks via NF. However, limitations in this study were the suboptimal design of the control group, the small group sizes and the missing significant interaction effects related to training group as well as the initial preferential performance in the alpha-theta and control groups.

In summary, these studies provided some evidence for specific effects of beta and especially of SMR training on cognitive performance in healthy adults.

Moreover, besides the studies performed by Professor Gruzelier and colleagues, there are some other studies which have employed different NF protocols (theta/beta, SMR, individual upper alpha power, gamma band neurofeedback) and examined their effects on cognitive performance.

Doppelmayr and Weber (2011) included a theta/beta (theta: 4.5 – 7.5 Hz, beta: 17-21 Hz, *n* = 14) and an SMR (12-15 Hz, *n* = 13) neurofeedback training[4] and a control group (*n* = 14), which received a NF training based on changing frequency bands, in their study in healthy adults in order to examine effects on reaction times, spatial abilities and creativity. Only the SMR group learned to modulate their EEG activity in the trained frequency band. Also regarding reaction times and spatial rotation abilities, improvements were only observed for the SMR compared to both other groups. No effects of the NF training were observed on creativity or performance in further attention-related tasks. Overall, the study has implemented an interesting new control training condition. Regarding the question as to why theta/beta regulation was not learned, the authors provided a long discussion but nevertheless the question remained to a certain extent unresolved. However, their findings regarding advantages for the SMR group were in line with the results presented in the previous section.

In a study by Hanslmayr and colleagues (Hanslmayr, Sauseng, Doppelmayr, Schabus, & Klimesch, 2005) NF training consisted of a single session of individual upper alpha power training with the aim of increasing alpha power and a single session of theta training aiming at decreasing theta power (*n* = 18, crossover design, balanced order). Subjects who were better able to increase their upper alpha power showed larger improvements in cognitive performance in a mental rotation task. In contrast, theta training neither had an effect on the EEG pattern nor on task performance. However, this study employing a single session of NF training per protocol was only able to measure short-term effects directly after a training session.

A training of individual upper alpha frequency in five sessions was examined in another study (Zoefel, Huster, & Herrmann, 2011). Cognitive control in a mental rotation task was observed to be enhanced and associated with increased upper alpha amplitude, which was only observed in the NF group (*n* = 14) and not in the non-

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[4] EEG activity was recorded from C3 and C4 referenced to the left earlobe and average peak-to-peak amplitudes of both electrodes in the trained frequency band were used as feedback signal in all groups.

training control group (*n* = 10). The authors acknowledged that using a different kind of training would have been a better control than a non-training control group.

Keizer, Verment, and Hommel (2010) evaluated the effects of local gamma band (*n* = 8) and beta band (*n* = 9) NF training on episodic memory. While gamma training improved recollection, beta training improved familiarity memory which may be a hint for specific effects. Yet, the missing control group and especially the missing discussion on the realization of an artifact-free gamma NF training, which is technically challenging, represent limitations in this study.

Overall, upper alpha training was observed to have positive effects on performance in a mental rotation task, differential effects of beta and gamma NF on memory were reported, and further evidence for positive effects of SMR training were provided. These studies further outline the wide variety of possible NF protocols and NF applications. More studies employing better controlled designs are needed in order to delineate the specific effects of particular NF protocols.

1.3.2.2 Peak performance and arts

Music performance in conservatoire musicians (*n* = 36) was observed to be marginally improved after a NF training that consisted of an SMR, beta1 and alpha/theta training but not in a training including additional interventions or in a non-training control group (Egner & Gruzelier, 2003). In addition, only regulation ability of alpha/theta was related to performance improvements. However, the authors of that study did not discuss why the group receiving the same NF training in combination with further training methods did not show improved performance. In addition, the association between regulation ability in alpha/theta and performance might also be related to alpha/theta training always being conducted in the second training block. Subjects were already familiar with the NF methods and might have succeeded better in learning alpha/theta training, but as regulation data were not presented in the paper this cannot be judged.

However, in a second experiment (*n* = 61) in which all training types were performed in independent groups (alpha/theta, SMR, beta1, physical exercise, mental skills, Alexander technique), performance improvements were only observed in the alpha/theta training group (Egner & Gruzelier, 2003). The critical points of this experiment were that no comprehensive statistical data were presented in the paper and regarding the alpha/theta group, regulation abilities were not reported as in the first experiment.

In an additional study (Gruzelier, 2009; Leach, Holmes, Hirst, & Gruzelier, 2008), musical performance improved after alpha/theta training but not after SMR training compared to a non-training control group in instrumental solos and novice singing in music students (*n* = 24).

Overall, these studies indicated that especially alpha/theta training seems to exert a positive influence on musical performance. Further research is needed to further delineate the specificity as well as the underlying mechanism mediating these effects.

Besides musical performance, the effects of NF trainings were also studied related to dance performance.

In ballroom and Latin dancers, for a group practicing theta/beta neurofeedback as well as for a group practicing heart rate variability biofeedback, advanced dance performance was observed for “overall execution” compared to a non-training control group (Raymond, Sajid, Parkinson, & Gruzelier, 2005). In addition, differential effects were present: theta/beta training improved timing, while heart rate variability biofeedback improved technique, both compared to the control group. Yet the subjects did not all have the same number of training sessions and subjects training longer were not equally distributed across groups. To control for the different number of training sessions, an improvement per practice session score was used for the analysis but is not clear in how far this controls for the additional sessions. Furthermore, regulation abilities were not reported and correlated with performance measures as in other studies of this working group. A further limitation is that the control group practiced dancing on their own so that the contact of the therapist with the biofeedback groups was not controlled for.

In a further study (Thompson, Steffert, Redding, & Gruzelier, 2008), the effects on creative dance performance of alpha/theta neurofeedback, heart-rate coherence training, and dance movement focus training were compared to a no-training control group (*n* = 45). Preliminary results revealed the following. Alpha/theta training was associated with improved creativity measures but not with improved creative dance performance. Hear-rate variability training lead to reduced anxiety, but no improved dance performance was observed for this group compared to the controls. No significant improvements were present in the dance movement focus group.

These two studies indicated that it may be worth to further examine the effects of different NF protocols on dance performance, yet to this date the advantages of NF are less visible compared to e.g. musical performance.

Future studies in the field of NF applications in arts should focus on providing a larger number of NF sessions per protocol, increase the duration of NF sessions and include larger group sizes to allow for a proper statistical analysis. Especially the association of self-regulation abilities and performance changes as reported for some studies may provide further information on the specificity of the effects.

1.3.2.3 Peak performance and mood / well-being

So far, only few studies have evaluated the effects of NF training on mood in non-clinical subjects[5].

Raymond and colleagues (Raymond, Varney, Parkinson, & Gruzelier, 2005) assigned 12 adults with high withdrawal scores to nine sessions of either an alpha/theta training or a mock feedback group. While no changes in personality were observed in both groups, improvements in mood were associated with alpha/theta NF training.

Boyton (2001; also see Vernon, 2005) used alpha/theta neurofeedback (*n* = 30) with the aim of enhancing creativity and well-being in comparison to a control training (*n* = 32). Well-being increased in both training groups while no differences in creativity and well-being were observed between groups. The fact that these training programs included several different training components was addressed as a limitation of this study, as effects of the different components could not be disentangled (see also Vernon, 2005).

Allen and colleagues (Allen, Harmon-Jones, & Cavender, 2001) examined the effects of five sessions of frontal alpha asymmetry training in women on self-reported emotional affect and facial muscle activity while watching film clips. They observed that training of increasing right relative to left frontal alpha activity compared to training in the opposite direction had effects on self-reported affect when seeing a happy

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[5] For an introduction to the application of neurofeedback training for altering mood also related to clinical applications, refer to Vernon and Gruzelier (2008).

but not when seeing a sad film. This effect was related to decreased positive affect in the training group which performed the training in the opposite direction (increasing left relative to right alpha activity). I.e. these findings did not provide any evidence for positive effects on mood related to training of increasing right relative to left frontal alpha training. Furthermore, unprovoked mood which was assessed after each training session was not associated with the direction of training.

Two of the described studies provided first hints for the specific effects of distinct NF training protocols on mood. However, regarding the question in how far NF training can lead to an increase in positive mood, positive affect and well-being, further research is needed which specifically targets this question in healthy subjects.

1.3.2.4 Peak performance and sports

For a review on distinct EEG patterns related to sporting expertise in relation to applications of NF training in sports, the reader is referred to the reviews by Vernon (2005) as well as by Thompson and colleagues (Thompson, Steffert, Ros, Leach, & Gruzelier, 2008). To date, there are only a few studies which have applied NF training in sports.

Landers et al. (1991) examined the effects of NF (at T3, T4) on archery performance in 24 experienced archers. Subjects who received feedback related to greater left hemisphere low frequency activity (correct feedback) showed improved performance after NF while subjects who were trained to produce greater low frequency activity in the right hemisphere (incorrect feedback) performed worse after NF. Control subjects who rested instead of receiving NF (no feedback) showed no change in performance. However, EEG analysis only revealed respective changes in EEG activity for the incorrect but not for the correct feedback group. Methodologically, comparing the effects of two opposite trainings on performance is a good approach, while the missing EEG changes in the correct feedback group, the small sample size and the application of only a single session of NF limit the conclusions to be drawn from this study.

In another study (Arns et al., 2008), the effects of real-time feedback of EEG parameters on golf performance were examined. Based on EEG activity at FPz related to successful and unsuccessful golf putts, individualized feedback parameters were determined for each subject (*n* = 6). Subjects showed more successful putts in the feedback compared to the no-feedback condition. This study did not apply NF in the classical sense since instead of training to achieve self-regulation abilities related to a specific EEG parameter, subjects were provided feedback on this parameter in order to perform a task (here to perform a golf putt, in the moment when their EEG activity coincidentally achieved a certain state). In addition, as the sample size was very small and no control condition was used, it cannot be differentiated whether the actual feedback parameter was related to the effects or only receiving any type of feedback. In addition, artifact control when measuring EEG activity at a prefrontal electrode site in combination with a bodily task is critical.

Although the application of NF training as peak performance in sports is a very interesting field, the present data are more than limited and it remains a task of future studies to show the effectiveness of NF application in different sports disciplines.

1.4 Neuronal mechanisms underlying neurofeedback and the specificity of training effects

Especially in recent years, studies have emerged that shed some light on the neuronal mechanisms underlying a successful NF training. Nevertheless, there remain some mysteries to be solved by further research on the neuronal mechanisms mediating effects of successful self-regulation, especially as a wide variety of NF protocols exist (see 1.2.3 Neurofeedback protocols), with a large spectrum of applications (see 1.3 Neurofeedback: applications and scientific evidence).

In the following, studies that have analyzed neuronal mechanisms in the context of NF applications in children with ADHD will be outlined first. In a next step, evidence regarding neuronal mechanisms underlying peak performance applications in various fields will be presented. As the implementation of an appropriate control condition is one important method for delineating the specificity of training effects both at the neurophysiological and the performance and behavioral level, a subchapter is introduced which elaborates this topic in some more detail.

1.4.1 Neuronal mechanisms underlying neurofeedback in ADHD

Regarding the neuronal mechanisms related to theta/beta as well as SCP neurofeedback training in children with ADHD, the evidence base is continuously growing. Interest in the neuronal mechanisms underlying these two NF protocols in children with ADHD is the main motivation for this thesis. For this reason, selected studies that have targeted the neuronal mechanisms underlying NF training in children with ADHD by e.g. analyzing regulation abilities, pre-post resting EEG or ERP measures will be presented in more detail including clinical, neuropsychological, and neurophysiological findings (if applicable) as well as limitations of these studies. Furthermore, the reader is referred to the recently published review article by Drechsler (2011) which also includes a chapter on neurophysiological mechanisms related to NF training in children with ADHD.

Heinrich and colleagues (2004) reported on the first controlled study in which both the concept of SCP training was applied in children with ADHD and its effects on ADHD symptomatology as well as neuronal mechanisms were examined.

Children with ADHD trained the regulation of their SCPs in 25 NF sessions. The training effects were examined by assessing parental trainings of the German ADHD rating scale as well as event-related potentials during a continuous performance test before and after the training in both the SCP training group (*n* = 13) and a waiting list group of children with ADHD (*n* = 9). After SCP training, a reduction of 25% in ADHD symptomatology, a decrease of impulsivity errors, and an increase in the CNV were observed, effects which were not present in the waiting list group.

This study provided evidence that SCP training in children with ADHD is related to behavioral improvements which might be mediated by improved resource allocation as indicated by a CNV increase after training.

Limitations in this study were constituted by the small sample size, the waiting list control group which does not allow to control for non-specific training effects, and by not controlling for the status of medication.

The abovementioned limitation regarding control group selection was addressed by another study (Drechsler et al., 2007) in which in children with ADHD, 15 double sessions of SCP training (*n* = 17) were compared to 15 double sessions of behavioral group therapy (*n* = 13). Parents’ and teachers’ ratings indicated larger improvements in the SCP training group especially related to attentional and cognitive abilities. Neuropsychological measures revealed similar improvements in both groups and therefore possibly rather reflected non-specific training effects in combination with practice effects. That half of the SCP group, which succeeded in learning self-regulation during transfer trials, also showed improved hyperactive/impulsive symptoms which represented a specific effect of the SCP training. However, the advantage of the SCP group in improving attentional and cognitive abilities was best accounted for by parental support and represented an unspecific training effect.

An analysis of the neurophysiological data of this study, which was published in a separate paper, provided some further evidence for specific effects related to SCP training (Doehnert et al., 2008). For children of the SCP group that had a diagnosis of ADHD combined type, a tendency towards a decreased theta/beta ratio after training was observed, while this effect was not present for the whole SCP group. In addition, some changes in resting EEG measure in the SCP group were positively correlated with behavioral improvements in the symptom domains impulsivity and hyperactivity. In contrast to results reported by Heinrich et al. (2004), a decrease in CNV amplitude was observed from pre to post training in both groups. However, this decrease was less pronounced in those children that successfully learned SCP self-regulation.

Taken together, this study provided some evidence on specific effects of SCP neurofeedback training. In addition, it showed that parental support plays a crucial role in the transfer to daily life situations and related behavioral improvements. That only one half of the children in the SCP training group succeeded in learning self-regulation of SCPs points to the fact that studying how self-regulation is learned and how an optimal training setting might look like needs to be addressed in further studies.

Limitations in this study were the rather small sample size, the not fully randomized group assignment, motivational problems at post assessment, and the small responder rate in the SCP group.

A further study (Leins et al., 2007) aimed at comparing the effects of SCP and theta/beta neurofeedback training on cognitive and behavioral measures. Children with ADHD performed 30 training sessions of either SCP training (*n* =19) or theta/beta training[6] (*n* = 19). For both groups, a similar improvement in cognitive and behavioral measures was achieved, which remained stable six months after the end of the training. Both groups learned the self-regulation of respective brain activity, however due to the

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[6] The theta-/beta training in that study differed from the one applied in this thesis in the following ways: a decrease as well as an increase in theta-/beta ratio was trained; EEG activity was derived from different electrodes positions; training consisted of many short trials instead of few long trials; the baseline was adjusted from trial to trial.

difference in the variability of amplitudes between the two NF protocols, effect sizes could not be compared.

In a randomized controlled study by Bakhshayesh (2007; Bakhshayesh, Hänsch, Wyschkon, Rezai, & Esser, 2011), 35 children with ADHD performed 30 sessions of a theta/beta neurofeedback training or of an EMG-biofeedback training. Both groups learned self-regulation as shown by a reduced theta/beta ratio across sessions and reduced EMG amplitudes, respectively. At the behavioral as well as at the performance level, some advantages of the NF compared to the EMG-biofeedback group were observed. Unfortunately, even though self-regulation measures were assessed, no associations between learned self-regulation and behavioral/performance measures have been analyzed which could have shed more light on the results presented.

In a randomized controlled study by Holtmann et al. (2009), 34 children with ADHD either performed 20 sessions à 30 minutes of a theta/beta neurofeedback training or a computerized attention training as part of a two-week behavior therapeutic holiday program. Regarding behavioral improvements, no differential effects were present for the two training methods. Yet in a stop-signal task, a reduction of impulsivity errors and a normalization of frontal NoGo-N2 amplitudes were only observed in the NF group. However, limitations in this study were constituted by the small sample size, the short duration of the training sessions, no follow-up assessment, and especially by pre-training group differences related to the number of impulsivity errors and no presentation of N2 amplitude data or grand average ERPs in the paper.

A multi-center study (Gevensleben, Holl, Albrecht, Vogel, et al., 2009) set out to overcome the limitations of previous studies by including a large sample of more than 100 children with ADHD that were randomly assigned to a NF (*n* = 64) or a computerized attention skills training group (*n* = 38). The NF training (36 sessions) was a combined training consisting of a block of theta/beta and a block of SCP training. According to parent as well as teacher ratings, behavioral improvements in the NF group were superior to those of the control group. These behavioral improvements induced by NF were maintained at a 6-month follow-up (Gevensleben, Holl, et al., 2010). These results point towards NF being an efficacious treatment module for children with ADHD.

At the neurophysiological level, an analysis of resting EEG measures revealed a reduction in theta activity in the NF group (Gevensleben, Holl, Albrecht, Schlamp, et al., 2009). In addition, protocol-specific pre-post EEG changes were related to behavioral improvements: theta/beta training – decrease of posterior-midline theta activity, SCP training – increase of central-midline alpha activity. ERP measures acquired during an attention test showed an increase of CNV specific for SCP training (Wangler et al., 2011). Furthermore, a larger CNV at pre-training was associated with larger behavioral improvements after SCP training. Taken together, these findings suggest specific neuronal mechanisms related to a successful NF training.

Advantages and limitations of this comprehensive study were: The study was methodologically well designed, comprising a large sample and using a control condition that is as similar as possible to a NF training without actually using a placebo NF training[7], not mixing up multiple interventions as children participated in the trainings without receiving a medication treatment or any other form of therapeutical treatment, assessing follow-up data, and examining the underlying neuronal mechanisms. Limitations are the limited responder rate of only about 50% of the children in the NF group as well as the missing analysis of data related to the regulation abilities achieved in the two NF protocols and correlations with behavioral or neurophysiological measures. A further discussion of the results observed by this comprehensive study can be found in an editorial by Brandeis (2011) as well as in an overview article by Gevensleben et al. (Gevensleben, Moll, et. al., 2010).

In a recent study (Bakhtadze, Janelidze, & Khachapuridze, 2011), 93 children with ADHD either performed a NF training (15 sessions of SMR/theta training followed by 15 sessions of beta/theta training) or were part of a non-treatment control group. The authors reported an increased P3 amplitude and reduced P3 latency after NF training in children with ADHD.

However, despite the impressingly large sample size, the results of this study have to be considered with caution for the following reasons: a non-treatment control group is not a good choice to control for unspecific effects; the training procedures were not

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[7] A placebo training was not used in this study due to ethical considerations related to withholding a treatment from children. Instead, in a next step, a study was designed comparing an SCP training in healthy adults to a placebo SCP training. This study was conducted in Göttingen, one of the sites of this multi-center study. Please refer to chapter 1.4.3 (Specificity of training effects and the design of a control training) for the presentation of some preliminary first results.

precisely documented in the paper; no eye movement artifacts control was implemented in the NF protocol which also questions training quality; pre-post changes in the EEG parameters trained were not reported; artifact correction procedures for ERP measures were either not applied at all or were at least not documented in the paper, which is a crucial flaw; and no information on how ERP components were determined was provided.

In the context of a master thesis (Kleemeyer, 2010), ten children with ADHD were trained during 13 sessions to regulate their SCPs. After NF training, positive effects on children's behavior were observed and children were shown to have learned to differentiate between positivity and negativity trials in the course of training. Standardized low resolution brain electromagnetic tomography (sLORETA) was applied on average ERPs as a source localization method and revealed fronto-parietal sources to underlie SCP regulation. However, source localization for individual ERP data revealed inconsistent results, which led the author to the conclusion that these findings may question the application of tomographic NF methods. Besides the small sample size and not including a control group, limitations of this study were constituted by not presenting any data related to associations between regulation abilities and behavioral/performance measures. A methodological advantage of this study was given by the amplifier and software used for NF training which allowed for an export of EEG data recorded during training to the VisionAnalyzer, a state-of-the-art software program for ERP analysis, which enabled good artifact correction methods to be applied in the analysis of regulation data.

Preliminary results of a tomographic NF training (theta/beta and SCP) in 13 children with ADHD in anterior cingulate cortex (ACC) revealed the following effects (Liechti, Maurizio, et al., 2010). Significant improvements were observed on the behavioral level and a trend towards the improvement of the CNV after NF training was observed. No significant change of theta/beta ratio in the ACC was observed across training sessions. However, since the data of the EMG-biofeedback control group was not yet available, the specificity of the effects cannot be judged.

In addition, to date there is one study (Beauregard & Levesque, 2006) that has applied functional imaging during a Stroop and go/no-go task to analyze the effects of

40 sessions of theta-/SMR and theta/beta neurofeedback training in children with ADHD (*n* = 15) compared to a control group (*n* = 5). In contrast to the control group, after NF training, an improvement of inattention and hyperactivity at the behavioral level as well as a normalization of activation patterns in brain systems mediating selective attention and response inhibition, e.g. in anterior cingulate cortex, was observed[8]. A major limitation of this study was the very small size of the control group.

In summary, the described studies have shed some light on the neuronal mechanisms involved in NF training in children with ADHD and have provided hints regarding the specificity of training effects which are encouraging findings. However, more research is needed to further clarify the mechanisms mediating a successful training of various NF protocols. Future studies with large sample sizes, an adequate control training, and including different groups performing different NF training protocols would be desirable. In addition to analyzing neurophysiological measures, such studies should also include an analysis of associations of self-regulation measures and behavioral / performance / neurophysiological data.

1.4.2 Neuronal mechanisms underlying neurofeedback in healthy adults

Also in healthy adults, there a variety of studies which have examined neuronal mechanisms underlying NF training.

Some studies in healthy adults relating regulation abilities to performance changes have already been described in the chapter on peak performance training (e.g. Hanslmayr et al., 2005; Ros et al., 2009; Vernon, 2005; see also 1.3.2 Peak performance studies of neurofeedback). These studies provided evidence for the specificity of NF protocols by relating the regulation abilities of the trained frequency bands to improved performance. However, so far there is no state-of-the-art method for the parameterization of regulation abilities. This is an important topic that should be targeted by further research in order to increase the validity of these regulation ability measures and enable the comparability of results across studies.

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[8] For the Stroop task, significant loci of activation in the neurofeedback group at post trainng were observed in right anterior cingulate cortex, left caudate nucleus, and left substantia nigra. For the go/no-go task, these loci were right ventrolateral prefrontal cortex, right anterior cingulate cortex, left thalamus, left caudate nucleus, and left substantia nigra.

Regarding resting EEG measures, NF training[9] was observed to affect spectral resting EEG measures (Egner, Zech, & Gruzelier, 2004). However, these effects were not directly related to the frequency bands or the scalp locations addressed by the NF training. These findings implicate that the neural dynamics involved in a NF training involve more complex dynamical systems (which remain a target for further research) instead of specifically affecting the frequency components at the scalp locations targeted during training.

With respect to ERP measures assessed in relation with NF, a study by Egner and Gruzelier (2001; results also presented in Gruzelier et al., 2006) observed increased P3 amplitudes in an oddball task after a combined SMR (12-15 Hz) and beta (15-18 Hz) NF training[10] in healthy adults. Moreover, the regulation abilities of both SMR and beta correlated positively with increased P3 amplitudes. In addition, successful SMR self-regulation was positively correlated with reduced commission errors in a continuous performance test. Nevertheless, the design of a combined NF training instead of training the two protocols in separate groups or separate blocks and not including a control group constituted limitations of this study. Furthermore, no information was provided regarding the parameterization of regulation abilities or data supporting the correlation between P3 amplitude and beta self-regulation.

The described limitations were partially addressed by a later study of the same working group (Egner & Gruzelier, 2004; see also Gruzelier et al., 2006). They reported NF protocol-specific changes on ERP measures, namely increased target P3 amplitudes after beta but not after SMR training in an oddball task. Due to this relatively simple task with almost 100% correct responses achieved before training, no improvement in error detection could be observed after training and the P3 increase in the SMR group was therefore not related to improved performance in this group. A critical point was that even though a non-NF control group was included in the study, P3 measures were only reported for the NF groups and not analyzed by a repeated measure ANOVA including the factors group and time (before/after training). In addition, in contrast to the previous study, regulation abilities were not analyzed and correlated with performance and ERP measure, which might have provided additional information.

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[9] low beta (12–15 Hz), beta1 (15–18 Hz), and alpha/theta (8–11 Hz/5–8 Hz)

[10] In both neurofeedback trainings, theta (4-7 Hz) and high beta (22-30 Hz) amplitudes were to be reduced in addition. Per session, each subject performed 15 min of SMR and 15 min of beta training.

Ros and colleagues (Ros, Munneke, Ruge, Gruzelier, & Rothwell, 2010) were the first to examine the effects of NF on corticomotor excitability by means of TMS. 24 participants took part in a single 30-minute session of NF training at C3, and TMS was applied at this site before and after training. Half of the participants trained to suppress alpha (8-12 Hz), while the other half trained to elevate low beta (12-15 Hz). Corticospinal excitability in the trained hemisphere was observed to increase after training, however without a significant interaction related to training group. No significant changes were observed for short-interval intracortical inhibition or fascilitation in the trained hemisphere, and no changes were present in either measure in the untrained hemisphere. Only Bonferroni corrected t-tests for the alpha training group in the trained hemisphere showed an enhancement of corticospinal excitability as well as a decrease in short-interval intracortical inhibition lasting for up to 20 minutes after training, which were not observed for the low-beta training group. In addition, Ros and colleagues (2010) concluded that the general NF effect on MEP amplitudes appears to be indirectly mediated via resting EEG changes.

The association between SCPs and the blood oxygen level dependent response (BOLD) as measured by functional magnetic resonance imaging (fMRI) is well summarized in the NF review article by Heinrich et al. (2007):

> Hinterberger et al. (2003) examined the relationship between negative and positive SCPs and changes in the fMRI BOLD signal of adults who were trained to successfully self-regulate SCPs at Cz. fMRI revealed that the generation of negativity was accompanied by widespread activation in central, dorsolateral prefrontal, and parietal brain regions as well as in the basal ganglia. Positivity was associated with widespread fMRI deactivations at several cortical sites (including central and temporo-hippocampal areas) as well as some activation, primarily in frontal and parietal structures, and in the insula and putamen. Cortical positivity could be predicted with high accuracy by pallidum and putamen activation and supplementary motor area (SMA) and motor cortex deactivation. These findings may contribute to a better understanding of the mechanisms of SCP training in ADHD or epilepsy. (S.7)

Taken together, the findings reported in this chapter provide some hints for neuronal processes related to a successful NF training in adult participants. Yet due to the different kinds of NF trainings applied as well as the complexity of the neuronal mechanisms involved, further research is needed to gain clearer insights into these mechanisms. A better understanding of these mechanisms might also have implications for the further development of NF protocols as well as training settings.

1.4.3 Specificity of training effects and the design of a control training

The importance of including an appropriate control training when performing a NF study in order to be able to distinguish specific from non-specific training effects has been paid regard to in an increasing number of NF studies. However, the question as to what kind of control training can be considered optimal to control for unspecific training effects is still subject to controversial discussions, and different approaches can be found in the literature. However, one aspect that these different approaches agree on is that a control training in contrast to a control condition like a waiting list group or pure administration of a drug is preferable in order to control for effects related to regularly attending training sessions as well as trainer-trainee interactions.

One approach for the design of control trainings is to use a different training method, either one that is well established in the field of application or one that is designed to target similar domains, and to parallel the training schedule and duration to the one of the NF trainings. In the field of NF training in ADHD, recent studies have used e.g. group therapy (Drechsler et al., 2007) or a computerized attention skills training (Gevensleben, Holl, Albrecht, Vogel, et al., 2009) as control training, with the difference of the latter being conducted in front of a computer as a NF training and with a one-to-one contact of trainer and trained child. Regarding peak performance training, e.g. in a study to evaluate the effects of NF training on dance performance, a dance movement focus training was used as a control training (Thompson et al., 2008) .

However, the mentioned control training approaches are not able to control for effects related to trying to self-regulate one’s own physiological activity, and do not provide a comparable amount of continuous feedback related to one’s own state.

One approach which addresses these points is implementing a biofeedback training like e.g. EMG biofeedback training (e.g. Bakhshayesh, 2007; Bakhshayesh et al., 2011; Drechsler, 2009) or heart-rate variability biofeedback training (e.g. Raymond, Sajid, et al., 2005) as a control training which, depending on the design, may also be considered as a potentially effective intervention[11]. However, regarding the susceptibility to artifacts as well as the degree of difficulty in acquiring self-regulation skills, for instance, it may not be necessarily comparable to a NF training.

Thus, a placebo NF training is often discussed as the ideal control condition for NF trainings as it parallels a NF training as closely as possible. Thereby it allows the control of unspecific training effects, especially if it is conducted in a double-blind setting, which is recommended. However, this view of a placebo training as being the optimal control condition remains controversial for various reasons, which will be discussed below. In the following, without claiming to provide a complete overview, some placebo-controlled NF studies will be mentioned and their limitations will be discussed, while the reader is referred to literature for further studies (e.g. deBeus & Kaiser, 2011).

In healthy volunteers, such a mock feedback condition was realized for alpha/theta training (Egner, Strawson, & Gruzelier, 2002). Results showed that within-session theta/alpha ratio increments were only observed in the contingent feedback group. However, no difference between groups was observed related to subjective activational phenomenology (relaxation) in these healthy volunteers. The authors of the study assumed that the awareness about the possible inaccuracy of the feedback received might have affected the subject’s expectancies and thereby the results. This aspect is important to keep in mind when judging the effects of NF training compared to placebo training, because knowing that the feedback might be false was observed to have negative effects on training performance.

Logemann et al. (Logemann, Lansbergen, Van Os, Bocker, & Kenemans, 2010) included students (*n* = 27) with relatively high scores on impulsivity/ inattention questionnaires in their sham-controlled, double-blind evaluation. They employed individualized NF protocols based on quantitative EEG (QEEG) assessments comparing EEG parameters of a participant with a normalized database to identify deviations. Based on these deviations, a specific location on the scalp as well as a specific frequency band was selected for training. As a sham signal, a simulated EEG signal was used. As after 16 training sessions, no trend towards an advantage of the real NF

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[11] Bakhshayesh (2007) considered the EMG biofeedback training employed in the PhD thesis as a placebo training. However, as also discussed by Drechsler (2011), the therapeutic effects of EMG training cannot be excluded per se. This is also addressed in their more recent publication (Bakhshayesh et al., 2011).

training as assessed by behavioral measures (stop signal task, continuous performances test, questionnaires) was observed, the experiment intended to last for 30 sessions was stopped. Major critical points of this study were constituted by basing training on EEG deviations relative to a normative data base, as normative data bases are controversial – especially since participants were academic students. Due to the individualized protocols, no pre-post changes in EEG measures related to these trained frequencies were reported. In addition, instructing subjects that no specific effort was needed and learning would happen unconsciously when they attended to the brightening of the screen and the audio sounds instead of instructing them to apply cognitive strategies is a procedure not shared by all NF working groups. Furthermore, most participants reported that they thought they received sham feedback. For all these reasons, conclusions drawable from this study remain very limited.

A similar training procedure was applied in children with ADHD (*n* = 14): using a double-blind placebo-controlled design together with individualized NF protocols, improvements in ADHD symptomatology were observed for both groups and not restricted to the contingent feedback group (Lansbergen, van Dongen-Boomsma, et al., 2011). Again, most families thought that they received the placebo training. The authors discuss using automatically adjusted reward thresholds and not having implemented active learning strategies as limitations of their study. In addition, group sizes were very small for performing statistical group comparisons.

In the Child & Adolescent Psychiatry at the University of Göttingen a randomized-controlled study on SCP training was conducted in healthy adults[12]. The results relating to regulation abilities were evaluated in a Bachelor Thesis (Neukirch, 2010). The results revealed that participants could not reliably rate which training group they belonged to. Successful self-regulation was only observed in the "real" SCP group and not in the placebo training group. No association between participants' ratings which group they belonged to and their self-regulation abilities were observed. Ratings for both groups tended towards the middle of the scale, indicating that they were unsure which kind of training they performed. But in contrast to the studies by Logemann et al. (2010) and Lansbergen and colleagues (Lansbergen, van Dongen-Boomsma, et al., 2011), the participants rather thought that they performed a regular training. This study

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[12] This study on SCP training was also funded by the German Research Foundation as part of the same project as the study of the present thesis.

points out that subjects were able to learn SCP self-regulation even in the context of a placebo-controlled study. However, the effectiveness of the training in terms of associations between regulation abilities and behavioral data remains to be analyzed. These data will be important for judging the specific effects of SCP training in healthy adults.

While the idea of using a double-blind placebo-controlled design sounds in fact like an optimal setting to control for unspecific training effects, the realization of a placebo training especially in a double-blind setting is not trivial. It has to be ensured that both EEG signal quality and artifact correction is guaranteed for and trainers cannot deduce which group (real vs. placebo NF) a participant belongs to. In Göttingen such a placebo training has been realized (Neukirch, 2010) and trainers seemed to be blind with respect to a subject performing a real or a placebo training. Trainer ratings (on whether in their opinion a participant was performing a real or a placebo training) could provide important information on the factual realization of such a double-blind setting.

Another important aspect regarding a placebo training is that from an ethical perspective, participants need to be informed about the existence of a placebo group. This knowledge of the possibility that one might be in the placebo group can have an impact on the real NF training group which in two of the abovementioned studies rather thought that they performed a placebo training (Lansbergen, van Dongen-Boomsma, et al., 2011; Logemann et al., 2010). The presence of a placebo training group might have negative effects on training performance in the real NF group, which is a confound when aiming at disentangling specific from unspecific effects of NF training.

Furthermore, from an ethical point of view, the realization of a placebo training is critical in patients who are searching for a treatment and especially in young patients like children with ADHD, which is one of the main fields of application of NF training. For a further discussion of the implementation of control trainings in the context of NF studies in children with ADHD, the reader is also referred to the recently published review article by Drechsler (2011).

In summary, so far there is no all-around optimal control training and each of the described approaches has its advantages and disadvantages. Using an active control condition like group therapy, computerized attention skills training, or (non-NF) biofeedback training has the advantage, especially for patients, that all participants receive a training that is intended to have positive effects. When performing NF training in patients, it also provides the possibility to compare a NF training to another established treatment method. On the other hand, comparing NF training to an active control training raises the bar for the NF group. A placebo training, in contrast, is intended to directly control for unspecific training effects without constituting an active training in the sense that specific improvements can be expected for the placebo group. However, its realization especially regarding artifact control and the impact of the knowledge of a placebo group on the real NF group in combination with an ethical question when performed in patients has to be considered.

Thus, as so far each approach has its advantages and disadvantages, it is reasonable that different approaches are used in different studies and it remains the task of researchers to select for each study the approach best suited for their purpose.

2 Research objective of the present study and hypotheses

2.1 Research objective of the present study

The objective of the present study was three-fold. In a first and main part, the aim was to further examine the neurophysiological mechanisms underlying theta/beta and SCP neurofeedback training. For this purpose, a training of these two NF protocols was conducted in adults and compared to a control training. Pre and post training assessments comprised the following measures: event-related potentials during an attention-demanding task and measures of transcranial magnetic stimulation to assess motor system excitability. The reason why these two NF protocols were selected is that they are established NF protocols for the treatment of children with ADHD. The present study is a continuation of a previous study that examined the effectiveness of these NF protocols in children with ADHD (Gevensleben, Holl, et al., 2010; Gevensleben, Holl, Albrecht, Schlamp, et al., 2009; Gevensleben, Holl, Albrecht, Vogel, et al., 2009; Gevensleben, Moll et al., 2010; Wangler et al., 2011).

The aim of the present study was to shed further light on the neuronal mechanisms underlying these protocols which are effectively applied in children with ADHD, but without a full understanding of the mechanisms mediating an effective training. While some evidence exists regarding the effects of NF trainings on mechanisms of attentional processing as reflected in ERPs, so far only one study has examined TMS measures in the context of NF trainings in healthy adults (Ros et al., 2010), albeit by using different NF protocols than in the present study. The motivation for applying TMS during pre and post assessments arose from findings of NF studies on children with ADHD where reduced impulsivity and hyperactivity were observed after NF training (Gevensleben, Holl, Albrecht, Vogel, et al., 2009; Holtmann et al., 2009). This raised the question whether these effects were possibly directly mediated via changes in cortical excitability induced by NF training. Thus, the present study set out to measure the potential effects of NF training on cortical excitability in adults.

A second objective was to examine the effectiveness of an adaptive NF training (ANF) in comparison to the control training as well as to the more established NF protocols theta/beta and SCP training. Since the application of this kind of adaptive NF training is spreading in the field of therapeutic as well as occupational therapy practices, the aim was to compare it to more established NF protocols to see whether further research should be directed towards examining the effects of this kind of NF training in its various clinical applications. The adaptive NF training protocols were derived from the Othmers’ approach but due to the necessary standardization needed for the implementation in the present study, some modifications were made.

Moreover, the study aimed at examining the effects of (theta/beta, SCP, and adaptive) NF training on well-being and mood as a potential new field in the realm of peak performance training. Previous studies have mainly focused on attention and cognitive performance measures and only very few studies have examined the effects of NF training on well-being and mood. A motivation for examining NF training in the context of well-being and mood was also derived from the adaptive NF training applied in affective disorder. From a scientific perspective, the effectiveness of the adaptive NF training has not been established. Therefore, the idea was to examine its effects on well-being and mood in the context of a peak performance training in adults as a first step, in addition to examining the effects of theta/beta and SCP neurofeedback protocols on well-being and mood.

The present study was conducted in ‘healthy’ adults and not in children with ADHD for the following reasons. Based on the concept of peak performance training, these protocols are also indicated for the training in healthy adults. Pre and post assessments were very comprehensive and therefore not well suitable for children with ADHD. Most notably, the adaptive NF training has not yet been scientifically established, wherefore it seemed more adequate to first examine this training protocol in adults. Moreover, it was assumed that a larger and more homogenous sample could be obtained when performing the study with ‘healthy’ adults.

In addition, a control training was implemented to delineate specific NF effects from unspecific effects related to repeating measurements, motivation or practicing cognitive strategies in daily life situations.

Hence, four training groups were included in the present study: theta/beta, SCP, and adaptive NF training, as well as a control training. Participants were randomly assigned to a training group and training effects on attention, well-being / mood, and motor system were examined at the behavioral, performance and neurophysiological level.

2.2 Hypotheses

The following hypotheses regarding pre-post training effects related to the different trainings were tested. For each hypothesis (H), relevant measures were listed in brackets in order to allow for a clear attribution of the hypothesis to be tested and the measures used[13]. For a detailed description of all measures, the reader is referred to the methods section (see 3.2.3 Assessments).

H 1: Each of the three NF protocols has stronger effects on attention than the control training (measures: total score of the Brown Scale, subscale concentration of the EWL-N, performance measures of the ANT).

H 2: Each of the three NF protocols affects mood and well-being more positively than the control training (measures: POMS, 5 selected subscales of the EWL-N). The strongest effect on mood and well-being is expected for the ANF group followed by the SCP group.

H 3: Each of the three NF protocols has a stronger effect on action orientation (measure: HAKEMP) as well as self-access (measure: self-access questionnaire) than the control training.

H 4: Regulation ability in the theta/beta and SCP groups is expected to be related to improvements in attention, well-being, and motor skills (measures: total score and subscales of the Brown scale, POMS, game of darts).

H 5: In comparison to the control group, stronger improvements in motor tasks are expected for each of the three NF groups (measure: darts performance).

H 6: Stronger improvements in performance in the WithStress condition as well as reduced perceived stress in everyday situations is expected for each of the three NF groups compared to the control group and especially for the ANF group (measures: game of darts WithStress, ANT WithStress, Perceived Stress Scale).

H 7: For each of the three NF groups, larger effects on working memory performance are expected compared to the control group (measure: performance in the working memory task).

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[13] Listing the measures already in the hypotheses section was chosen in order to increase readability and the attribution of the hypotheses and measures, which would have been more difficult to introduce and less clearly arranged in the methods section.

H 8: NF training is expected to be associated with larger effects on the attention networks (as assed by the ANT) than the control group (measure: attention network measure at the performance and ERP level during the ANT). This to be seen as an exploratory analysis especially with respect to the ERP level.

H 9: Each of the three NF protocols in contrast to the control training is expected to have effects on spectral resting EEG measures (measure: resting EEG).

H 10: At the level of event-related potentials, larger increases in contingent negative variation amplitude, cue- and target-P3 amplitudes are expected for each of the three NF groups in comparison to the control group. Specifically, the strongest increase in contingent negative variation is expected after SCP training. The strongest increase of cue- and target-P3 amplitudes is expected for the theta/beta group. Regarding the ANF group, no specific hypotheses could be formulated (measures: event-related potentials assessed during the ANT).

H 11: Both SCP and theta/beta training in comparison to the control training are expected to have prolonged effects on the excitability of the motor system, while no directed hypotheses could be formulated. This effect is not expected for the ANF training (measure: TMS double-pulse paradigm in a resting condition).

H 12: The EEG self-regulation abilities of subjects in the theta/beta and SCP groups are associated with improvements on the performance level (Brown Scale, POMS, game of darts): good performers show larger improvements than bad performers. In addition, good performers in the SCP group are expected to show larger pre-post increases in CNV amplitudes in the ANT than bad performers. In the theta/beta group, good performance is related to stronger pre-post improvements in cue- and target-P3 amplitudes compared to bad performance in self-regulation.

In addition, in a mainly exploratory analysis (except if concrete hypotheses were stated above) for all described measures also differential effects related to the three different NF protocols were analysed (mainly based on effect size measures).

3 Methods

3.1 Participants – Screening and final sample

3.1.1 Screening interview and assessments

One hundred and fifteen adults between 19 and 35 years participated in the screening interview. This clinical interview was among others based on the screening questions of the structured clinical interview for DSM-IV (SKID; Wittchen, Zaudig, & Fydrich, 1997) and intended to assess whether interested subjects were ‘healthy’ adults. In the following, whenever the term healthy adults is used with direct reference to the participants of the present study, healthy will be written in hyphens in order to indicate the somewhat more clinically noticeable feeling and behavior in several participants as outlined below.

In addition, the German version of the Symptom Checklist-90-R (SCL-90-R; Derogatis & Savitz, 2000; Franke, 2003) was assessed. The SCL-90 is a self-report questionnaire that evaluates a wide range of psychological as well as psychiatric or somatic problems observed within the last seven days. The 90 items are subdivided in nine symptom scales: somatization, obsessive-compulsive, interpersonal sensitivity, depression, anxiety, hostility, phobic anxiety, paranoid ideation, and psychoticism. As a measure of overall psychological distress, the Global Severity Index (GSI) was used to determine whether subjects’ GSI scores lay within the norm (women: $M_{GSI} < .83$, men: $M_{GSI} < .54$).

Next, subjects performed those subtests of the German version of the Wechsler Adult Intelligence Scale (WIE) that form the basis for the Verbal Comprehension Index (VCI) and the Perceptual Reasoning Index (PRI). The mean value of the VCI and PRI was required to be above 80. To ease readability the mean value of the VCI and PRI will be referred to as estimated IQ even though strictly speaking it is only an index value and no IQ estimate.

Exclusion criteria were: a psychiatric diagnosis, a neurologic diagnosis (e.g. epilepsy), a cardiovascular disease, estimated IQ below 80, pregnancy, clinically noticeable feeling and behavior (observed in the interview and/or GSI value higher than norm).

After about one third of participants had completed their participation in the study, one subject experienced a brief seizure and loss of consciousness during TMS resting motor threshold measurement at pre assessment. This incident was thoroughly examined and is documented in a publication (Kratz, Studer, Barth, et al., 2011). In the literature so far no such case had been reported for single-pulse stimulation in a healthy individual. The local ethics committee was consulted as to how to proceed with the TMS measurements of this study and until an agreement was achieved all TMS measures were stopped. The further course of actions approved by the ethics committee was to increase safety procedures. Since this incident, EEG and electrocardiogram (ECG) were assessed for all subjects before their participation in the study. In case of a pathological EEG or ECG subjects were excluded from the study. In addition, sensitivity to fainting was assessed in the screening interview as a contraindication for participating in TMS assessments, but based on a consultation with the assistant medical director of our department it was not necessarily a contraindication for participating in the non-TMS parts of the study.

After the screening appointment 33 subjects were excluded from further participation in the study due to ADHD diagnosis (*n* = 2), clinically noticeable feeling and behavior (*n* = 7), deviations in the EEG or ECG (*n* = 14), estimated IQ below 80 (*n* = 2), for reasons of time (*n* = 4), or due to various somatic reasons like e.g. tinnitus or tremor (*n* = 5).

3.1.2 Participants

81 ‘healthy’ adults participated in the study and were randomly assigned to one of four groups: theta/beta frequency band training (FQ), training of slow cortical potentials (SCP), adaptive neurofeedback training (ANF), control training (CON). Six subjects were dropouts: dropouts during pre-assessment (*n* = 3, i.e. before subjects got to know the group assignment), dropouts after the first few training sessions due to reasons of time (*n* = 3, all in the adaptive training group). Thus, 75 subjects remained that completed the training and the pre and post assessments (FQ: *n* = 19, SCP: *n* = 20, ANF: *n* = 18, CON: *n* = 18). For all further analyses, two further subjects were excluded for the following reasons: difficulties in understanding instructions due to German language difficulties in a non-native speaker (*n* = 1), severe problems in personal life with recommendation to contact a psychotherapist (*n* = 1). Therefore, the final sample comprised 73 subjects: 19 subjects in the FQ group, 19 subjects in the SCP group, 18

subjects in the ANF group, and 17 subjects in the CON group. An overview over demographic and psychological characteristics of the sample is given in Table 1.

Table 1

Demographic and psychological characteristics of the sample

	All *n* = 73	FQ *n* = 19	SCP *n* = 19	ANF *n* = 18	CON *n* = 17
Age (years)	24.35 ± 2.57	24.62 ± 2.56	25.08 ± 2.47	24.76 ± 1.75	23.59 ± 3.06
Sex: m / f	31 / 42	7 / 12	10 / 9	7 / 11	7 / 10
Estimated IQ	105.17 ± 8.00	105.95 ± 6.19	105.24 ± 7.67	105.72 ± 9.12	103.65 ± 9.31
GSI (SCL-90)	.22 ± .19	.23 ± .18	.14 ± .10	.20 ± . 24	.33 ± .20

Note. For the whole sample as well as for each group demographic and psychological characteristics (including standard deviations) are depicted. All: whole sample, FQ: theta/beta frequency band training group, SCP: SCP training group, ANF: adaptive neurofeedback training group, CON: control training group, m: male, f: female, GSI: Global Severity Index of the Symptom-Checklist-90-R self-report measure.

Groups did not differ regarding age (M_{age} = 24.53 years, SD_{age} = 2.57 years, age range: 19– 31 years; $F(3,69) = 1.10$, n.s.) and estimated IQ (M_{IQ} = 105.17, SD_{IQ} = 8.00, IQ range: 88– 123; $F(3,69) = .29$, n.s.).

Regarding the GSI score of the SCL-90, a significant difference between groups was observed ($F(3,67) = 3.30$, $p < .05$), with the lowest score observed in the SCP and the highest score observed in the control group. Post-hoc tests based on pairwise comparisons revealed significant group differences between the SCP and CON group ($t(33) = -2.43$, $p = .021$) and between the ANF and CON group ($t(31) = -2.62$, $p = .013$) as well as a trend for group differences between the FQ and CON group ($t(33) = -1.98$, $p = .056$). After Holm-Bonferroni correction results no longer were significant as smallest $p > .05 / 6$.

All participants gave their written informed consent. The experiment was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Medical Faculty of the University of Erlangen-Nuremberg (accepted ethics proposal number 3672).

3.2 Design of the study

Subjects were randomly assigned to one of four groups: theta/beta frequency band training (FQ), training of slow cortical potentials (SCP), adaptive neurofeedback training (ANF), or control training (CON).

Pre-training assessments took place before the start of training[14] and post-training assessments were scheduled to the week after the end of training. Taken together with the screening interview, subjects participated in the study for about two months. All trainings were conducted in the period between October 2007 and December 2009 in the Department of Child and Adolescent Mental Health at the University of Erlangen-Nürnberg.

Subjects were informed about group assignment not until completion of the pre-training assessments. All trainings were administered by the same trainers who were instructed to take a neutral attitude concerning the effects of the individual training programs.

Subjects received 75 € for their participation in the study. In addition, starting from the first and 5th training session in the control and NF groups, respectively, as well as during post assessments, participants collected points for their performance. At the end of their participation in the study these points were translated into an additional monetary reward of up to 10 €.

Evaluation scales assessed at the end of training were used to control for ‘placebo factors’ like participants’ expectations on how much they expected the training to influence their attention and well-being as well as to assess their satisfaction with the training.

3.2.1 Neurofeedback trainings

The NF trainings of the three NF groups (FQ, SCP, ANF) consisted of 20 sessions conducted as 10 double sessions of about 2 x 50 minutes each. In the majority of subjects two double sessions were conducted per week (number of double sessions per week: *M* = 2.27, *SD* = .54) so that the training lasted about 5 weeks (number of weeks: *M* = 4.68, *SD* = 1.23).

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[14] In the control group pre-training assessments took place about two to three weeks before the start of training, as the training period in the control group was shorter and with the aim to keep the distance between pre- and post-assessments similar in both groups (please refer to chapter 3.2.2 Control training).

At the beginning of a training session subjects rated their momentary satisfaction with their life situation (see 3.2.3.2 Assessments during training).

From the 5th double session on, at the end of each double session subjects practiced the transfer of their mental state during a successful training to another attention-demanding situation by means of their strategies developed during the training. In the 5th, 7th, and 9th double session subjects practiced this transfer while playing darts, and in the 6th, 8th, and 10th session while performing a cued continuous performance test (CPT-OX) at a personal computer (see 3.2.3.2 Assessments during training).

In addition, participants were instructed to practice this transfer of their strategies at least once each day in daily-life situations in which this mental state is relevant for them. Exercises were documented on a “transfer situations” sheet and discussed at the beginning of the next training session.

During the training participants sat in front of a monitor on which changes in their brain electrical activity were displayed as variations in a selected feedback animation. By modulating their brain electrical activity, participants controlled a kind of computer game. A trainer sat next to the participant in front of another monitor that displayed the participant’s EEG signals.

3.2.1.1 Theta/beta frequency band training

Training

In the theta/beta-protocol subjects were asked to reduce their theta (4-8 Hz) activity while simultaneously increasing their beta activity (13-20 Hz). The aim of the training is to learn how to achieve an alert focused but relaxed state. By training a state of sustained attention this training addresses the tonic aspects of cortical arousal.

As amplitudes in these frequency bands vary from person to person and also from day to day, individual baseline values are determined at the beginning of each session during a three minute long resting state. The following training session is based on these baseline values. However, if baseline values were too difficult and a reasonable amount of positive feedback was not achieved, they were adjusted accordingly, mostly by increasing and/or decreasing the theta and/or beta value by about 10 % respectively.

Changes in theta activity were continuously depicted as a changing bar on the left side of the screen while the aim was to reduce this bar. Similarly, changes in beta activity were visible in a changing bar on the right side of the screen which had to be increased (see Figure 2). At the start of training self-regulation blocks lasted for five minutes, while they were extended to 10 minutes as the training proceeded, i.e. a training session consisted of few but long trials in order to address sustained attention. In addition to self-regulation blocks with contingent feedback, about 40 % of the self-regulation blocks were conducted as transfer trials, i.e. subjects trained to achieve the desired state without receiving contingent feedback about their brain states. Transfer blocks represented the first step towards a transfer of the training state to daily life situations in which also no feedback about their current brain state is provided.

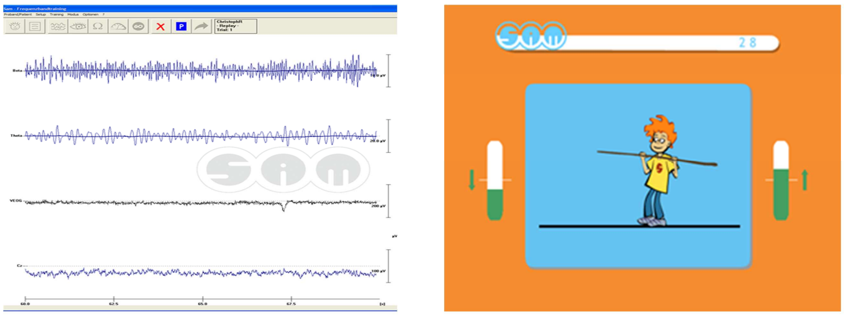

Figure 2. Theta/beta training screens.

Left: The trainer's screen depicts the time course of the following signals (from top to bottoum): beta, theta, EOG, whole spectrum EEG (Cz). Right: On the participant's screen the feedback animation "balancing Sam" is depicted. The green bars represent continuously changing activity in the theta (left bar) and beta (right bar) band. The white horizontal line in the middle of each bar indicates the threshold value of the respective frequency band. The participant is instructed to decrease theta activity and to increase beta activity relative to this threshold value. The arrows next to the green bars indicate the direction of the desired change. Whenever regulation is successful Sam makes a further step on the rope and on the right top the score is increased by a point.

Software and recordings

For the theta/beta and SCP trainings the neurofeedback system SAM (Self-regulation and Attention Management) was used, which was developed by PD Dr. Hartmut Heinrich[15]. Brain electrical activity was calculated from Cz (reference: one mastoid, bandwidth: 1–30 Hz, sampling rate: 250 Hz). Two additional EOG electrodes were placed above and below one eye in order to record eye movements. The time course of the EOG signal was also depicted on the trainer's monitor. Vertical eye

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[15] Affiliation: Department of Child and Adolescent Mental Health, University of Erlangen-Nürnberg

movements were corrected online using a regression-based algorithm (Semlitsch, Anderer, Schuster, & Presslich, 1986). When artifacts exceeded ± 100 µV in the EEG channel or ± 200 µV in the EOG channel, for these segments no feedback was provided to the subject.

Feedback animations

As the software was developed for children, the game-like feedback animations were rather designed for children, but they were adopted well by the adult participants. Participants were free to choose between the following feedback animations: balancing Sam, Puzzles, or games against the computer (Göfi, car race). In all animations, the bars depicting the subject’s theta and beta activity were included.

In the “balancing Sam” animation participants controlled the movement of a boy called Sam on a rope: successful regulation resulted in Sam making another step on his high wire. For each step they collected points that were depicted in the right corner of the screen and their aim was to make Sam balance as many steps as possible on this rope within a given time.

The “Puzzles” game consisted of a picture that was covered with 48 grey squares. Whenever regulation was successful one square disappeared and revealed the view on this part of the picture and when it was no longer successful the gray square reappeared. After 5s of successful regulation (or longer for longer trials) one gray square disappeared for good. The aim of this game was to uncover the whole picture by making one grey square after the other disappear due to successful regulation.

The “Göfi” game was very similar to the “Puzzles” with the difference that instead of covering a whole picture each square covers a number representing the number of points to be won by successful regulation. The score of each player was depicted on the screen and continuously updated. The aim of this game was to collect as many points as possible and especially to collect more points than the computer player. Regulation of the computer player was based on simulated signals and the strength of the computer player could be adjusted.

In the “car race” the trainee directs a car that moves forward on a given route and the computer player directs a car that moves along on the same route. The aim of this game was to make the car drive as many rounds as possible and to outperform the computer player. The number of rounds achieved by each player was depicted on the screen.

Contingent feedback and transfer self-regulation blocks

In feedback blocks, subjects received contingent feedback about their theta and beta activity represented as continuously changing bars on the left and right side of the screen. A white line in the middle of each bar reflected their baseline theta and beta activity.

In transfer blocks, these bars were frozen, i.e. immobile and did not reflect the current amplitudes of subject’s theta and beta activity. Feedback about how successful subjects were in regulating their theta and beta activity was only provided at the end of a whole block. Nevertheless, subjects received some feedback of whether they succeeded in achieving the desired state, e.g. the number counting the steps in the “balancing Sam” animation was still continuously updated, but no information about their current theta or beta amplitude was provided. For these transfer blocks, the monitor of the NF trainer was turned sideward to ensure that subjects did not receive feedback by looking at the trainer’s monitor from the corner of their eye.

Strategies

Subjects either learned the regulation of their brain activity intuitively due to the contingent feedback provided or by means of cognitive strategies. As there is no strategy valid for everybody the trainer supported subjects in developing their personal strategy.

Most subjects used cognitive strategies to direct their brain activity in the desired direction. They imagined daily-life situations in which they succeed easily to be in a state of sustained attention (e.g. an attentive situation during performing a sport or playing a musical instrument). Subjects tried different situations until they found one or two that worked well for them. They tried to put themselves mentally in this situation and to experience it as real as possible. They used the real-time feedback provided by the software as well as the final feedback provided in transfer trials to find their personal strategy that supported them in achieving a state of sustained attention.

Transfer tasks

Starting in the 5th double session, subjects performed a transfer task at the end of this double session. During these feedback tasks electrical brain activity was no longer recorded, i.e. subjects were not provided with any feedback about their success in regulation. Before the start of such a transfer task, subjects took their time to put themselves into this state of sustained attention. Some subjects did this intuitively by remembering their mental state of a successful training trial. Most subjects used their strategies to activate this state. Whenever they felt that they had succeeded in becoming focused they gave their trainer a sign and the transfer task was started. In addition, also during performing the task they were instructed to reactivate this mental state, when they felt they were losing it.

Transfer to daily life situations

Similarly to these transfer tasks performed in the training and also starting after the 5th double session, subjects were asked to train activating this state of sustained attention also in daily-life situations at least once a day. They were free to choose any situation in which they wanted to become more focused (e.g. at work, when studying for an exam, when reading a text). As during transfer tasks the use of their strategies was recommended. In addition they were asked to apply their strategy to situations in which they wanted to relax or lighten up their mood. Subjects documented the situations in which they exercised and how successful they estimated their activation of this focused state to be.

3.2.1.2 Training of slow cortical potentials

Training

In the SCP training subjects trained to change their brain electrical activity alternatingly towards more negative or more positive potentials. This training aims at subjects learning how to switch between an activated / attentive and a deactivated / relaxed state. Increasing cortical negativity is related to activation, while increasing cortical positivity is related to deactivation.

Feedback was provided in the form of a ball that subjects were to direct upwards in negativity trials and downwards in positivity trials (see Figure 3). The number of positivity and negativity trials was kept equal, while their order was randomized. A trial lasted for 8 seconds and consisted of a 2 s baseline period and a 6 s feedback period. I.e. in contrast to the theta/beta-training, training consisted of many short trials, and baseline values were determined in the first two seconds of every trial instead of only once per session. Intertrial interval was set to 5 ±1 s. Training was performed in blocks of 40 to 60 trials. As in the FQ training, transfer blocks were included in 40 % of all training blocks.

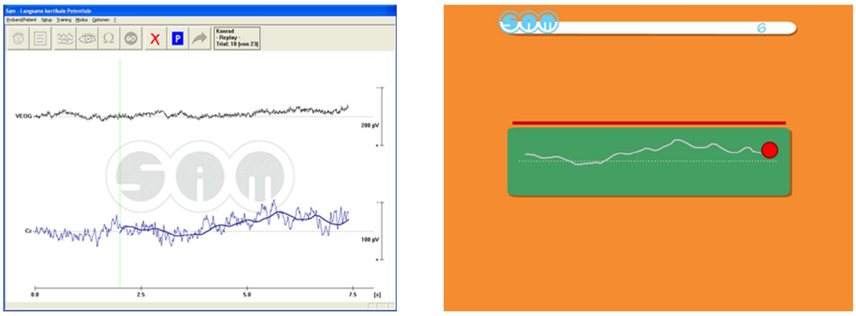

Figure 3. SCP training screens.

Left: The trainer’s screen depicts the time course of EEG (Cz, bottom) and EOG signals (top). Right: On the participant’s screen the feedback animation “Retro” is depicted. The red horizontal bar, which appeared after a 2 s baseline, indicates that the trial is a negativity trial, i.e. the participant is asked to achieve an active and attentive state. Feedback of the EEG parameter to be trained is provided by the time course and color of a ball which is moving from left to right. A successful negativity trial is associated with the ball moving upwards and changing its color from white to red. For each successful trial the score, which is depicted on the right top the screen, is increased by a point.

Software and recordings

Recording of brain electrical activity and artifact correction were similar to the theta/beta-training with the only two differences that the bandwidth of the EEG recording was set to .01–30 Hz and that another regression-based algorithm was used for correction of vertical eye movements (Kotchoubey, Schleichert, Lutzenberger, & Birbaumer, 1997).

Feedback animations

As the same software was used as for the FQ training, two feedback animations were the same (“Puzzles”, “Göfi”) while one other differed (“Retro”).

“Retro” is the most basic animation, as the animation only consists of the ball that moves along the screen. At the beginning of a trial, the ball is white and remains immobile on the left side of a rectangle depicted on the screen; this state corresponds to the two seconds baseline measurement at the beginning of each trial. Next, either a red bar appears at the top of the rectangle or a blue bar appears at the bottom, indicating the task to achieve an activated (negativity trial) or relaxed (positivity trial) state respectively. In the moment when this bar indicating the required condition appears, the ball starts moving towards the right side of the rectangle (this represents the time course) changing its way upwards whenever the amplitude gets more negative or downwards when it becomes more positive. In addition the ball changes its color towards red and blue color shades representing the amount of negativity and positivity achieved up to this time point. The darker the shade the more change in activity is achieved relative to the baseline. The aim is to move the ball upwards and color it dark red in negativity trials, and to move the ball downwards and color it dark blue in positivity trials. The number of successful trials was depicted on the right top of the screen.

In all other animations this moving ball was imbedded at the bottom of each animation.

Contingent feedback and transfer trials

In all trials with contingent feedback the moving ball indicated the amount of negativity or positivity achieved. In addition, two kinds of transfer trials were conducted: transfer trials with delayed feedback and transfer trials without feedback of the time course of the underlying brain activity represented in the ball movement.

In transfer trials with delayed feedback, the ball remained motionless and colorless on the left side of the rectangle until the six seconds long regulation period was over. Then, the course of the ball as well as its final color was depicted. In addition, the number on the top of the feedback screen, which represented the number of correct trials, was increased if the trial was successful.

In transfer trials without feedback the course of the ball and its color did not become visible at the end of a trial, i.e. subjects did not receive information about their brain state. The only feedback given was provided by the number representing the number of correct trials which indicated whether the trial was successful.

For these transfer blocks, the monitor of the NF trainer was turned sideward to ensure that subjects did not receive feedback by looking at the trainer’s monitor from the corner of their eye.

Strategies

As in the FQ training subjects either learned the regulation of their brain activity intuitively or by means of individually developed cognitive strategies. Cognitive strategies related to negativity trials (red strategy) were based on situations in which it was important to be prepared and fully focused for a special situation (e.g. waiting for the start signal for a sprint). Strategies for positivity trials (blue strategy) represented a situation in which the subject “descended” to a calm and relaxed state. Figuratively, strategies for negativity trials are related to accelerating the speed of a car while slowing down in positivity trials.

Transfer tasks

Similar to the FQ group, subjects trained the application of their strategies in transfer tasks. They mainly used their red strategy to prepare for the task and become focused. But some subjects for whom it was important to calm down used their blue strategy additionally or instead of the red one. In addition, they were instructed to reactivate this mental state also during performing the task when they felt they were losing it.

Transfer to daily life situations

Subjects practiced their strategies in daily-life situations in which it was important for them to be alert (red strategy), to calm down/ relax (blue strategy), or to lighten up their mood (red or blue strategy depending on the situation). Subjects documented the situations in which they exercised and estimated how well their strategy helped them to acquire the desired state.

3.2.1.3 Adaptive neurofeedback training

Training

The adaptive NF training as applied in the present study was principally based on the approach by Othmer and Othmer. Their approach is to choose protocols for training individually for each person depending on the clinical symptomatology. In contrast, as in the present study training was performed in ‘healthy’ subjects, three NF protocols were chosen for all subjects based on the three mental states to be targeted by the training (see below). These three NF protocols were trained successively within a session.

A first protocol aimed at training a state of well-being, emotional stability and positive mood. Feedback was provided regarding the inter-hemispheric difference between temporal sites of the left and right hemispheres in a 3 Hz wide frequency band (reward band) with the aim of increasing the inter-hemispheric difference in this specific frequency band. According to Othmer & Othmer (2006) this type of temporal training targets emotional regulation and it is the training site they usually start their training with.

In addition, two inhibit frequency bands were implemented which prevented the subject from producing extreme values in any frequency band, thereby acting as a sort of artifact detection which lead to a brief disruption of the feedback signal whenever it exceeded a threshold value[16]. The low inhibit band ranged from 2–13 Hz while the high inhibit band ranged from 14–30 Hz (Othmer & Othmer, 2006).

The frequency band to be trained (i.e. the reward band) was adjusted individually starting at 12–15 Hz and decreasing or increasing the frequency band to be trained based on the feedback provided by the subject. Subjects are asked about every two minutes to rate their alertness, relaxation and mood on a 10-point rating scale. The aim was to find a frequency range for which feedback reinforced a general state of well-being in subjects. A heuristic used was to increase the frequency range when subjects were underaroused, e.g. reported getting tired and to decrease the frequency range if they were overaroused, e.g. became too agitated or tense. However, adjustment of the frequency range was mainly done by trial and error and based on the feedback provided by the subject related to his/her current state of well-being[17].

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[16] "Joel Lubar was the first to employ inhibit functions with the overt objective of training toward more normal distributions." Othmer, S., Neuromodulation Technologies: An Attempt at Classification (p.2). Retrieved August 5, 2011, from
http://www.eeginfo.com/research/researchpapers/Neuromodulation_Technologies.pdf
Othmer and Othmer adapted this idea towards including two broad-band inhibits in the training.

[17] "It is the responsiveness to optimized-frequency training that makes this training approach practical. The immediate response of the reinforcement is in terms of state shifts in the arousal, attentional, and affective domains. These state shifts are readily perceived within a matter of a minute or two or three by anyone who responds sensitively to this training. Reports on perceived state change are elicited by the therapist, and on this basis the reward frequency is adjusted on the timescale of minutes. As the optimum reward frequency is approached, the trainee achieves a more optimal state in terms of arousal, vigilance, alertness, and euthymia. At the same time, the strength of the training increases perceptibly. For those familiar with the theory of resonant systems, this maps out a conventional resonance curve, and it is our impression that the person's felt states and the responsivity to reinforcement map out essentially the same curve. […] Since this behavior can be observed in different people across the entire frequency band from 0.01 Hz to 45 Hz, it is likely that the same general organizing principles apply for every part of the band." Othmer, S., Neuromodulation Technologies: An Attempt at Classification (p.9). Retrieved August 5, 2011, from http://www.eeginfo.com/research/researchpapers/Neuromodulation_Technologies.pdf

At the beginning of this protocol a 30 seconds baseline was assessed before feedback was provided in order to adjust the thresholds for the reward and inhibit bands. At the end of this baseline period the threshold values were determined in the following way. The threshold for the reward band was set to provide 75 % positive feedback. The threshold for the inhibit bands was set such that the low inhibit band did not exceed the threshold in more than 10 % of the time and the high inhibit band did not exceed the threshold in more than 5 % of the time. Thresholds were adjusted whenever the reward band was changed or when feedback frequency dropped or increased considerably (based on the judgment of the trainer). Feedback was provided in the form of sounds in combination with visual animations as described below. This training protocol lasted for 20 minutes.

A second protocol aimed at training a state of relaxation. For this purpose electrodes were placed at parietal sites of the left and right hemisphere and an increase in alpha (8.5–11.5 Hz) synchrony between these sites was trained. According to Othmer and Othmer (2006) parietal training targets body relaxation and awareness. This training was performed in a comfortable sitting position with eyes closed. Whenever the reward band exceeded the threshold feedback was provided in the form of Musical Instrument Digital Interface (MIDI) sound 99 “atmosphere” that was played. The subject was instructed to try to achieve a relaxed state in which the sound is played continuously for a longer time and more often. For this training, the low inhibit band was set to 2–11.5 Hz and the high inhibit band to 11.6–30 Hz. In comparison to the first training protocol the threshold for the low inhibit band was changed to allow exceeding of this threshold only in 5 % of the time. This training protocol lasted for 10 minutes.

A third protocol aimed at training a focused state without getting distracted by other thoughts. According to the Othmer and Othmer (2006) prefrontal training targets reducing internal distraction and improving planning and organization as well as short-term memory. The procedure was very similar to the first training protocol but with the following differences: training was based on frontal areas and adjustment of the reward frequency was mainly based on the subject’s rating regarding alertness.

Software and recordings

For the ANF training the neurofeedback system Atlantis I by BrainMaster Technologies Inc. (Beford, Ohio, U.S.) was used.

For the training at temporal sites EEG was recorded with bipolar montages at T3-C3 and T4-C4. Instead of a bipolar montage at T3-T4 like used by Othmer and Othmer this setup was chosen with the original aim of being able to analyze the EEG frequency spectrum in each hemisphere and monitor whether changes occurred due to training[18]. To achieve a training similar to a bipolar training a new software implementation within Brain Master system was used which is based on channel recombination (addition and subtraction) that differentially emphasizes synchronous or asynchronous EEG activity (Collura, 2005). This implementation was used to calculate the feedback parameter within the 3 Hz wide reward frequency band based on the difference (subtraction) of the two recorded signals.

For the training at parietal sites EEG was recorded at P3 and P4, with linked mastoids as reference. The software calculated the sum between these two recorded signals within the alpha frequency range which was used as feedback signal.

For the training at frontal sites EEG was recorded with bipolar montages at Fp1-F3 and Fp2-F4 and again the software calculated the difference signal which was used as feedback parameter for the reward frequency band.

The scalp positions where sintered Ag/AgCl electrodes were placed were prepared with Nuprep abrasive skin prepping gel and Ten20 EEG paste was used as conductive paste.

The training was performed using a two monitor solution: on one monitor the EEG signals were displayed and observed by the trainer while the second monitor was used as display for the feedback animations.

Feedback animations and sounds

In contrast to the NF trainings described above, in the ANF training feedback was either provided via a combination of sounds and visual feedback animations (for

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[18] However this analysis is not part of the present thesis as the software did not allow performing this type of analysis. If this possibility will be implemented in the software in the future, analysis will still be inaccurate as long as no markers are saved together with the EEG data whenever the reward frequency band is changed.

training at temporal and frontal sites) or solely via sounds (for training at parietal sites) depending on the training protocol. Subjects were instructed to attend to the moments when the animation is moving and when a sound is played, knowing that it tells them that their brain is in the desired state (Brenninkmeijer, 2010).

At the beginning of training subjects were allowed to choose from a set of “peep” or “click” sounds and choose the one that they experienced as most comfortable. They either chose the same or two different sound for the training at temporal and for the training at frontal sites. For the training at parietal sites the MIDI sound 99 “atmosphere” was played for all subjects that was modulated in frequency and duration as described above.

Visual feedback animations were only used for the training at temporal and frontal sites as the training at parietal sites was performed with closed eyes. On each training day subjects were allowed to choose from a set of animations that comprised video clips with changing colorful or abstract patterns as well as e.g. scenes of a swimming dolphin. Brain activity changes were used to modulate the speed of the video which ranged between normal speed and a pause of the movie. In addition, photographs on a whole variety of topics were available that were covered by small squares and were gradually uncovered as squares disappeared and revealed parts of the picture whenever the feedback criterion was fulfilled. Starting from the day when transfer tasks were introduced into training a training protocol always ended with the same picture to be uncovered or the same movie clip in order to anchor the state achieved during this training period.

Contingent feedback and transfer trials

Due to the concept behind the adaptive training, training always was accompanied by contingent feedback and no transfer trials were included as they are not realizable within this training concept.

Strategies

For the same reason that transfer trials cannot be included in the adaptive training also strategies are not part of this training concept.

However, on each training day always the same picture or video clip were presented at the end of a training protocol and subjects were asked to anchor their state achieved during training to this picture or video. For the training at parietal sites the “atmosphere” sound acted as such an anchor.

Transfer tasks

Similarly as in the FQ and SCP neurofeedback groups, subjects trained the application of the mental states achieved during training in transfer tasks. They mainly used the state trained during training at frontal sites to prepare for the task and become focused. Many subjects used the anchor image or video scene to activate the desired state. But some subjects, for whom it was important to calm down or motivate themselves, used the mental state of the parietal or temporal training additionally or instead of the state related to frontal training. In addition, they were instructed to reactivate this mental state also during performing the task when they felt they were losing it.

Transfer to daily life situations

Subjects practiced these mental states in daily-life situations in which it was important for them to be alert, to calm down/ relax, or to lighten up their mood. Subjects documented the situations in which they exercised and estimated how well their strategy helped them to acquire the desired state.

3.2.2 Control training

On the one hand, the control training was designed to control for practice effects due to repeated testing in the NF groups. For this reason subjects of the control group performed the same pre and post assessments as the NF groups within a similar time interval. In addition, their training consisted of completing the same questionnaire regarding their satisfaction with their life situation and performing the same transfer tasks (darts, CPT-OX) as the NF groups.

On the other hand, the control training was designed to control for unspecific training effects related to the NF trainings, i.e. the use of a cognitive strategy to activate a mental state favorable for the task to be performed. For this reasons, subjects of the control group also used cognitive strategies while performing the transfer tasks.

The control training comprised six sessions of about 20-30 minutes each. In order to keep the time interval between pre- and post-assessment as well as the time interval between pre-assessment and the first transfer task similar to the NF groups, the first training session of the control group started about two weeks after the pre-training assessment. As for the NF groups the transfer tasks started in the 5th double session and as the control training was designed to start with these transfer tasks, the training of the control group (mean number of weeks: *M* = 3.17, *SD* = .99) was a bit shorter than the training of the NF groups. On average also two sessions were conducted per week (number of sessions per week: *M* = 2.08, *SD* = .67).

Similar to the NF groups, before performing the transfer tasks, subjects developed individual cognitive strategies that helped them to achieve a relaxed but focused state of mind or a state of sustained attention. Most subjects used mental imagery of situations in which they experienced this state (e.g. performing a sport, reading an interesting book). Subjects were then instructed to activate these strategies before starting the transfer task.

Subjects of the control group were asked in the same way as subjects of the NF groups to practice their strategies in daily-life situations in which they wanted to achieve a focused or relaxed state, or lighten up their mood. Exercises were discussed at the beginning of each training session. Subjects documented the situations in which they exercised and estimated how well their strategy helped them to acquire the desired state.

As in the NF groups, momentary well-being as well as satisfaction with their life situation were assessed (see 3.2.1 Neurofeedback trainings).

3.2.3 Assessments

3.2.3.1 Pre- and post-training assessments

The pre-training as well as the post-training assessments consisted of a short and a long assessment that took part on different days as well as self-report measures to be filled out at home.

At the short assessment (duration: about 15 minutes) subjects performed a game of darts as a task related to motor skills.

After the short assessment subjects were handed out self-report measures[19] (questionnaires) to be filled out at home (duration: about 1 hour). They were asked to base their ratings on the last seven days. Subjects of the NF group brought the

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[19] All self-report measures were in German. In the following, descriptions for each measure were translated into English as best as possible.

questionnaires to the first training session while subjects of the control group sent them back within one week in a stamped envelope provided by the investigator[20]. They were asked to fill out the questionnaires in a state of mind that they consider “normal”[21] for themselves.

The long assessment (duration: about 3 hours) started like the short assessment, i.e. subjects performed a game of darts. In a next step, EEG electrodes were hooked up and a resting EEG was recorded. Then, subjects performed two attention-demanding tasks while event-related potentials were recorded: a working memory task, and the Attention Network Test. Finally, transcranial magnetic stimulation parameters were assessed in a resting-state.

Self-report measures

Brown Scale

A German short version of the Brown attention-deficit disorder scales (Brown, 1996) was used as a measure for attention. It consists of 20 items that are rated on a four-point scale indicating how often the described behavior occurred within the last week (*never*, *once*, *twice*, *almost daily*). The questionnaire provides a total score (calculated as the sum of all item ratings) which will be used for analysis of training effects.

In addition, the questionnaire provides the following five subscores: 1. organizing, prioritizing, activation to work; 2. focusing, sustaining and shifting attention to tasks; 3. regulating alertness, sustaining effort and processing speed; 4. managing frustration and modulating emotions; 5. utilizing working memory and accessing recall. These subscores will be used for the analysis relating NF regulation abilities to attentional abilities as assessed by this questionnaire.

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[20] The training of the control group started later than for the neurofeedback groups as the training of the control group consisted of the transfer tasks that started in the 5th session of the neurofeedback trainings. For this reason they were asked to send the questionnaires back by mail in order to make sure that they were filled out within one week from the short and long pre assessments like in the neurofeedback groups.

[21] compared to being in an especially good or bad mood.

Adjective Checklist EWL-N

The adjective checklist (“Eigenschaftswörterliste” EWL-N; Janke & Debus, 1978) is a more dimensional method to describe aspects of well-being. It consists of a list of 161 adjectives that are rated on a two-point scale (*applicable*, *not applicable*). The questionnaire consists of the following 15 scales which are formed by summing up the number of the respective item ratings: activation, concentration, deactivation, fatigue, benumbed, extraversion, introversion, self-confidence, mood, arousal, sensitiveness, anger, anxiety, dejection, and dreaminess. As this is a very comprehensive questionnaire, six scales that were considered most relevant to assess training effects were selected for data analysis: concentration, deactivation, self-confidence, mood, sensitiveness, and dejection.

Profile of Mood States (POMS)

The POMS is a questionnaire assessing mood states (McNair, & Dropleman, 1992). The German version of the POMS (Albani et al., 2005) consists of a list of 35 adjectives that are rated on a seven-point scale (ranging from *not at all* to *very strong*) and assesses the following four scales: dejection, fatigue, displeasure, and vigor which are formed by summing up the respective item scores.

HAKEMP-90

The HAKEMP-90 (Kuhl, 1990, 1994) assesses action orientation after failure (AOF) as well as prospective action orientation (AOP). The questionnaire consists of 24 questions describing a situation and for each questions two possible answers are provided out of which one answer is to be selected. The two scales AOF and AOP are calculated by summing up the number of answers selected that belonged to items of the respective scale.

Self-access questionnaire

The self-access questionnaire consists of 14 items that are rated on a 4-point scale ranging from *not applicable* to *exactly applicable*. Scores of negatively formulated items are transformed by subtracting them from four. The total score is then formed by summing up all item scores.

Perceived Stress Scale (PSS)

The PSS (Cohen, Kamarck, & Mermelstein, 1983) assesses the amount of perceived stress by means of 14 statements that are rated on a 5-point scale ranging from “never” to “very often”. The score is calculated by summing across all 14 items.

Short assessment

Game of darts

In the game of darts subjects threw darts on a concentric dart board (see Figure 4) on which scores got higher from the border towards the center (outermost circle: 1 point, circle around the bull’s eye: 11 points, bull’s eye: 20 points). Subjects were instructed to score as high as possible from a distance of 2.35 meters. The game of darts consisted of two variants.

Figure 4. Concentric dart board.

Variant 1 (NoStress): Subjects threw 6 darts in a row (= 1 trial) on the board (within 30 seconds) while standing on a pedestal of 20 cm height.

Variant 2 (WithStress): Subjects played darts as described in variant 1, but this time the pedestal was vibrating and in addition from loudspeakers behind them a noise sound[22] was played. The aim of this variant was to generate a situation that was more demanding and stressful.

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[22] The noise sound was a white noise signal modulated with some special effects using the software Audacity (for further information please refer to http://audacity.sourceforge.net/).

First of all, subjects performed one test trial of each variant. Then, subjects performed each variant three times, i.e. they threw the darts 36 times. The two variants were presented alternatingly.

The game of darts was assessed again at the long assessment in order to obtain more stable results.

Parameterization: For each variant, the mean score of all throws (of the short and long assessment taken together) was calculated.

Long assessment

The long assessment started like the short assessment with a game of darts. In a next step, EEG electrodes were hooked up.

EEG recordings

Electroencephalogram was recorded from 23 sites (electrodes of the 10–20 system and Fpz and Oz; recording reference: FCz; ground electrode: CPz; bandwidth: 0.016–120 Hz; sampling rate: 500 Hz) using a BrainAmp amplifier (Brain Products, Munich, Germany). Sintered silver/silver-chloride (Ag/AgCl) electrodes and Abralyt 2000 electrolyte were used for recordings. In addition, vertical and horizontal EOG were recorded from two electrodes placed above and below the right eye and at the outer canthi. Impedences were kept below 20 kΩ. These recording parameters are valid for all tasks described below in which EEG or ERPs were recorded.

Resting EEG: Recording and data analysis

Two minutes of EEG were recorded in an eyes-open resting condition while subjects sat quietly in front of a monitor looking at the center of a blank screen.

Data analysis was done using the software program Vision Analyzer (Brain Products, Munich, Germany). EEG was down-sampled to 256 Hz, re-referenced to the mastoids, and filtered offline with a .1–30 Hz, 12 dB/octave Butterworth filter, and a 50-Hz notch filter. The method of Gratton and colleagues (Gratton, Coles, & Donchin, 1983) was used for correction of occular artifacts. EEG recordings were segmented into four-second long, non-overlapping segments. A segment was removed from further analysis if the amplitude at any EEG electrode exceeded ± 80 µV. If less than 10 artifact-free segments were available, this subject was excluded from further analysis.

For each segment, the Fast Fourier transform was calculated. The spectra obtained for each subject were averaged. Voltage values were calculated for the following frequency bands: theta (4–7.75 Hz), alpha (8–12.75 Hz) and beta (13–20 Hz). For further analysis the midline electrodes Fz, Cz, and Pz were considered. Effect size measures (Cohen's d) were based on electrode Cz for the theta and beta frequency band, as this is the electrode site targeted by theta/beta training in the FQ group, and on electrode Pz for the alpha frequency band, as this is the electrode site target by alpha synchrony training in the ANF group.

Working memory task

Subjects performed a visual working memory task while their ERPs were recorded. They were comfortably seated in front of a monitor and their ERPs were recorded with the same setup as for the resting EEG (ERP data of this task will not be presented in the thesis at hand). The working memory task was very similar to the one employed by Studer and colleagues (2010). The only differences were that instead of line drawings pictures of the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2005) were used, and that due to the higher complexity of these pictures presentation time of a picture was slightly increased.

In the working memory task five or six pictures were presented consecutively on a computer screen using Presentation software (Neurobehavioral Systems, Albany, US). Stimuli for each trial were randomly chosen from a set of 270 pictures selected from the IAPS. Pictures presented in a trial belonged to one of three categories of emotional content: neutral, positive, or negative. As depicted in Table 2, based on the IAPS data

Table 2

Working memory task: valence and arousal ratings

	valence	arousal
neutral	5.00 ± .27	2.75 ± .43
positive	7.07 ± .55	5.64 ± .63
negative	2.69 ± .61	5.69 ± .59

Note. Mean valence and arousal (with STD) for neutral, positive and negative pictures used in the working memory task. These valence and arousal values are based on the IAPS ratings of male and female subjects combined as in our study gender of participants was mixed. Ratings are based on a 9-point scale with the value 1 representing very low valence or arousal ratings and the value 9 representing very high valence or arousal ratings.

base neutral pictures were rated as having a neutral valence indicated by a valence value of 5.00 which lies exactly in the middle of the valence scale which ranges from 1 (very negative) to 9 (very positive). As expected for neutral pictures the arousal rating resulted in a relatively low value. Valence ratings for positive and negative pictures were comparably distant from the mean of the valence scale (i.e. the neutral value), indicating that their valence values are comparable within their respective category. In addition, the mean arousal of positive and negative pictures was the same. For practice trials an additional set of 45 pictures (15 of each category) were used.

Each picture was presented at a visual angle of 7.45 degrees for 700 ms with a stimulus onset asynchrony of 1100 ms (encoding phase). The encoding phase was followed by a blank screen for 4000 ms (retention phase). Next, one of the pictures presented during the encoding phase was shown as probe picture and subjects were asked to press a button indicating its position in the original sequence (retrieval phase). Following their response, a sound indicated whether the response was correct. The task comprised four blocks consisting of 24 trials each. All pictures of a trial were of the same emotional content. In each block the same number of trials with pictures with neutral, positive, and negative emotional content were presented, while the order of these trials was randomized. The four task blocks comprised two variants: 2 blocks consisting of trials in which five pictures were presented consecutively (variant 1: lower working memory load) and 2 blocks of trials in which 6 pictures were presented consecutively (variant 2: higher working memory load). Task blocks of variant 1 and variant 2 were presented alternatingly.

Each block was preceded by practice blocks of four trials. Practice blocks were repeated until the subject scored correctly on three out of four trials, but maximally seven practice blocks were conducted. The aim of these practice blocks was to give the subjects the chance to try different strategies of how to remember the order of the pictures. They were asked to keep their strategy throughout the task and to use the same strategy in the post assessment. In the post assessment each block was preceded by only one practice block.

Parameterization: The mean number of correct responses was calculated for all trials, separately for trials with lower and higher working memory load as well as separately for trials with pictures of neutral, positive, and negative emotional content. ERP results of this working memory task will not be presented in the present thesis.

Attention Network Test (ANT)

Subjects performed the Attention Network Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002; Posner & Petersen, 1990) while brain electrical activity was recorded. The ANT in the present study was realized in the same way as described in Kratz and colleagues (Kratz, Studer, Malcherek, et al., 2011) with the only difference being that in the present study two different conditions were included as described below.

The ANT is based on an attention network theory developed by Posner and Petersen (1990) which describes a system of selective attention. This system consists of three functionally segregated networks with each network being related to a specific form of attention: alerting, orienting, and executive attention (Posner & Rothbart, 2007). Alerting attention is defined as being able to achieve and maintain a state in which one is very sensitive to appearing information. Orienting attention comprises being able to select information from sensory input. Executive attention is related to conflict monitoring and resolution, which is why this attention network is also known as the conflict network.

The ANT version (see Figure 5) as developed by Rueda et al. (2004), which is a version designed for children, was realized in Presentation (Neurobehavioral Systems, Albany, CA, USA). A fixation cross was presented on the center of the screen, and subjects were instructed to visually fixate on this point. Their task was to feed a hungry fish which appeared above or below the fixation cross (about 1°) by pressing the left and right mouse button if the fish looked to the left and right, respectively. This fish was the target fish, which was visible for 350 ms. The target fish was surrounded by four flanking fish, two on each side, which were presented 100 ms before the target fish appeared. These flanking fish were used to construct congruent trials, in which all fish pointed in the same direction, and incongruent trials, in which the flanking fish pointed in the other direction than the target fish. Each fish subtended 1.6 degrees of visual angle and the contours of adjacent fish were separated by 0.21 degrees.

Furthermore, three cue conditions were included in the task, which were all valid cue conditions and which were presented with equal probability. These cues appeared 1400 ms before the target fish and were shown for 150 ms. The duration of the cue-target interval was increased with respect to the original ANT version (Fan et al., 2002), in order to be able to measure a CNV during the preparatory phase before the target fish appeared. In the first type of cue condition no cue was presented (NoCue condition). In the second type of cue condition, an asterisk appeared at the center of the screen and indicated the target fish was to be presented soon (NeutralCue condition). A third type of cue condition was a cue which was shown exactly at the location where the target fish will be presented, thus indicating besides the information that the target fish will appear soon also its location (SpatialCue condition). Viewing distance was about 72 cm. The intertrial interval varied randomly between 3.5 and 5.0 s.

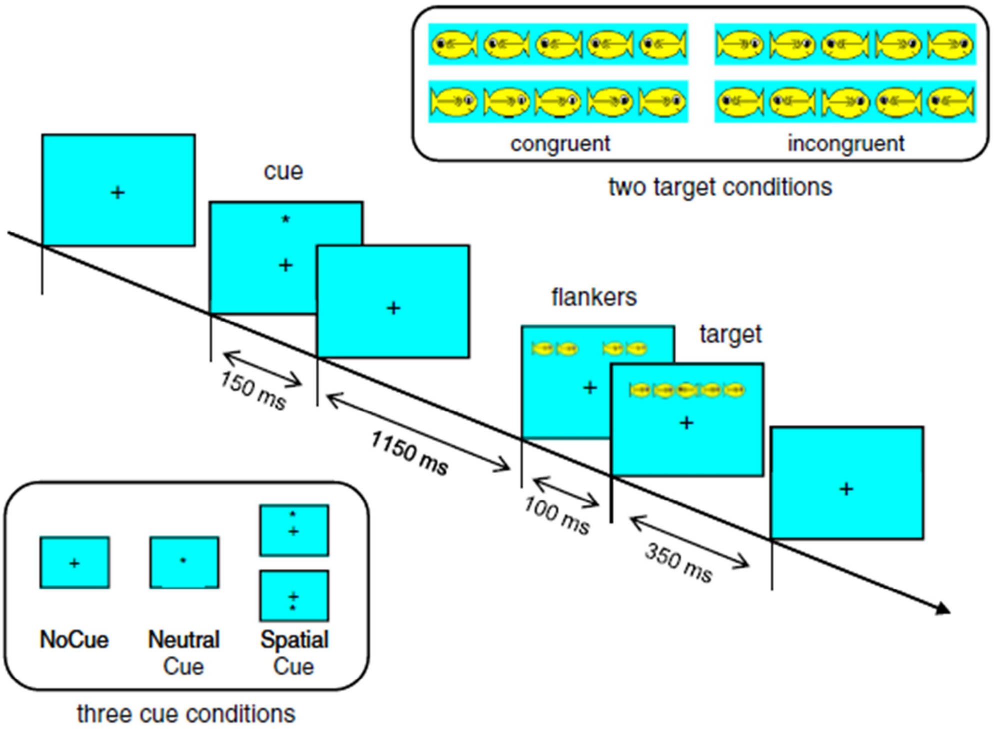

Figure 5. Illustration of the Attention Network Test (ANT).

The ANT version used in the present study is depicted. “In each trial, one of three cue conditions (NoCue, NeutralCue, and SpatialCue) preceded the target fish which either pointed to the left or to the right. The flanker fish either pointed in the same (congruent) or opposite direction than the target fish (incongruent). […] [Participants] were asked to feed the target fish by pressing the button that matched the direction in which the target fish was pointing.” (Kratz, Studer, Malcherek, et al., 2011, p. 85).

The task was performed in two variants: in variant 1 the task was performed as described above, while in variant 2 in addition a noise sound (the same sound used for the darts game) was presented via loudspeakers positioned on the left and right side of the monitor.

Instruction of participants was performed in a standardized way. Next, participants performed a practice block of 12 trials of variant 1, followed by a practice block of 12 trials of variant 2. The test itself consisted of four blocks of 48 trials each, two blocks of each variant. The two variants were presented in the order 1-2-2-1 or 2-1-1-2.

At the end of a block the number of correct responses was presented on the screen next to a picture of a fish. If participants succeeded in achieving 40 or more hits, this fish was blowing bubbles to indicate good performance. The test lasted for about 20 minutes including short breaks between the blocks.

The following performance measures were determined according to Fan et al. (2002). Hits, mean reaction time (mean RT), and variability of RT (RTV) were assessed as basic performance parameters. Reaction time measures were based on trials with correct responses which were required to occur between 200 and 1500 ms after onset of the target stimulus. In addition, related to the attention networks the following measures were assessed: alerting score (RT for NoCue trials minus RT for NeutralCue trials), orienting score (RT for NeutralCue trials minus RT for SpatialCue trials) and conflict score (RT for incongruent trials minus RT for congruent trials). The interpretation of training effects related to these attention network scores will be based on the following assumption: a smaller alerting score could be related to the ability to maintain alertness even without a cue and thus indicate stronger alerting. Thus, training effects are expected to be reflected in smaller scores (Tang et al., 2007).

ERP data was analyzed with the VisionAnalyzer software (Brain Products, Munich, Germany). Electrical activity was filtered from .05 to 30 Hz using 24 dB/oct. Butterworth filters and a 50 Hz notch filter was applied. Signals were rereferenced to linked mastoids. Eye movement artifacts were corrected with the method of Gratton et al. (1983). If the amplitude exceeded ±80 μV at any electrode, a section of -500 to +500 ms around this artifact was excluded from further analyses.

Separate analyses were performed for cue and target processing based on averaged responses of the following segments. For the analysis of the interval between cue and target presentation, segments of 1800 ms length were formed, which started 230 ms before cue presentation. Target processing was analyzed based on segments of 1250 ms length, which started 125 ms before target presentation. In order to avoid distortion of the ERP topography no baseline correction was applied (e.g. Brandeis et al., 1998). Only trials with correct responses were considered for further analysis. Averaged responses of a participant were also required to be based on at least 20 artifact-free segments in order to be included in further analysis. If an artifact was detected in one channel, the segment containing the artifact was removed in all channels.

As the CNV was most pronounced at Cz, analysis was based on this site. For all cue conditions, CNV was determined as the mean amplitude in the time window 1000 to 1300 ms after cue onset. CNV amplitudes of the NeutralCue and SpatialCue conditions were considered for further analysis[23].

P3 amplitudes to cue as well as to target stimuli were maximal at Pz, which is why analysis was based on Pz. For the analysis of cue processing, the P3 was determined as the most positive peak at Pz in the time window 200–800 ms after cue presentation. For the analysis of target processing, the P3 was determined in a similar way but based on the time window 280–450 ms after target presentation. For cue-P3 amplitudes peaks of the NeutralCue and SpatialCue conditions were considered for further analysis[24], while for the target-P3 also amplitudes of the NoCue condition were included.

Transcranial Magnetic Stimulation (TMS)

TMS measurements based on the double-pulse paradigm (Kujirai et al., 1993) were performed while subjects remained in a resting state. During TMS measurements, ERPs were recorded simultaneously with the same setup as described above. The only difference was that electrode C3 was removed for this measurement, as the magnetic coil was to be placed on the scalp around this area. Analysis of these ERP measures is not included in the thesis at hand. For the TMS measurements, two additional electrodes were adjusted at the right hand, in order to measure EMG activity of the musculus abductor digiti minimi. One electrode was placed at the little finger, and the other one at the edge of the hand on the side of the little finger. A ground electrode was attached to the forearm close to the wrist. For these EMG recordings, the recording settings of the amplifier were adjusted accordingly (bandwidth: 8–1000 Hz, sampling frequency: 5 kHz). TMS measurements were performed using a figure-of-eight coil (diameter of one wing: 70 mm) connected to a Magstim Bistim unit with two Magstim 200^2 stimulators (Magstim, Whitland, UK).

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[23] As there is no CNV in the NoCue condition CNV analysis was based on the neutral and spatial cue conditions.

[24] As there is no cue-P3 in the NoCue condition CNV analysis was based on the neutral and spatial cue conditions.

Optimal stimulation position over the left motor cortex was determined while subjects rested their right forearm on an armrest, while their hand was hanging down in a relaxed position. Intensity of a single-pulse stimulus was increased until a motor evoked potential (MEP) became visible in the recorded EMG signal of the musculus abductor digiti minimi. Single-pulse stimuli of this intensity were repeated while the position of the magnetic coil was changed. This was continued until the position of the coil was found which elicited the largest MEP. This optimal stimulation position was used for all further measurements.

Before starting with the double-pulse measurement, some basic TMS measurements were carried out in order to adjust all further measurements to the individual parameters of each subject.

First, the resting motor threshold (RMT) – the minimal stimulus intensity that did not elicit an MEP larger than 50 µV in five consecutive trials – was determined while subjects kept their hand in a relaxed position (as described above), i.e when the target muscle was at rest.

Next, the suprathreshold stimulus intensity was determined such that MEP amplitude was about 1 mV (peak-to-peak). For this purpose, single-pulse stimuli were elicited in a range of 10–15% stimulation intensity above the RMT, until the intensity was determined that resulted in an MEP of about 1 mV. In addition, the intensity of the conditioning stimulus was set to 75% of RMT.

In the double-pulse assessment, paired pulses were used for stimulation which consisted of the conditioning stimulus followed by the suprathreshold stimulus. The inter-stimulus-interval of these two pulses was set to 2, 3, 4, or 5 ms for inhibitory trials and to 7, 9, 12, or 18 ms for facilitatory trials. The task consisted of 50 trials that were pseudo-randomized in such a way that within the first 5 trials one single-pulse suprathreshold stimulus was included as well as two inhibitory and two facilitatory trials. The next 5 trials were combined in a similar way and so on. The task consisted of 10 single-pulse stimuli[25], 20 inhibitory trials, and 20 facilitatory trials, while each type of inhibitory and facilitatory condition was presented 5 times. The task was performed

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[25] The stimulation intensity of the suprathreshold stimulus was adjusted during the task within a few percent of stimulation intensity if the amplitude during single-pulse stimulation dropped below 500 µV or exceeded 2 mV in two consecutive trials. Adjustment was only done between the above described blocks of 5 trials.

twice with a short break in between. Presentation (Version 11.0; Neurobehavioral Systems, Albany, CA, USA) was used for triggering of the magnetic stimulators.

Analysis of the EMG data was performed using VisionAnalyzer software (Brain Products, Munich, Germany). Data were segmented into one segment per trial before two types of peak detection were carried out. The first peak detection was used to detect muscle tension occurring directly before stimulation. For this purpose the most positive and most negative peak was determined in a window of 40 ms duration before stimulation. If peak-to-peak amplitude of these peaks exceeded 45 µV, this trial was discarded due to initial muscle tension. The second peak detection was performed to determine the maximum MEP amplitude elicited by TMS stimulation. The most positive and most negative peak was determined in a window of 65 to 100 ms after stimulation. The MEP amplitude was determined as the peak-to-peak amplitude of these two peaks. If MEP amplitude was below 400 or above 2000 µV, the whole block of 5 trials related to this single-pulse trial was discarded. The whole block was discarded as later analysis of facilitatory and inhibitory trials was always performed relative to this single-pulse trial. If less than 14 trials with sufficient data quality remained for inhibitory or for facilitatory trials in the pre or post measurement, this subject was excluded from further analysis.

For all remaining trials of a subject, the MEP amplitude of each inhibitory and facilitatory trial was divided by the amplitude of the single-pulse trial of the corresponding block of 5 trials. Thereby, relative MEP amplitudes were obtained with the corresponding single pulse MEP amplitude being defined as 1. These relative MEP amplitudes were averaged over all inhibitory conditions as well as over all facilitatory conditions. This procedure resulted in an average of inhibitory and facilitatory relative MEP amplitudes per subject reflecting SICI and ICF, respectively.

General information regarding all assessments

For those tasks that were performed in two variants, the variant with which the task started was randomly selected. The order was balanced within each group. For each subject the order was kept the same in pre and post assessments.

At post assessments subjects were asked to bring themselves in the state-of-mind as during a successful training by using their strategies as they did when performing the transfer tasks at the end of a training session.

At both post assessments subjects were able to collect points for successful performance as part of a reward system in which they were able to receive up to 10 € in addition to the fixed amount of money they received for their participation. Points were obtained for showing equal or better performance than in the previous performance of the task (For darts previous performance was the last darts played as a transfer task in the training while for all other tasks previous performance was the pre assessment. In the second post assessment previous performance in darts was the first post assessment). Points were distributed among the different tasks as follows:

- Darts: 1 point for each variant
- Working memory task: 2 points for each variant
- Attention network test: 2 points for the mean number of hits, and 2 points for reaction time.

3.2.3.2 Assessments during training

Satisfaction with life situation

At the beginning of a training session subjects rated their momentary satisfaction with their life situation on a 7-point rating scale ranging from zero (*not content at all*) to six (*very content*).

Evaluation scales

Evaluation scales assessed after the last training session were used to control for ‘placebo factors’ like participants’ expectations on how much they expected the training to influence their attention and well-being and their satisfaction with the training. The questionnaire consisted of 13 items and was rated on a 5-point scale ranging from *not at all / never* to *exactly / always*.

Transfer task: Game of darts

The game of darts[26] was performed in the same way as in the pre- and post-assessments. Subjects were instructed to activate the desired mental state (e.g. by means of their cognitive strategy developed during training) before the start of each trial and if

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[26] As the purpose of the game of darts was mainly to practice with subjects how to activate the desired mental state in a „real life“ situation, these data were not analyzed and will not be presented in the present thesis.

needed also within trials as described in the training section. The trial was started when they signaled that they were ready.

Transfer task: Continuous performance test (CPT-OX)

As a second type of transfer task a cued continuous performance test CPT-OX[27] was used. Subjects were instructed to activate the desired mental state (e.g. by means of their cognitive strategy developed during training) before the start of the task as well as during the task (e.g. in moments when an irrelevant stimulus was presented) as described in the training section. The cued continuous performance test (van Leeuwen et al., 1998) was started when they signaled they were ready.

A short version of the CPT-OX was used, in which 200 letters were consecutively presented in the center of a monitor. Stimulus duration was set to 200 ms with an interstimulus interval of 1400 ms. Subjects were instructed to press a mouse button as fast and as accurately as possible, whenever the target-letter X was presented after the cue-letter O and to withhold their response to any other sequence of letters. Probabilities for the sequence “O – X” as well as for the sequence “O – not-X” were 10 %. As performance measures the number of hits (O – X), commission errors (not-O – X), and impulsivity errors (O – not-X) were analyzed.

Before performing the task for the first time, subjects were presented with a short practice block.

Reward system during transfer tasks

For each transfer task performed during training, subjects were able to collect points for successful performance as part of a reward system as mentioned above. Points were received for performing equally well or better than the previous time. For the first game of darts during training, the previous performance was the darts performed at the last pre-assessment, while for the further games of darts during training it were the game of darts of the previous training. As the CPT-OX was not performed during pre-assessment no points were collected when first performing it. For further training sessions, points were based on the CPT-OX performance of the previous training session.

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[27] As the purpose of the CPT-OX was mainly to practice with subjects how to activate the desired mental state in a „real life“ situation, these data were not analyzed and will not be presented in the present thesis.

Points were distributed among the different transfer tasks as follows (number of points that can be gained by each performance of the task):

- Darts: 1 point for each variant
- CPT-OX: 1 point for number of hits, 1 point for reaction time

3.2.3.3 Self-regulation abilities in theta/beta and SCP training

For the FQ and SCP training group regulation abilities, i.e. how well subjects succeed in self-regulation of specific EEG parameters, have been analyzed in a diploma thesis (Fischer & Schmüser, 2010). As it is important to relate these findings on self-regulation abilities to the further findings of the comprehensive study presented in this thesis, a short version of the methods and results reported more extensively in the diploma thesis will be reported. Self-regulation results presented here were recalculated for the final sample which was included in the thesis at hand, and associations of self-regulation abilities and ERP measures were analyzed in addition.

As described in the introduction (see 1.4 Neuronal mechanisms underlying neurofeedback and the specificity of training effects), measures of self-regulation provide valuable insights regarding the question of specificity of NF training effects: it can be analyzed in how far subjects learned to change their brain activity in the desired direction, and these changes in brain activity in the course of training can be related to changes observed on the behavioral level. Unfortunately, self-regulation abilities could not be analyzed for the ANF group as EEG measures could not be exported from the BrainMaster system for further analysis. In addition, changes in the reward frequency band were not marked within the recorded EEG data, which also would have made tracking of EEG changes related to the respective reward frequency band trained impossible. For this reason, analysis of regulation abilities was restricted to the FQ and SCP groups.

So far, there exists no clear standard for how to best parameterize self-regulation abilities. For a discussion on why the below presented methods were chosen the reader is referred to the diploma thesis. In the diploma thesis, different parameterization methods were presented while here only the combined methods (FQ: theta/beta ratio, SCP: differentiation) will be described[28] with the exception of the analysis related to CNV amplitudes (see below).

For the FQ training group, self-regulation was parameterized as the theta/beta ratio and an improvement in self-regulation abilities is represented by a reduction of the ratio. In the SCP group differentiation between positivity and negativity trials was calculated as the difference of mean amplitudes of these two conditions; an improvement in self-regulation abilities is related to an increase in this difference.

In order to analyze whether subjects learned the desired self-regulation in the course of training, self-regulation in the first two training sessions (average value of session one and two) was compared to self-regulation of the last two training sessions (average value of session nine and ten). Self-regulation measures presented here do not differentiate between trials with contingent feedback and transfer trials.

In a second step, based on these changes in self-regulation abilities from the start to the end of training each group was divided into good and bad performers by means of a median split. It was assessed whether good performers improved more from pre- to post in attention (Brown Scale total score and subscores for the 5 clusters), well-being (POMS), motor skills (game of darts), and ERP measures (CNV, P3) than bad performers. Change from pre to post training for a particular measure was calculated by subtracting the score obtained at pre assessment from the score obtained at post assessment and will be referred to as change score.

In addition to the above described analyses, for the analysis related to CNV amplitudes self-regulation abilities were analyzed based solely on regulation abilities in negativity trials. This approach was chosen as negative SCPs are closely related to the CNV, which has been shown to be increased after SCP training (Wangler et al., 2011).

3.2.4 Statistical data analysis

3.2.4.1 General information on statistical analysis

Due to the unintended heterogeneity of the sample (as discussed in chapter 5.1 The sample) in combination with a relatively small sample size, the following procedure

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[28] In the diploma thesis the good/bad performer analysis was e.g. also performed in FQ training for theta and beta measures separately, as well as in SCP training for positivity and negativity measures separately. Here, only the combined parameterization methods were chosen in order to represent regulation ability per training type by a single parameter, for which results will be presented.

of analysis was chosen. Outliers were determined for each measure and excluded from further analyses. Outliers were defined as deviations of more than ± 2.5 standard deviations[29] of the mean value of a measure. The mean value of a measure was calculated for the whole sample based on the pre and post assessment data taken together. If a value of a subject at pre or post assessment was defined as outlier, this subject was excluded from this specific analysis. The number of subjects included in each analysis can be extracted from Appendix A, B, and C.

In order to assure that this approach of excluding outliers did not affect the result pattern two further data analyses were performed. One analysis included only those subjects that would have been admitted to the study ($n = 48$) based on the originally more strict selection criteria of healthy adults without a sub-clinical symptomatology of some kind. Another analysis was performed including all subjects, i.e. without exclusion of outliers. Both additional analyses yielded a very similar results pattern to the one obtained by the final analysis[30]. These findings support the chosen approach of data analysis as adequate.

Statistical analyses were performed with the software PASW Statistics (v.18). In order to adjust for violations of sphericity, Greenhouse-Geisser correction was applied to critical *p*-values. Statistical significance was assumed if $p \leq .05$. For significant results as well as for trends obtained in ANOVA analyses, effect sizes were calculated as partial eta square (η_p^2). Small effects are observed if $\eta_p^2 > .01$, medium effects if $\eta_p^2 > .06$, and large effects if $\eta_p^2 > .14$ (Cohen, 1988).

Furthermore, in these cases post-hoc tests were performed and due to multiple testing Holm-Bonferroni correction was applied to adjust the significance level. If *n* post-hoc tests were performed, the resulting *p*-values were ordered and the smallest *p*-value was compared to '$.05 / n$', the next smallest *p*-value was compared to '$.05 / (n – 1)$', and so on. As soon as the first *p*-value did not meet to criterion to be smaller or equal to the critical *p*-value, which is determined according to the procedure described above, all further post-hoc tests were considered non-significant.

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[29] A more common and at the same time more strict approach would have been to define outliers as deviations of more than ± 2 standard deviations of the mean. This approach was not selected as too many subjects would have been classified as outliers, which would have resulted in an even smaller sample size.

[30] These additional analyses could not be performed for the TMS measures because group sizes became too small, since TMS measures had not been assessed for all subjects.

In addition, in order to control for potential pre-training differences between groups for all measures ANOVAs were calculated for pre-training data. These results were only reported if significant pre training differences were observed.

Due to relative small group sizes and adherent small statistical power, in addition to results based on ANOVAs effect sizes (Cohen's *d*) were reported. Effect sizes were used to depict training effects of each NF group compared to the control group.

In order to calculate these effect sizes, first the difference of the mean values of a measure from pre to post assessment was calculated for each group resulting in a so called change score for each group. Next, the difference of the change score of one NF group and the corresponding change score of the control group was calculated and divided by the pooled standard deviations of these two change scores (see Equation 1). For each measure, this calculation was performed for each NF group compared to the control group.

Effects were interpreted following the notion that Cohen's $d \geq .20$ indicates a small, Cohen's $d \geq .50$ a medium, and Cohen's $d \geq .80$ a large effect.

$$Cohen's\ d = \frac{change_{\text{ NF}} - change_{control}}{\sqrt{\frac{SD_{NF}^2 + SD_{control}^2}{2}}}$$

Equation 1. Calculation of the effect size (Cohen's *d*).
Note. $\text{Change}_{\text{group}} = \text{M}_{\text{post\_group}} - \text{M}_{\text{pre\_group}}$

In order to visualize these gradations in tables, Cohen's *d* values were depicted in grey letters if there was no effect, in black letters if there was a small effect, in bold black letters if there was a medium effect, and in underlined bold black letters if there was a large effect. To improve readability, the sign of Cohen's *d* values reported was changed in such a way, that positive values indicate a larger improvement / smaller decline in the NF compared to the control group and negative values indicate a larger improvement / smaller decline in the control compared to the NF group.

In a similar way, in order to compare effects of the three different NF protocols, effect sizes for all measures were also calculated for each NF group compared to each other NF group. The only difference regarding the depiction of these effect sizes in a table will be that positive values indicate a larger improvement / smaller decline in the

NF group mentioned first, while negative signs indicate a larger improvement / smaller decline in the NF group mentioned second.

An exception of this convention of the utilization of positive and negative signs for effect sizes was made in the resting EEG analysis as well as in the TMS analysis. For these two measures it was not fully clear which direction of a pre-post change (increase vs. decrease) constituted an improvement. For this reason, effect sizes were reported within brackets to indicate that positive and negative signs may have another significance than for all other measures. Clear information will be provided below each table to indicate the way in which effect sizes are reported.

3.2.4.2 Statistics: self-report measures

For each self-report measure (for the total score if available, otherwise for each subscale) a repeated measure ANOVA with the within-subject factor TIME (pre, post) and the between-subject factor GROUP (FQ, SCP, ANF, CON) was calculated.

3.2.4.3 Statistics: performance data

Game of darts

The effects of type of training on darts performance were analyzed by means of a repeated measure ANOVA with the within-subject factors TIME and STRESS (NoStress, WithStress) and the between-subject factor GROUP.

Working memory task

In order to assess effects of type of training on working memory performance a repeated measure ANOVA was calculated with the within-subject factors TIME, LOAD (5 pictures, 6 pictures), and EMOTION (neutral, positive, negative) and the between subject-factor GROUP.

Attention network test

Data analysis was performed analogue to the methods described by Kratz and colleagues (Kratz, Studer, Malcherek, et al., 2011) but with the difference that here pre-post effects were analyzed additionally.

In order to assess the effects of training type on the basic performance parameters hits, reaction time, and variability of reaction times separate repeated measure

ANOVAs were calculated with the within-subject factors TIME and STRESS and the between-subject factor GROUP.

In a further step, for the analysis of the effects of training type on the three attention networks separate repeated measure ANOVAs were calculated for the RT data related to each attention network. These ANOVAs included the same factors as for the basic performance parameters. In addition, a within-subject factor was introduced depending on the attention network to be analyzed: ALERTING (NoCue, NeutralCue), ORIENTING (NeutralCue, SpatialCue), or CONFLICT (congruent, incongruent).

Effect size measures related to the attention networks were based on the alerting, orienting, and conflict scores (confer page 70 for calculation of these scores).

3.2.4.4 Statistics: neurophysiological data

Resting EEG

Repeated measure ANOVAs with the within-subject factors TIME and ELECTRODE (Fz, Cz, Pz) and the between-subject factor GROUP were calculated for each frequency band to assess effects of training on these resting EEG parameters.

Attention network test

Analogue to the performance data, ERP measures were analyzed based on the three attention networks[31]. For target-P3 amplitudes analyses were performed for all three networks, while for cue-P3 and CNV amplitudes only the orienting network could be analyzed[32]. That is, for cue-P3, target-P3 as well as for CNV amplitudes repeated measure ANOVAs were calculated with the within-subject factors TIME, STRESS and ORIENTING and the between-subject factor GROUP. For target-P3 amplitudes, in addition ANOVAs were calculated including the within-subject factor ALERTING or CONFLICT instead of ORIENTING.

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[31] As for the performance data, analysis methods of ERP data related to the attention networks was also based on Kratz et al. (Kratz, Studer, Malcherek, et al., 2011).

[32] As in the preparatory interval no cue-P3 or CNV is elicited if no cue is presented, the NoCue condition was not analyzed for these processing stages. As the NoCue condition is needed to analyze alerting effects, alerting effects could not be calculated related to cue-P3 and CNV measures. As the conflict measure is related to target stimuli it cannot be analyzed for the cue-P3 and CNV which occur before target stimuli are presented.

TMS

Repeated measure ANOVAs with the within-subject factor TIME and the between-subject factor GROUP were calculated separately for SICI and ICF measures.

3.2.4.5 Statistics: assessments during training

Satisfaction with life situation

The scores obtained from the satisfaction with life situation ratings of a participant were averaged across all training sessions und subjected to a one-way ANOVA with the between-subject factor GROUP.

Evaluation scales

One-way ANOVAs with the between-subject factor GROUP were calculated for participants' ratings on the expected effect of training on attention (item 1) and well-being (item 2) as well as for their satisfaction with the training (average score of items 6 to 13).

3.2.4.6 Statistics: self-regulation abilities in theta/beta and SCP training

One-sided Student's t-tests were applied for the analysis of training effects related to self-regulation abilities as well as to establish a relation between good/bad performers and behavioral or ERP measures. Because using a median split resulted in very small group sizes for analysis, outliers were not excluded, except in special cases where it is specifically stated in the results section. Results will be reported on the one hand based on the significance level $p \leq .05$ as well as for $p \leq .01$ in order to somewhat account for multiple testing (Bonferroni correction was considered too strict and therefore not appropriate for this analysis). Due to multiple testing trends ($p \leq .10$) will not be considered.

4 Results

4.1 Self-report measures (pre-post)

4.1.1 Brown Scale: Attention

For the total score of the Brown Scale (see Figure 6), the repeated measure ANOVA revealed a trend for the factor TIME ($F(1,65) = 2.98$, $p < .10$, $\eta_p^2 = .04$) indicating a trend towards reduced values at post measurement, i.e. increased attention. However, no significant interaction of TIME × GROUP ($F(3,65) = .60$, n.s.) was obtained denoting no significant difference in improvement of attention from pre to post between groups. In addition, no significant effect was present for the factor GROUP ($F(3,65) = .91$, n.s.), i.e. there were no significant group differences in general regarding attention as measured with the Brown Scale.

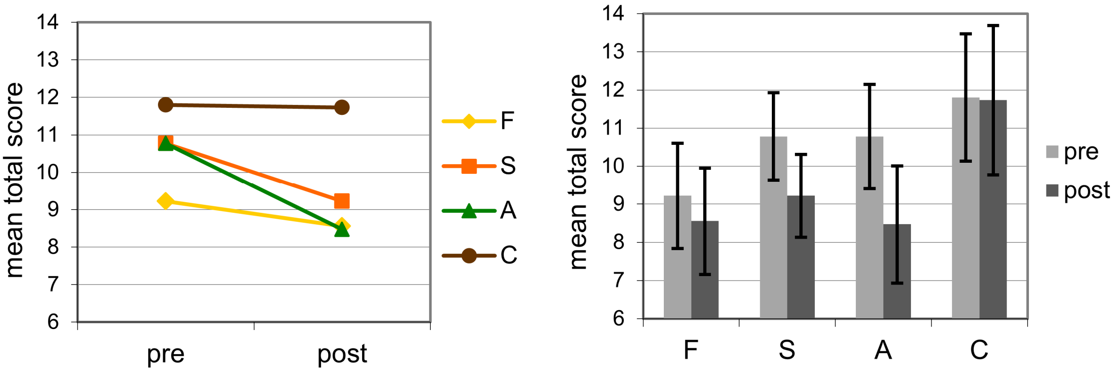


Figure 6. Brown Scale.

For the pre- and post-assessment, the mean total score of the Brown Scale is depicted for each group. If smaller scores are observed at post-assessment these indicate improved attentional abilities. Left: Illustration of the comparison of pre-post changes in the mean total score of the Brown Scale between groups. Right: Illustration of the comparison of the change from pre- to post-assessment per group including error bars. Pre: pre assessment, post: post assessment, F: theta/beta training group, S: slow cortical potential training group, A: adaptive neurofeedback group, C: control training group.

Note. In principle both figures depict exactly the same data. However, in order to allow for a clear illustration of both comparisons of pre-post changes between groups as well as pre-post change within a group, both types of figures are displayed. This procedure was also applied in the following results section.

When looking at effect sizes, only small effects were observed (see Table 4). A small effect was obtained for the SCP (SCP vs. CON: Cohen’s $d = .25$) and ANF group (ANF vs. CON: Cohen’s $d = .41$) compared to the CON group. Comparison of effect sizes for pre-post changes between NF groups yielded small effects for the ANF group in comparison to the FQ and SCP groups (FQ vs. ANF: Cohen’s $d = -.35$, SCP vs. ANF: Cohen’s $d = -.23$).

4.1.2 Adjective checklist EWL-N: Attention and well-being

For each group, mean scores at pre- and post-assessment for all subscores of the EWL-N are depicted in Table 3. The repeated measure ANOVA for the subscale concentration yielded a significant interaction of TIME × GROUP ($F(3,65) = 2.86$, $p < .05$, $\eta_p^2 = .12$) while the factors TIME ($F(1,65) = 1.14$, n.s.) and GROUP ($F(3,65) = .76$, n.s.) did not reach significance.

Post-hoc tests based on paired comparisons revealed significant effects for the ANF compared to the FQ (TIME × GROUP for ANF vs. FQ: $F(1,33) = 5.58$, $p = .024$, $\eta_p^2 = .15$) and CON group (TIME × GROUP for ANF vs. CON: $F(1,30) = 5.35$, $p = .028$, $\eta_p^2 = .15$). In addition, trends were obtained for the SCP compared to the FQ (TIME × GROUP for SCP vs. FQ: $F(1,35) = 2.90$, $p = .098$, $\eta_p^2 = .08$) and CON group (TIME × GROUP for SCP vs. CON: $F(1,32) = 3.28$, $p = .080$, $\eta_p^2 = .09$). These effects were related to pre-post increases in concentration in the ANF group in combination with a decrease in the FQ and CON groups and a slight increase in the SCP group. No significant results were obtained for the FQ compared to the CON group (TIME × GROUP for FQ vs. CON: $F(1,31) = .22$, n.s.) and for the SCP compared to the ANF group (TIME × GROUP for SCP vs. ANF: $F(1,34) = .26$, n.s.). However, when applying Holm-Bonferroni correction, no significant results were obtained as the smallest p value was larger than .05 / 6.

A trend for the interaction of TIME × GROUP ($F(3,67) = 2.66$, $p < .10$, $\eta_p^2 = .11$) was obtained for the subscale deactivation, but no significant effect were obtained for the factors TIME ($F(1,67) = 2.25$, n.s.) and GROUP ($F(3,67) = 1.15$, n.s.).

Post-hoc tests based on paired comparisons yielded significant effects for the FQ and ANF compared to the CON group (TIME × GROUP for FQ vs. CON: $F(1,34) = 6.26$, $p = .017$, $\eta_p^2 = .16$; TIME × GROUP for ANF vs. CON: $F(1,33) = 4.27$, $p = .047$, $\eta_p^2 = .12$), and a trend for the SCP compared to the CON group (TIME × GROUP for SCP vs. CON: $F(1,32) = 3.53$, $p = .070$, $\eta_p^2 = .10$). These post-hoc effects were mainly related to an increase in deactivation in the CON group. No significant results were obtained for the FQ compared to the SCP (TIME × GROUP for FQ vs. SCP: $F(1,34) = .16$, n.s.) and ANF group (TIME × GROUP for FQ vs. ANF: $F(1,35) = .43$, n.s.), and

Table 3

Adjective checklist EWL-N

EWL	Pre	Post
Concentration		
FQ	4.67 ± 1.14	4.06 ± 1.51
SCP	4.11 ± 1.33	4.32 ± 1.49
ANF	4.53 ± 1.12	5.00 ± 1.32
CON	4.93 ± 1.16	4.07 ± 1.83
Deactivation		
FQ	3.05 ± 3.98	2.63 ± 3.02
SCP	2.59 ± 3.36	2.65 ± 3.33
ANF	2.44 ± 3.03	2.67 ± 4.21
CON	3.00 ± 3.76	5.65 ± 4.47
Self-confidence		
FQ	4.32 ± 2.45	3.47 ± 2.41
SCP	4.74 ± 2.31	4.21 ± 2.51
ANF	4.33 ± 2.91	5.00 ± 2.25
CON	4.29 ± 2.69	3.65 ± 2.57
Mood		
FQ	10.37 ± 4.02	8.00 ± 4.68
SCP	11.05 ± 4.21	11.05 ± 3.76
ANF	9.67 ± 4.58	10.67 ± 3.85
CON	10.65 ± 5.10	8.71 ± 4.84
Sensitiveness		
FQ	1.63 ± 1.42	1.68 ± 1.42
SCP	1.53 ± 1.26	.95 ± 1.18
ANF	1.61 ± 1.54	1.44 ± 1.34
CON	1.59 ± 1.42	1.94 ± 1.39
Dejection		
FQ	2.05 ± 2.90	1.53 ± 2.59
SCP	2.00 ± 2.87	.67 ± 1.50
ANF	.40 ± .74	.60 ± 1.84
CON	1.67 ± 2.35	2.73 ± 2.81

Note. For each group the mean score (and *SD*) of each subscale of the EWL-N are depicted at both pre- and post-assessment. If for the subscales concentration, self-confidence, and mood higher scores are observed at post-assessment these indicate an improvement in the respective subscale, while for the other subscales it is the other way round. FQ: theta/beta training group, SCP: slow cortical potential training group, ANF: adaptive neurofeedback group, CON: control training group.

for the SCP compared to the ANF group (TIME × GROUP for SCP vs. ANF: *F*(1,33) = .02, n.s.). Yet, when applying

Holm-Bonferroni correction, no significant results were obtained as the smallest *p*-value was larger than .05 / 6.

No significant results were obtained for the subscales self-confidence, mood, and sensitiveness (e.g. TIME: $F(1,69) < 2.13$, $p > .15$; TIME × GROUP: $F(3,69) < 1.96$, $p > 1.2$).

Regarding dejection, no significant effects were observed for TIME and the interaction of TIME × GROUP, but general group differences were present (GROUP: $F(3,63) = 2.82$, $p < .05$, $\eta_p^2 = .12$).

Post-hoc tests based on paired comparisons revealed significantly lower dejection in the ANF group compared to the FQ (GROUP for ANF vs. FQ: $F(1,32) = 4.89$, $p = .034$, $\eta_p^2 = .13$), and CON group (GROUP for ANF vs. CON: $F(1,28) = 8.68$, $p = .006$, $\eta_p^2 = .24$), as well as a trend for smaller dejection in the ANF compared to the SCP group (GROUP for ANF vs. SCP: $F(1,31) = 3.42$, $p = .070$, $\eta_p^2 = .10$). No significant results were obtained for the FQ compared to the SCP (GROUP for FQ vs. SCP: $F(1,35) = .60$, n.s.) and CON group (GROUP for FQ vs. CON: $F(1,32) = .35$, n.s.), and for the SCP compared to the CON group (GROUP for SCP vs. CON: $F(1,31) = 2.11$, n.s.). The group difference between the ANF and CON group remained significant after Holm-Bonferroni correction as $p \leq .05 / 6$ indicating higher dejection in the CON compared to the ANF group.

For the adjective check-list, a more differential pattern was obtained when looking at effect sizes (for precise effect size values please refer to Table 4).

For the FQ group a small effect size was observed for dejection and a large effect size for deactivation compared to the CON group. In the SCP group in comparison to the CON group a small effect size was present for mood, while medium effect sizes were obtained for concentration, deactivation, sensitiveness, and dejection. In the ANF group compared to the CON group, effects were present for all subscales with small effect sizes for self-confidence, sensitiveness, and dejection, medium effect sizes for deactivation and mood, and a large effect size for concentration.

Regarding effect size measures for the three NF groups, for concentration a medium effect was observed in the SCP and compared to the FQ group, and a large effect for the ANF compared to the CON group. Effect size measures for deactivation yielded a small effect for FQ compared to ANF. For self-confidence a medium effect emerged for the ANF compared to the FQ group and a small effect for the ANF compared to the SCP group. Regarding mood, a large effect was observed for the ANF compared to the FQ group and small effects for the SCP compared to the FQ and the ANF compared to the SCP group. Small effects for sensitiveness were observed in the SCP compared to the FQ and ANF groups. For dejection a medium effect was obtained for the SCP compared to the ANF group and small effects were obtained for the SCP compared to the FQ group and for the FQ compared to the ANF group.

4.1.3 Profile of Mood States: Mood

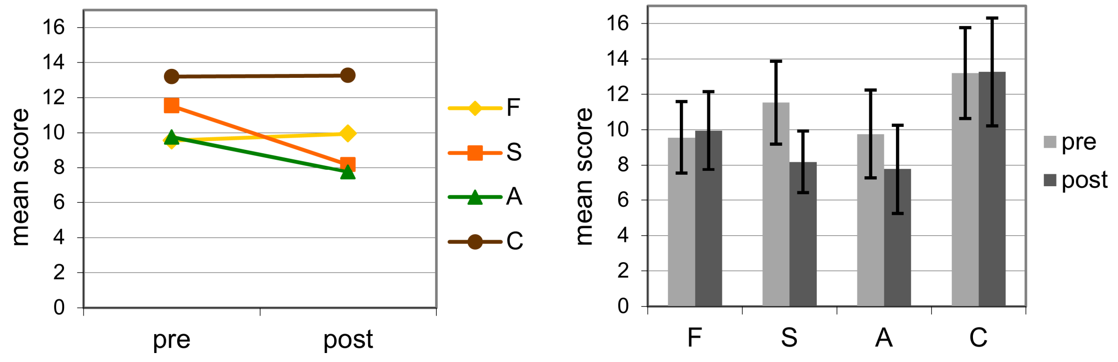
For each group, mean scores at pre- and post-assessment for the subscales dejection, fatigue, and displeasure of the POMS are depicted in Figure 7, while for the subscale vigor data are displayed in Figure 8. The repeated measure ANOVAs for the subscales dejection, fatigue and displeasure revealed no significant effects (TIME: $F(1,62) < .99$, $p > .32$; TIME × GROUP: $F(3,62) < .53$, $p > .66$; GROUP: $F(3,62) < 1.65$, $p > .18$).

For the subscale vigor a significant effect was obtained for TIME ($F(1,65) = 8.40$, $p = .005$, $\eta_p^2 = .11$) denoting a decrease of vigor from pre to post assessment. However, no significant interaction of TIME × GROUP ($F(3,65) = 1.88$, n.s.) was obtained, i.e. no significant differential effects of type of training on vigor were observed. In addition, no general groups differences were present regarding the subscale vigor (GROUP: $F(3,65) = .32$, n.s.).

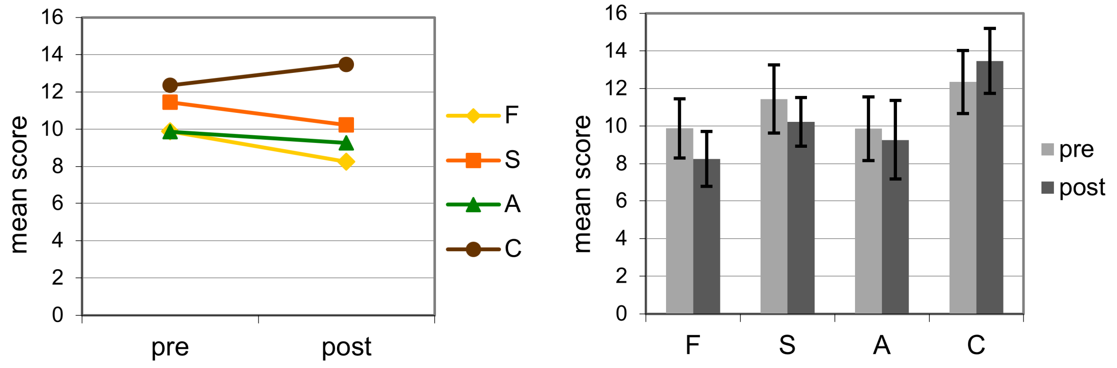
Effect sizes yielded a more differential pattern (for precise effect size values please refer to Table 4). Compared to the CON group small effect sizes were obtained for the subscale dejection in the SCP and ANF group. The subscale fatigue yielded small effect sizes for each of the three NF groups compared to the CON group. Regarding the subscale displeasure, small effect sizes were obtained for the FQ and SCP group compared to the CON group. For the subscale vigor a medium effect size emerged for the ANF compared to the CON group.

Regarding effect size measures for the three NF groups, small effects were observed for dejection in the SCP and ANF compared to the FQ group while no effects were present for fatigue. In addition, small effects were observed for displeasure in the FQ and SCP compared to the ANF group. Regarding vigor, a large effect was present in the ANF compared to the FQ group and a medium effect for the ANF compared to the SCP group.

Dejection



Fatigue



Displeasure

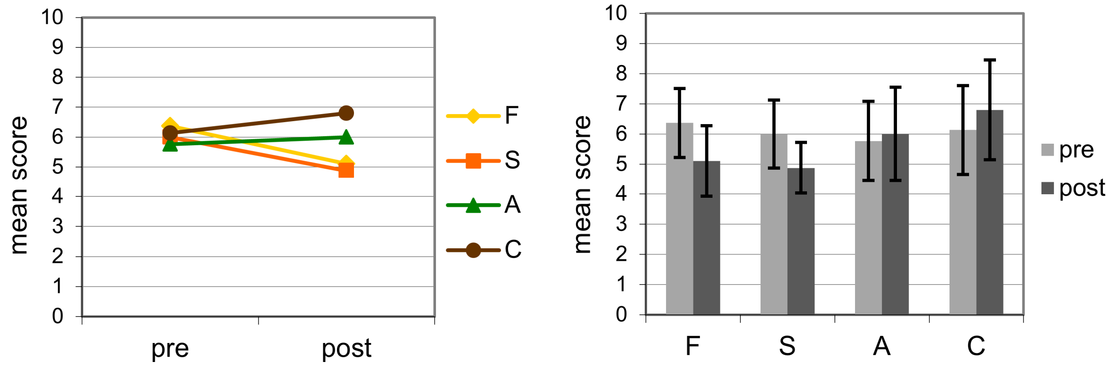


Figure 7. Adjective checklist EWL-N: Dejection, fatigue, displeasure

For the subscales dejection (top), fatigue (middle), and displeasure (bottom) the mean score at pre- and post-assessment is depicted for each group. If smaller scores are observed at post-assessment these indicate an improvement in the respective scale. Right: error bars are included. F: theta/beta training group, S: slow cortical potential training group, A: adaptive neurofeedback group, C: control training group.

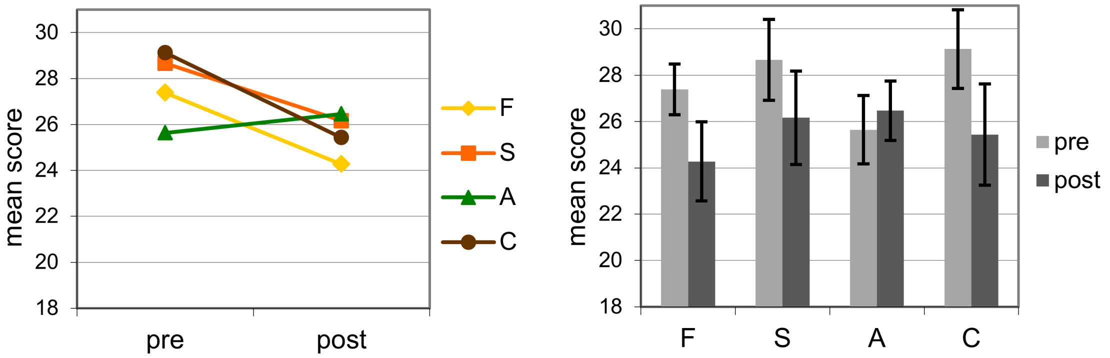


Figure 8. Adjective checklist EWL-N: Vigor

For the subscale vigor the mean score (and STD) at pre- and post-assessment is depicted for each group. If larger scores are observed at post-assessment these indicate an increase in vigor. Right: error bars are included. F: theta/beta training group, S: slow cortical potential training group, A: adaptive neurofeedback group, C: control training group.

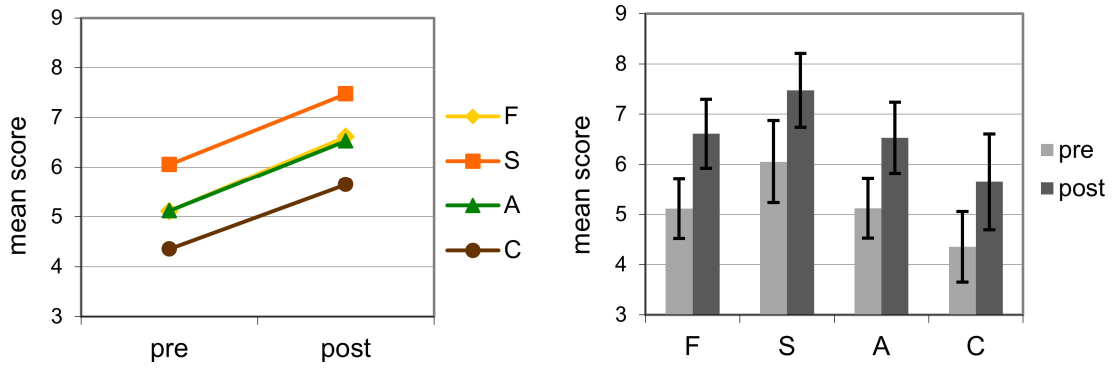
4.1.4 *HAKEMP-90: Action control after failure and prospective*

For each group, mean scores at pre- and post-assessment for the subscales AOF and AOP of the HAKEMP-90 are depicted in Figure 9. For the subscales action orientation after failure and prospective action orientation the respective repeated measure ANOVA revealed a significant effect for TIME (AOF: $F(1,67) = 30.03$, $p < .001$, $\eta_p^2 = .31$; AOP: $F(1,68) = 16.61$, $p < .001$, $\eta_p^2 = .20$) indicating an improvement with training. As no significant interaction of TIME × GROUP ($F(3,68) = .99$, n.s.) was obtained, this improvement was not significantly related to the type of training.

Analysis of effect sizes (see Table 4) yielded no effects for the subscale AOF in all three neurofeedback groups compared to the CON group. For the subscale AOP compared to the CON group a medium effect was obtained in the FQ group (FQ vs. CON: Cohen's *d* = .55) and small effects in the SCP (SCP vs. CON: Cohen's *d* = .29) and ANF (ANF vs. CON: Cohen's *d* = .48) groups.

Comparison of effect sizes for the pre-post changes of the different NF groups did not yield effects for neither subscale.

Action orientation after failure



Prospective action orientation

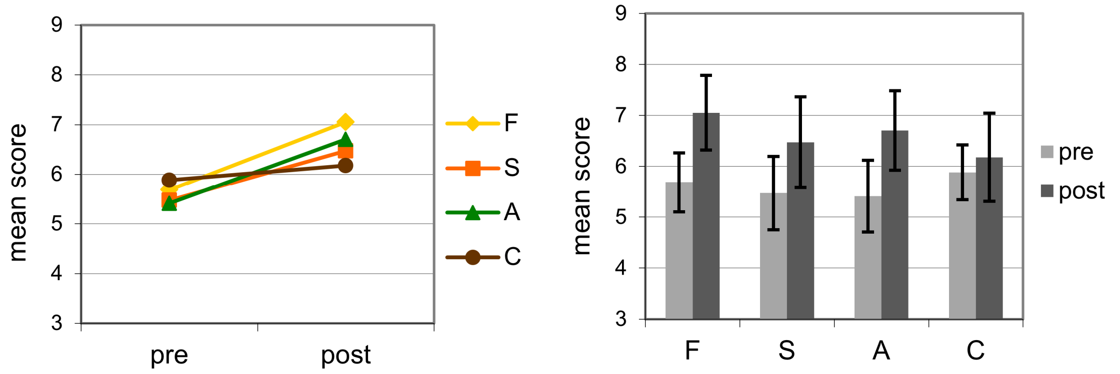


Figure 9. Action orientation after failure and prospective

For the subscales AOF (top) and AOP (bottom) of the self-report measure HAKEMP-90 the mean score at pre- and post-assessment is depicted for each group. If larger scores are observed at post-assessment these indicate an increase in action orientation. Right: error bars are included. F: theta/beta training group, S: slow cortical potential training group, A: adaptive neurofeedback group, C: control training group, AOF: action orientation after failure, AOP: prospective action orientation.

4.1.5 Self-access questionnaire: Self-access

Self-access was observed to increase from pre to post training (TIME: $F(1,64) = 4.49$, $p < .05$, $\eta_p^2 = .07$) independent of the type of training (TIME × GROUP: $F(3,64) = .91$, n.s.). The data are depicted in Figure 10.

Effect sizes (see Table 4) denoted a small effect in the SCP group compared to the CON group (SCP vs. CON: Cohen's $d = .33$) while no effects were observed for the FQ and ANF groups compared to the CON group.

Furthermore, a medium effect size was obtained in the SCP (FQ vs. SCP: Cohen's $d = -.53$) compared to the FQ group, and small effects for ANF (FQ vs. ANF: Cohen's $d = -.34$) compared to the FQ group and for the SCP (SCP vs. ANF: Cohen's $d = .29$) compared to the ANF group.

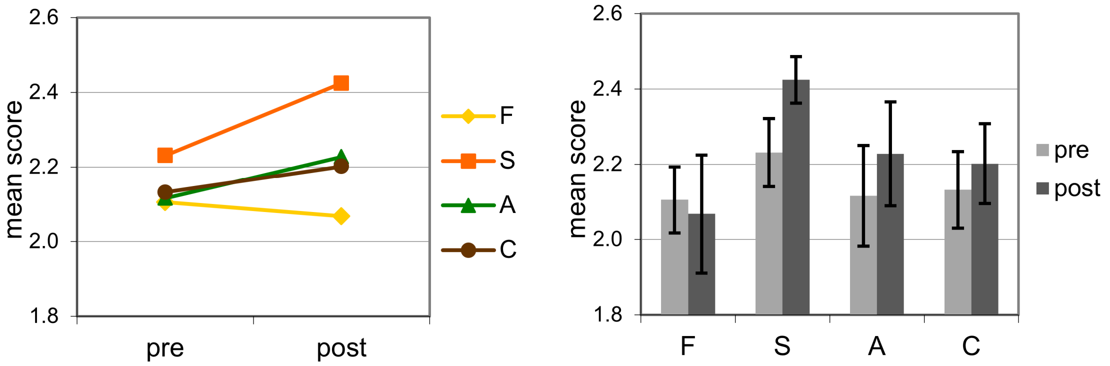


Figure 10. Self-access

The mean score (and STD) at pre- and post-assessment is depicted for each group. If larger scores are observed at post-assessment these indicate an increase in self-access. Right: error bars are included. F: theta/beta training group, S: slow cortical potential training group, A: adaptive neurofeedback group, C: control training group.

4.1.6 Perceived Stress Scale: Perceived stress

The repeated measure ANOVA yielded no significant effects for perceived stress (TIME: *F*(1,59) = .01, n.s. ; TIME × GROUP: *F*(3,59) = 1.31, n.s.; see Figure 11).

Effect sizes (see Table 4) revealed no effect for the FQ group, a small effect for the SCP group (SCP vs. CON: Cohen's *d* = .37) and a medium effect for the ANF group (ANF vs. CON: Cohen's *d* = .67) compared to the CON group.

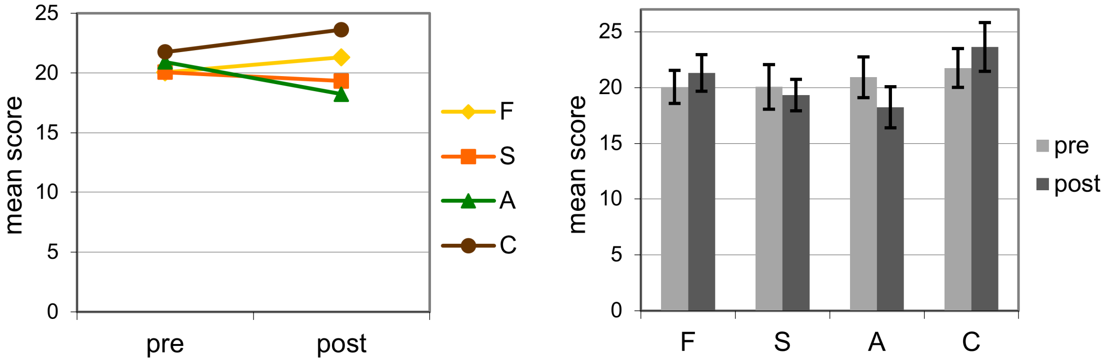


Figure 11. Perceived Stress Scale

The mean score at pre- and post-assessment is depicted for each group. If smaller scores are observed at post-assessment these indicate reduced perceived stress. Right: error bars are included. F: theta/beta training group, S: slow cortical potential training group, A: adaptive neurofeedback group, C: control training group.

Regarding the comparison of effect sizes for the pre-post changes of the different NF groups a medium effect size was obtained for the ANF compared to the FQ group (FQ vs. ANF: Cohen's *d* = -.59). Small effect sizes were observed for the SCP compared to the FQ group (FQ vs. SCP: Cohen's *d* = -.29) as well as for the ANF compared to the SCP group (SCP vs. ANF: Cohen's *d* = -.32).

4.1.7 Summary of effect size measures for all self-report measures

Table 4

Effect sizes (Cohen's d) based on self-report measures

	FQ_CON	SCP_CON	ANF_CON	FQ_SCP	FQ_ANF	SCP_ANF
Brown Scale	.09	.25	.41	-.17	-.35	-.23
POMS						
Dejection	-.06	.30	.25	-.32	-.27	.10
Fatigue	.29	.29	.21	.03	.11	.09
Displeasure	.27	.38	.09	-.02	.20	.29
Vigor	.05	.17	**.66**	-.16	**-.81**	**-.67**
EWL-N						
Concentr.	.16	**.62**	**.81**	**-.56**	**-.80**	-.17
Deactivation	**.83**	**.64**	**.69**	.13	.22	.05
Self-confid.	-.06	.04	.41	-.12	**-.55**	-.43
Mood	-.08	.33	**.60**	-.49	**-.91**	-.22
Sensitiven.	.17	**.61**	.35	-.40	-.14	.35
Dejection	.45	**.70**	.32	-.22	.25	**.54**
HAKEMP-90						
AOF	.10	.06	.05	.04	.04	.00
AOP	**.55**	.29	.48	.18	.04	.-14
Self-access	-.18	.33	.12	**-.53**	-.34	.29
PSS	.08	.37	**.67**	-.29	**-.59**	-.32

Note. Effect size measures (Cohen's *d*) are depicted for all self-report measures for the comparison of pre-post change scores between groups. Positive values of effect sizes indicate a larger improvement (or smaller decline) in the group mentioned first compared to the group mentioned second. Black numbers indicate small effect sizes, black bold numbers medium effect sizes, and black bold underlined numbers large effect sizes, while grey numbers indicate no effect. FQ: theta/beta training group, SCP: slow cortical potential training group, ANF: adaptive neurofeedback group, CON: control training group, Concentr.: concentration, Self-confid.: self-confidence, Sensitiven.: Sensitiveness, HAKEMP-90: action orientation self-report measure, AOM: action orientation after failure, AOP: prospective action orientation, PSS: Perceived Stress Scale.

4.2 Performance (pre-post)

4.2.1 Game of darts

Darts performance (mean darts score, see Figure 12) increased from pre to post training (TIME: $F(1,67) = 22.29$, $p < .001$, $\eta_p^2 = .25$) and this increase tended to be stronger in the condition WithStress (TIME × STRESS: $F(1,67) = 2.93$, $p < .10$, $\eta_p^2 = .04$). However, the increase in darts performance from pre to post did not depend significantly on the type of training (TIME × GROUP: $F(3,67) = .89$, n.s.) and no significant effect was observed for STRESS ($F(1,67) = .30$, n.s.).

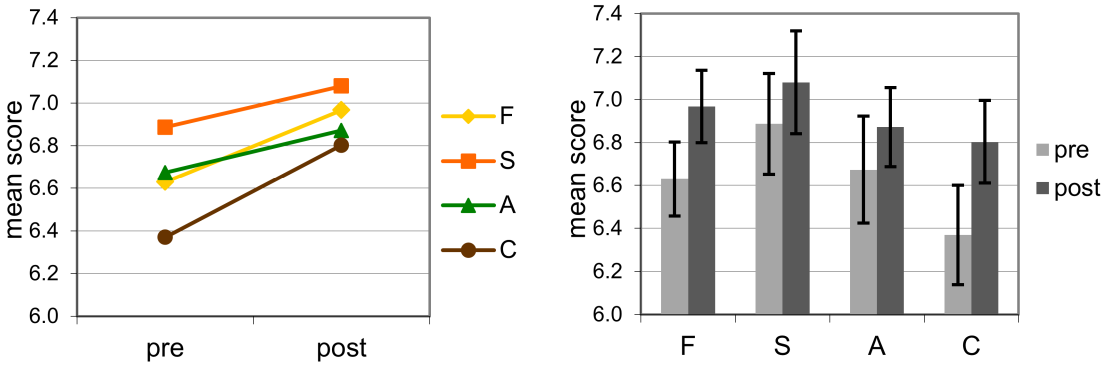


Figure 12. Darts performance

The mean score at pre- and post-assessment is depicted for each group (values are averaged over the NoStress and WithStress conditions). If larger scores are observed at post-assessment these indicate improved darts performance. Right: error bars are included. F: theta/beta training group, S: slow cortical potential training group, A: adaptive neurofeedback group, C: control training group.

For the overall darts performance, effect sizes (see Table 7) revealed medium effect sizes for the CON compared to the SCP (SCP vs. CON: Cohen's *d* = -.43) and ANF groups (ANF vs. CON: Cohen's *d* = -.40).

The comparison between neurofeedback groups revealed small effects for the FQ compared to the SCP (FQ vs. SCP: Cohen's *d* = .32) and ANF groups (FQ vs. ANF: Cohen's *d* = .29).

For darts performance related to the NoStress and WithStress conditions effect sizes indicated a medium effect for the CON compared to the SCP group in the NoStress condition (SCP vs. CON: Cohen's *d* = -.56) and a small effect in the CON compared to the ANF group in the WithStress condition (ANF vs. CON: Cohen's *d* = -.49). Both effects were related to a larger pre-post improvement in darts performance in the CON group.

Effect sizes related to the comparison of darts performance between NF groups yielded small effect sizes in the FQ and ANF compared to the SCP group (FQ vs. SCP: Cohent's *d* = .48; SCP vs. ANF: Cohen's *d* = -.44) in the NoStress condition. In the WithStress condition small effect sizes were obtained for the FQ and SCP compared to the ANF group (FQ vs. ANF: Cohen's *d* = .42; SCP vs. ANF: Cohen's *d* = .42).

4.2.2 Working memory task

Subjects improved their working memory performance (mean number of correct responses; see Figure 13 and Table 5) from pre to post training (TIME: *F*(1,67) = 93.51, $p < .001$, $\eta_p^2 = .58$), but this improvement was not affected significantly by the type of training (TIME × GROUP: *F*(3,67) = 1.01, n.s.).

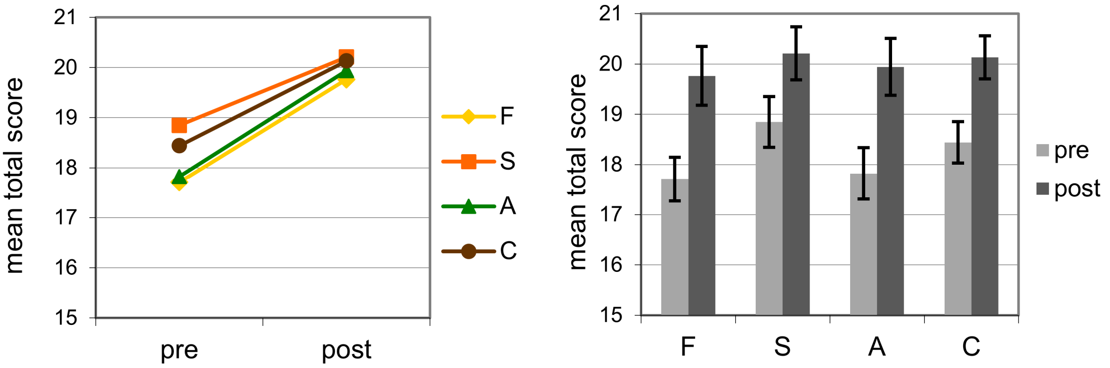


Figure 13. Working memory performance

The mean score at pre- and post-assessment is depicted for each group (values are averaged over the lower and higher load conditions). If larger scores are observed at post-assessment these indicate improved working memory performance. Right: error bars are included. F: theta/beta training group, S: slow cortical potential training group, A: adaptive neurofeedback group, C: control training group.

Performance was better for lower compared to higher WM load (LOAD: *F*(1,67) = 93.80, $p < .001$, $\eta_p^2 = .58$) while emotional content of stimuli had no significant effect on performance (EMOTION: *F*(2,134) = .52, n.s.). However, no significant interactions including the factor LOAD (e.g. TIME × LOAD: *F*(1,67) = 2.62, n.s.; TIME × LOAD × GROUP: *F*(3,67) = .43, n.s.) or EMOTION (e.g. TIME × EMOTION: *F*(2,134) = .12, n.s.; TIME × EMOTION × GROUP: *F*(6,134) = 1.60, n.s.) were obtained.

At the level of effect sizes (see Table 7) related to overall working memory performance (i.e. averaged over lower and higher load conditions) a small effect was observed in the FQ compared to the CON group (FQ vs. CON: Cohen's *d* = .33) and in the CON compared to the SCP group (SCP vs. CON: Cohen's *d* = -.25).

For the comparison between neurofeedback groups, a medium effect size was obtained in the FQ compared to the SCP group (FQ vs. SCP: Cohen's *d* = .50) and a small effect size in the ANF compared to the SCP group (SCP vs. ANF: Cohen's *d* = -.35).

Regarding effect size measures related to working memory load small effects were observed for the FQ compared to the CON group in the higher load condition (FQ vs. CON: Cohen's *d* = .28), for the ANF compared to the CON group in the lower load condition (ANF vs. CON: Cohen's *d* = .21), as well as for the CON compared to the SCP group in the lower load condition (SCP vs. CON: Cohen's *d* = -.36).

Table 5

Working memory performance

	Pre		Post	
	Lower load	Higher load	Lower load	Higher load
FQ	18.92 ± 2.47	16.50 ± 2.44	20.50 ± 2.56	19.03 ± 3.12
SCP	20.06 ± 2.66	17.64 ± 2.01	20.83 ± 2.63	19.58 ± 2.19
ANF	19.12 ± 1.79	16.53 ± 2.74	21.12 ± 1.88	18.76 ± 3.14
CON	19.62 ± 1.90	17.26 ± 2.54	21.12 ± 1.77	19.15 ± 2.04

Note. For each group mean values (and *SD*) for the lower and higher working memory load conditions are depicted at both pre- and post-assessment. If higher values are observed at post-assessment these indicate improved working memory performance. FQ: theta/beta training group, SCP: slow cortical potential training group, ANF: adaptive neurofeedback group, CON: control training group.

Comparisons between NF groups revealed small effects for the FQ compared to the SCP group in both load conditions (FQ vs. SCP lower / higher load: Cohen's *d* = .40 / Cohen's *d* = .32) and a small effect for the FQ compared to the ANF group in the higher load condition (FQ vs. ANF: Cohen's *d* = .27). In addition, a medium effect sizes was obtained for the ANF compared to the SCP group in the lower load condition (ANF vs. SCP: Cohen's *d* = -.54).

4.2.3 Attention Network Test

4.2.3.1 ANT performance: basic parameters

Regarding the basic performance parameters of the ANT (see Table 6), no significant change was observed from pre to post assessment for the number of correct responses (TIME: $F(1,61) = 1.19$, n.s.; TIME × GROUP: $F(3,61) = .84$, n.s.), but subjects had more hits in the NoStress compared to the WithStress condition (STRESS: $F(1,61) = 16.17$, $p < .001$, $\eta_p^2 = .21$).

Mean reaction time decreased from pre to post assessment (TIME: $F(1,64) = 26.74$, $p < .001$, $\eta_p^2 = .30$) and was shorter for the WithStress condition (STRESS: $F(1,64) = 41.79$, $p < .001$, $\eta_p^2 = .40$). Furthermore, a trend was obtained for the interaction of TIME × GROUP ($F(3,64) = 2.24$, $p < .10$, $\eta_p^2 = .10$). Post-hoc tests based on paired comparisons revealed a significantly larger decrease in RT in the FQ compared to the SCP group (TIME × GROUP for FQ vs. SCP: $F(1,33) = 5.86$, $p = .021$, $\eta_p^2 = .15$) as well as a trend for a larger decrease in the FQ compared to the CON group (TIME × GROUP for FQ vs. CON: $F(1,31) = 3.12$, $p = .087$, $\eta_p^2 = .09$). No significant results were obtained for the FQ compared to the ANF group (TIME × GROUP for FQ vs. ANF: $F(1,32) = 1.13$, n.s.), for the SCP compared to the ANF (TIME × GROUP for SCP vs. ANF: $F(1,33) = 2.35$, n.s.) and CON group (TIME × GROUP for SCP vs. CON: $F(1,32) = .37$, n.s.), and for the ANF compared to the CON group (TIME × GROUP for ANF vs. CON: $F(1,31) = .75$, n.s.). However, no significant results were obtained after Holm-Bonferroni correction of p-values as the smallest $p > .05 / 6$.

Variability of reaction times significantly decreased from pre to post assessment (TIME: $F(1,64) = 15.94$, $p < .001$, $\eta_p^2 = .20$), was significantly smaller for the WithStress condition (STRESS: $F(1,64) = 10.80$, $p < .01$, $\eta_p^2 = .14$), and decreased significantly more for the NoStress condition (TIME × STRESS: $F(1,64) = 4.60$, $p < .05$, $\eta_p^2 = .07$). No significant TIME × GROUP interaction ($F(3,64) = .35$, n.s.) was obtained for the variability of reaction times.

For a summary of effect size measures related to these basic performance parameters of the ANT the reader is referred to Table 7.

Table 6

Attention Network Test performance

	Pre		Post	
	NoStress	WithStress	NoStress	WithStress
Hits				
FQ	95.00 ± 1.22	94.88 ± .93	95.41 ± .71	94.76 ± 1.35
SCP	94.81 ± 1.05	94.50 ± 1.15	94.94 ± 1.57	94.63 ± 1.09
ANF	95.41 ± .80	94.41 ± 1.28	95.18 ± .73	94.35 ± 1.46
CON	94.40 ± 1.40	94.47 ± 1.51	95.13 ± .92	94.60 ± 1.55
RT				
FQ	426.14 ± 32.07	417.22 ± 32.83	400.19 ± 33.28	392.36 ± 27.73
SCP	415.07 ± 41.41	407.38 ± 39.15	408.87 ± 46.41	402.81 ± 43.70
ANF	411.38 ± 26.83	402.08 ± 27.47	392.96 ± 28.89	383.47 ± 34.26
CON	419.14 ± 36.81	409.51 ± 36.14	404.54 ± 29.20	401.45 ± 29.85
RTV				
FQ	72.84 ± 16.91	64.44 ± 13.97	59.96 ± 19.81	55.93 ± 9.57
SCP	75.59 ± 22.07	63.33 ± 15.15	62.74 ± 23.87	64.42 ± 21.30
ANF	69.85 ± 18.71	63.25 ± 13.17	58.46 ± 9.88	56.99 ± 11.16
CON	73.97 ± 19.72	69.75 ± 20.74	67.13 ± 15.77	64.62 ± 19.98
Alerting				
FQ	17.79 ± 18.45	12.07 ± 20.33	13.10 ± 15.34	11.88 ± 16.06
SCP	16.89 ± 23.04	11.83 ± 17.35	16.06 ± 14.04	9.67 ± 14.65
ANF	14.19 ± 16.86	4.44 ± 14.00	13.81 ± 16.72	11.56 ± 13.16
CON	6.81 ± 23.06	2.39 ± 23.43	15.24 ± 19.60	9.53 ± 17.72
Orienting				
FQ	24.13 ± 21.10	19.24 ± 15.91	22.37 ± 12.96	18.32 ± 9.67
SCP	15.53 ± 15.65	20.44 ± 9.84	12.06 ± 7.15	12.51 ± 11.88
ANF	14.90 ± 18.18	24.94 ± 12.05	13.74 ± 10.33	16.01 ± 10.32
CON	23.48 ± 24.08	22.88 ± 16.89	19.44 ± 11.88	21.73 ± 18.21
Conflict				
FQ	63.32 ± 22.63	60.69 ± 18.68	55.08 ± 11.82	50.50 ± 9.84
SCP	67.74 ± 14.93	61.91 ± 14.35	58.17 ± 18.23	55.26 ± 19.50
ANF	59.48 ± 10.93	62.73 ± 19.14	53.85 ± 15.49	58.41 ± 17.05
CON	67.15 ± 26.28	59.88 ± 23.18	54.19 ± 21.96	53.73 ± 25.53

Note. For each group the mean score (and *SD*) of each measure of the ANT are depicted at both pre- and post-assessment. If for hits higher scores, for RT, RTV, and the attention networks lower scores are observed at post-assessment these indicate an improvement in the respective measure. FQ: theta/beta training group, SCP: slow cortical potential training group, ANF: adaptive neurofeedback group, CON: control training group, ANT: Attention Network Test, RT: reaction time, RTV: variability of reaction time.

4.2.3.2 ANT performance: alerting, orienting, and conflict

Concerning the attention networks, the following results were obtained. An alerting effect was present in the performance data (ALERTING: $F(1,64) = 69.22$, $p < .001$, $\eta_p^2 = .52$) which was related to shorter reaction times in the NeutralCue compared to the NoCue condition. In addition, a significant effect was obtained for the interaction of ALERTING × STRESS ($F(1,64) = 9.06$, $p < .01$, $\eta_p^2 = .12$) as alerting scores were smaller in the WithStress compared to the NoStress condition. However, no training related changes in alerting were observed (e.g. TIME × ALERTING: $F(1,64) = .68$, n.s.; TIME × ALERTING × GROUP: $F(3,64) = 1.14$, n.s.).

Furthermore, an orienting effect was obtained for the performance data (ORIENTING: $F(1,64) = 288.06$, $p < .001$, $\eta_p^2 = .82$) which was related to shorter reaction times in the SpatialCue compared to the NeutralCue condition. The orienting score decreased from pre to post assessment (TIME × ORIENTING: $F(1,64) = 4.74$, $p < .05$, $\eta_p^2 = .07$) as reaction times decreased more in the NeutralCue compared to the SpatialCue condition. Yet, type of training had no significant effect on the orienting score (e.g. TIME × ORIENTING × GROUP: $F(3,64) = .38$, n.s.). No significant interactions including the factors ORIENTING and STRESS were obtained (e.g. ORIENTING × STRESS: $F(1,64) = .86$, n.s.).

Similarly, for the conflict network a significant effect was present for CONFLICT ($F(1,64) = 1071.01$, $p < .001$, $\eta_p^2 = .94$) which was associated with shorter reaction times for congruent compared to incongruent trials. In addition, the conflict score decreased from pre to post assessment (TIME × CONFLICT: $F(1,64) = 18.12$, $p < .001$, $\eta_p^2 = .22$) as reaction times decreased more in incongruent compared to congruent trials. However, type of training had no significant effect on the conflict score (e.g. TIME × CONFLICT × GROUP: $F(3,64) = .31$, n.s.). No significant interactions including the factors CONFLICT and STRESS were obtained (e.g. CONFLICT × STRESS: $F(1,64) = 2.10$, n.s.).

For a summary of effect size measures related to the performance data of the ANT at the level of the attention networks the reader is referred to Table 7.

In summary, the significant effects for ALERTING, ORIENTING and CONFLICT demonstrated that the ANT exerts the desired modulating effects on attention network related reaction time measures which is an important basis for the analysis of training effects on these attention network measures. However, no significant interactions of ALERTING/ORIENTING/CONFLICT × TIME × GROUP were observed indicating that alerting, orienting, and conflict were not significantly altered related to the type of training performed.

4.2.4 Summary of effect size measures for all performance data

Table 7

Effect sizes (Cohen's d) based on performance measures

	FQ_CON	SCP_CON	ANF_CON	FQ_SCP	FQ_ANF	SCP_ANF
Darts						
total	-.15	-.43	-.40	.32	.29	-.01
n/w	-.10 / -.14	**-.56** / -.17	-.15 / -.49	.48 / .02	.05 / .42	-.44 / .42
WM						
total	.33	-.25	.15	**.50**	.17	-.35
low/high	.10 / .28	-.36 / .01	.21 / .01	.40 / .32	-.06 / .27	**-.54** / -.01
ANT n/w						
Hits t	-.28	-.33	**-.63**	.02	.27	.27
Hits n/w	-.24 / -.15	-.39 / .00	**-.79 /** -.12	.18 / -.14	**.52** / -.04	.24 / .11
RT t	**.61**	-.21	.30	**.82**	.36	**-.52**
RT n/w	0.48 **/ .67**	-.29 / -.12	.17 / .37	**.80 / .79**	.44 / .26	**-.51 /** -.48
RTV t	.34	-.01	.21	.26	.16	-.16
RTV n/w	.37 / .17	.25 / -.27	.25 / .06	.00 / .48	.09 / .17	.06 / -.39
Alerting t	.48	.43	.24	.05	.42	.35
Alerting n/w	.45 / .32	.31 / .39	.33 / .00	.15 / -.10	.20 / .42	.02 / **.50**
Orienting t	-.08	.22	.18	-.30	-.27	.06
Orienting n/w	-.09 / -.01	-.02 / .37	-.13 / .47	-.07 / -.38	.03 / -.49	.12 / -.07
Conflict t	-.02	-.09	-.27	.08	.28	.22
Conflict n/w	-.20 / .22	-.15 / .03	-.34 / -.09	-.07 / .24	.14 / .30	.23 / .13

Note. Effect size measures (Cohen's *d*) are depicted for all performance measures for the comparison of pre-post change scores between groups. Positive values of effect sizes indicate a larger improvement (or smaller decline) in the group mentioned first compared to the group mentioned second. Black numbers indicate small effect sizes, black bold numbers medium effect sizes, and black bold underlined numbers large effect sizes, while grey numbers indicate no effect. FQ: theta/beta training group, SCP: slow cortical poential training group, ANF: adaptive neurofeedback group, CON: control training group, t: total score (ie. based on data averaged over NoStress and WithStress conditions), n: NoStress condition, w: WithStress condition, ANT: Attention Network Test, RT: reaction time, RTV: variability of reaction time.

Table 8

Resting EEG measures

	Pre			Post		
	Fz	Cz	Pz	Fz	Cz	Pz
Theta						
FQ	1.15 ± .23	1.24 ± .25	1.24 ± .31	1.16 ± .23	1.27 ± .27	1.25 ± .28
SCP	1.17 ± .22	1.23 ± .21	1.29 ± .25	1.24 ± .26	1.34 ± .24	1.32 ± .30
ANF	1.21 ± .22	1.30 ± .25	1.26 ± .20	1.25 ± .22	1.30 ± .18	1.34 ± .21
CON	1.18 ± .25	1.20 ± .25	1.20 ± .24	1.21 ± .26	1.24 ± .32	1.20 ± .30
Alpha						
FQ	1.12 ± .29	1.21 ± .30	1.55 ± .47	1.16 ± .32	1.28 ± .32	1.69 ± .58
SCP	1.09 ± .24	1.29 ± .38	1.79 ± .63	1.18 ± .30	1.34 ± .40	1.78 ± .50
ANF	1.19 ± .34	1.38 ± .43	1.75 ± .68	1.36 ± .50	1.57 ± .59	2.10 ± .93
CON	1.11 ± .31	1.19 ± .34	1.56 ± .52	1.22 ± .31	1.34 ± .45	1.71 ± .63
Beta						
FQ	.99 ± .19	1.04 ± .21	1.23 ± .24	.97 ± .14	1.04 ± .14	1.23 ± .19
SCP	1.09 ± .24	1.19 ± .24	1.46 ± .36	1.14 ± .30	1.25 ± .29	1.45 ± .37
ANF	1.13 ± .28	1.19 ± .34	1.40 ± .43	1.14 ± .28	1.24 ± .37	1.46 ± .47
CON	1.06 ± .25	1.08 ± .27	1.28 ± .32	1.10 ± .26	1.13 ± .34	1.33 ± .36

Note. For each group mean EEG activity (in μV, and *SD*) in each frequency band at both pre- and post-assessment is depicted for electrode sites Fz, Cz, and Pz. FQ: theta/beta training group, SCP: slow cortical potential training group, ANF: adaptive neurofeedback group, CON: control training group.

4.3 Neurophysiological results (pre-post)

4.3.1 Resting EEG

The eyes-open resting EEG measures are depicted in Table 8. From pre to post a significant increase in theta activity was observed (TIME: $F(1,63) = 6.85$, $p < .05$, $\eta_p^2 = .10$) which was not significantly affected by type of training (TIME × GROUP: $F(3,63) = .81$, n.s).

Alpha activity increased from pre to post training (TIME: $F(1,60) = 18.84$, $p < .001$, $\eta_p^2 = .24$). In addition, for the alpha band a significant interaction of TIME × ELECTRODE × GROUP ($F(6,120) = 2.90$, $p = .024$, $\eta_p^2 = .13$). Post-hoc tests were based on separate ANOVAs calculated for each electrode. No significant interaction of TIME × GROUP was obtained for electrode Fz ($F(3,60) = 1.23$, $p = .307$, n.s.) and Cz ($F(3,60) = 1.52$, $p = .219$, n.s.). For Pz a significant interaction of TIME × GROUP was observed ($F(3,60) = 2.92$, $p = .041$, $\eta_p^2 = .13$) which according to visual inspection seemed to be related to a larger increase in alpha activity in the ANF group relative to the other groups. Yet, when applying Bonferroni-Holmes correction the interaction obtained for electrode Pz no longer remained significant as $p > .05 / 3$.

A trend for an increase in beta activity from pre to post was obtained (TIME: $F(1,61) = 2.86$, $p < .10$, $\eta_p^2 = .05$) while type of training did not result in differential pre-post effects (TIME × GROUP: $F(3,61) = .62$, n.s.).

Effect size measures are displayed in Table 9.

Table 9

Effect sizes (Cohen's d) for resting EEG measures

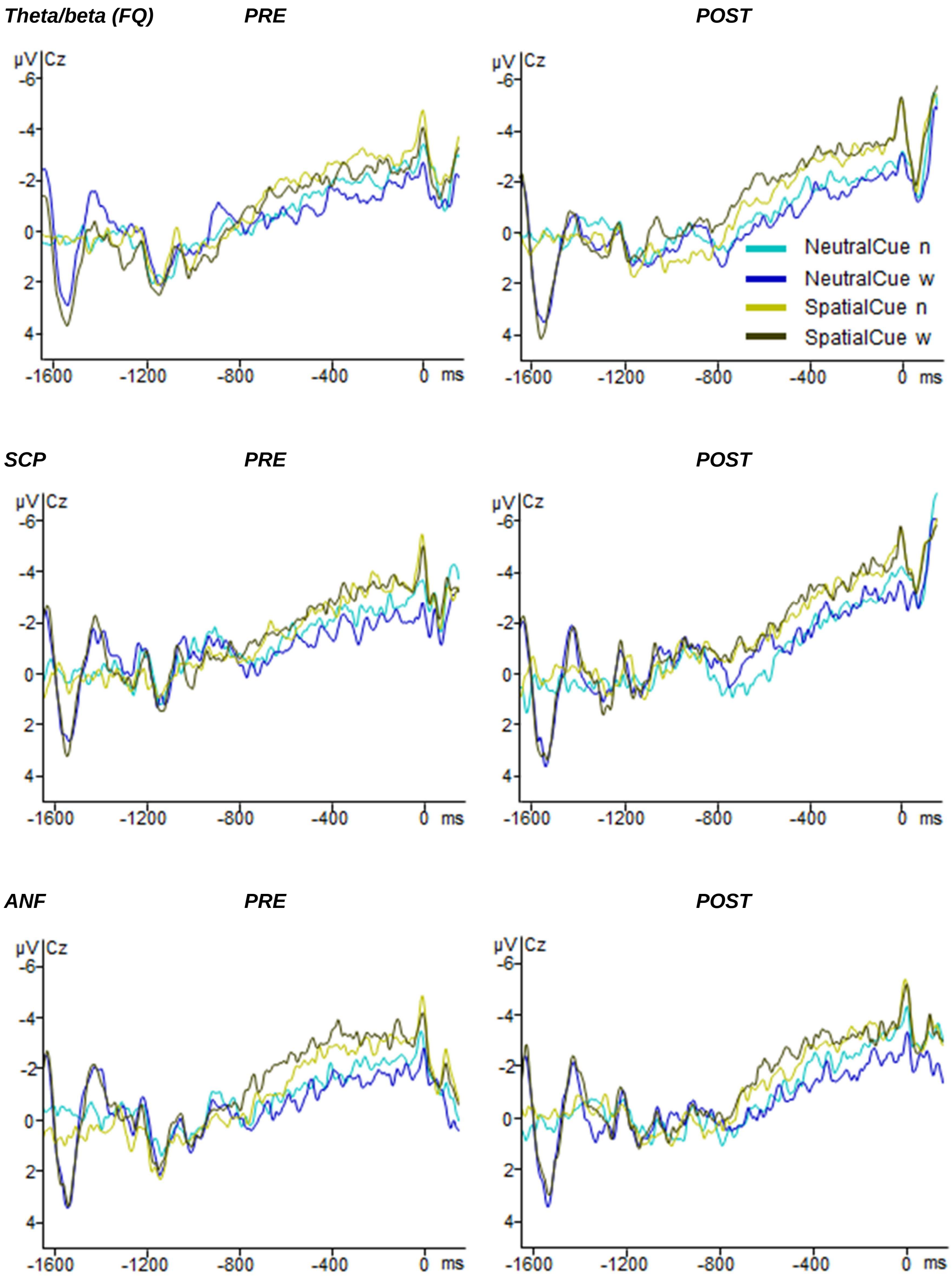
	FQ_CON	SCP_CON	ANF_CON	FQ_SCP	FQ_ANF	SCP_ANF
Theta (Cz)	|-.12|	|.41|	|-.26|	**|-.54|**	|.18|	**|.60|**
Alpha (Pz)	|-.03|	**|-.57|**	**|.60|**	|.44|	**|-.54|**	**|-1.06|**
Beta (Cz)	|-.38|	|.00|	|-.08|	|-.37|	|-.33|	|.08|

Note. Effect size measures (Cohen's *d*) are depicted for all resting EEG measures at the most relevant electrode site for the comparison of pre-post change scores between groups. Positive values of effect sizes indicate a larger increase (or smaller decrease) of activity in the respective frequency band in the group mentioned first compared to the group mentioned second. Black numbers indicate small effect sizes, black bold numbers medium effect sizes, and black bold underlined numbers large effect sizes, while grey numbers indicate no effect. Effect sizes are depicted in brackets since it is not clear a change in which direction constitutes an improvement. FQ: theta/beta training group, SCP: slow cortical poential training group, ANF: adaptive neurofeedback group, CON: control training group.

4.3.2 Attention Network Test

4.3.2.1 CNV amplitudes

Regarding CNV amplitudes (see Figure 14 and Figure 15) a significant effect was observed for ORIENTING ($F(1,57) = 63.82$, $p < .001$, $\eta_p^2 = .53$) indicating larger CNV amplitudes in the SpatialCue compared to the NeutralCue condition. This finding shows that cues exerted the intended effects on CNV amplitudes resulting in an orienting effect on the level of CNV amplitudes. In addition, a trend was obtained for STRESS ($F(1,57) = 2.93$, $p < .10$, $\eta_p^2 = .05$) which was related to a tendency for smaller CNV amplitudes


Theta/beta (FQ) PRE POST

SCP PRE POST

ANF PRE POST

Figure 14. CNV amplitudes for the NF groups

Grand average ERPs (at Cz) during the preparation phase in the ANT are depicted for both pre- and post-assessment for each NF group in order to illustrate CNV amplitudes. ERPs for NeutralCue and SpatialCue trials are shown separately for the NoStress and WithStress conditions. At -1400 ms a cue was presented, flanking fish appeared at -100 ms, and the target fish appeared at 0 ms. CNV was dertermined as the mean area between -400 and -100 ms. FQ: theta/beta training group, SCP: SCP raining group, ANF: adaptive neurofeedback group, CNV: contingent negative variation, ANT: Attention Network Test.

in the WithStress condition. But no significant interactions including the factor STRESS were obtained (e.g. TIME × STRESS: $F(1,57) = 1.22$, n.s.).

Regarding changes in CNV amplitudes from pre to post training no significant effect was observed for TIME ($F(1,57) = .34$, n.s.). Yet, a trend was obtained for the interaction of TIME × GROUP ($F(3,57) = 2.57$, $p < .10$, $\eta_p^2 = .12$).

Post-hoc tests based on pairwise comparisons revealed significant interaction effects for the FQ compared to the CON group (TIME × GROUP for FQ vs. CON: $F(1,29) = 8.71$, $p = .006$, $\eta_p^2 =.23$), the SCP compared to the CON group (TIME × GROUP for SCP vs. CON: $F(1,25) = 5.47$, $p = .028$, $\eta_p^2 =.18$), and the ANF compared to the CON group (TIME × GROUP for ANF vs. CON: $F(1,27) = 5.04$, $p = .033$, $\eta_p^2 =.16$) while no significant effects were obtained for the comparisons between NF groups (TIME × GROUP for FQ vs. SCP: $F(1,30) = .01$, n.s.; TIME × GROUP for FQ vs. ANF: $F(1,32) = .31$, n.s.; TIME × GROUP for SCP vs. ANF: $F(1,28) = .15$, n.s.).

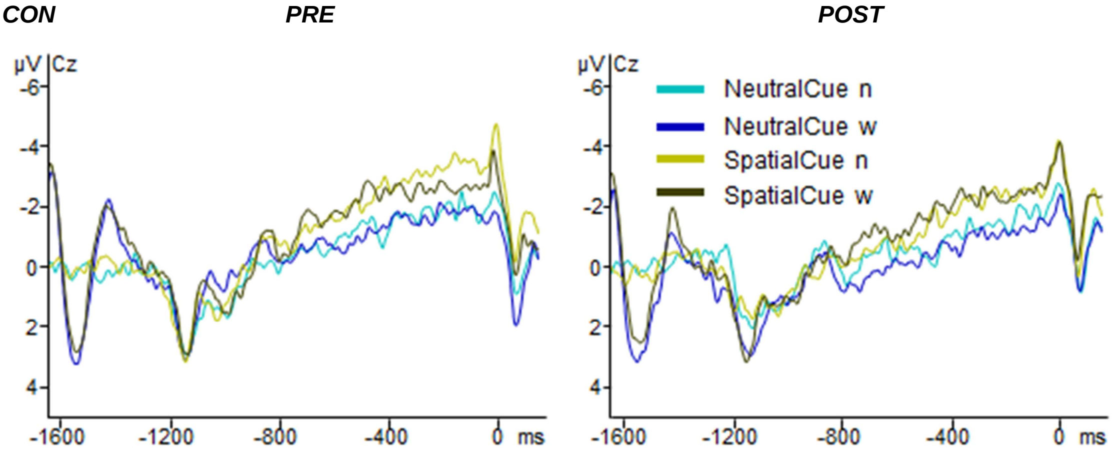


Figure 15. CNV amplitudes for the CON group

Grand average ERPs (at Cz) during the preparation phase in the ANT are depicted for both pre- and post-assessment for the CON group in order to illustrate CNV amplitudes. ERPs for NeutralCue and SpatialCue trials are shown separately for the NoStress and WithStress conditions. At -1400 ms a cue was presented, flanking fish appeared at -100 ms, and the target fish appeared at 0 ms. CNV was dertermined as the mean area between -400 and -100 ms CON: control training group, CNV: contingent negative variation, ANT: Attention Network Test.

These results indicated a tendency towards stronger increases in CNV amplitudes from pre to post in the three NF groups compared to the CON group for which amplitudes rather decreased. However, after Holm-Bonferroni correction of p-values only the effect obtained for the comparison of the FQ and CON group remained significant as $p \leq .05 / 6$ while the next smallest p-value did not meet the criterion of $p \leq .05 / 5$.

Table 10

Effect sizes (Cohens' d) based on ERP measures during the ANT

	FQ_CON	SCP_CON	ANF_CON	FQ_SCP	FQ_ANF	SCP_ANF
CNV n / w	**.66 / 1.01**	**.57 / .84**	**.87 /** .42	.00 / .06	-.17 / **.57**	-.15 / .45
Cue-P3 n / w	-.22 / .06	.10 / -.25	-.06 / -.35	-.45 / .30	-.16 / .41	.18 / .03
Targ.-P3 n / w	-.33 / .05	-.31 / .08	-.09 / .26	.06 / -.03	-.21 / -.21	-.22 / -.14

Note. Effect size measures (Cohen's *d*) are depicted for all ERP measures assessed during the ANT for the comparison of pre-post change scores between groups. Positive values of effect sizes indicate a larger increase (or smaller decline) of the respective measure in the group mentioned first compared to the group mentioned second. Black numbers indicate small effect sizes, black bold numbers medium effect sizes, and black bold underlined numbers large effect sizes, while grey numbers indicate no effect. FQ: theta/beta training group, SCP: slow cortical potential training group, ANF: adaptive neurofeedback group, CON: control training group, n: NoStress condition, w: WithStress condition, ANT: Attention Network Test, Targ.-P3: target-P3.

As described above, an orienting effect was present at the level of CNV amplitudes, but no significant interaction of e.g. TIME × ORIENTING (*F*(1,57) = .01, n.s.) or TIME × ORIENTING × GROUP (*F*(3,57) = .39, n.s.) was obtained, i.e. orienting did not change from pre to post.

Effect sizes based on CNV amplitudes[33] (see Table 10) in the NoStress condition revealed a medium effect for the FQ (FQ vs. CON: Cohen's *d* = .66) and SCP (SCP vs. CON: Cohen's *d* = .57) compared to the CON group as well as a large effect for the ANF (ANF vs. CON: Cohen's *d* = .87) compared to the CON group. In the WithStress condition large effect sizes were obtained for both the FQ (FQ vs. CON: Cohen's *d* = 1.01) and SCP (SCP vs. CON: Cohen's *d* = .84) group compared to the CON group, and a small effect size for the ANF (ANF vs. CON: Cohen's *d* =.42) compared to the CON group. These effects were mainly related to an increase in CNV from pre to post in the respective NF group in combination with a decrease in CNV in the CON group.

Effect sizes for the comparisons between NF groups revealed no effects in the NoStress condition. In the WithStress condition, a medium effect was obtained for FQ (FQ vs. ANF: Cohen's *d* = .57) compared to ANF group, and a small effect for SCP (SCP vs. ANF: Cohen's *d* = .45) compared to ANF group related to larger pre-post

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[33] Effect size calculations were based on the average of CNV amplitudes of the NeutralCue and SpatialCue conditions, i.e. including all trials for which CNV amplitudes could be calculated.

increases in CNV amplitudes in the FQ and SCP groups compared to no change in the ANF group.

4.3.2.2 Cue-P3 amplitudes

For cue-P3 amplitudes a highly significant effect for ORIENTING was obtained ($F(1,57) = 31.78$, $p < .001$, $\eta_p^2 = .36$) indicating larger cue-P3 amplitudes in the SpatialCue compared to the NeutralCue condition. These results represent an orienting effect at the level of cue-P3 amplitudes indicating that ANT network effects can also be observed at the level of cue-P3 amplitudes. Cue-P3 amplitudes were not significantly modulated by STRESS ($F(1,57) = .28$, n.s.) and no significant interactions including the factor STRESS were obtained (e.g. TIME × STRESS: $F(1,57) = .84$, n.s.; TIME ×

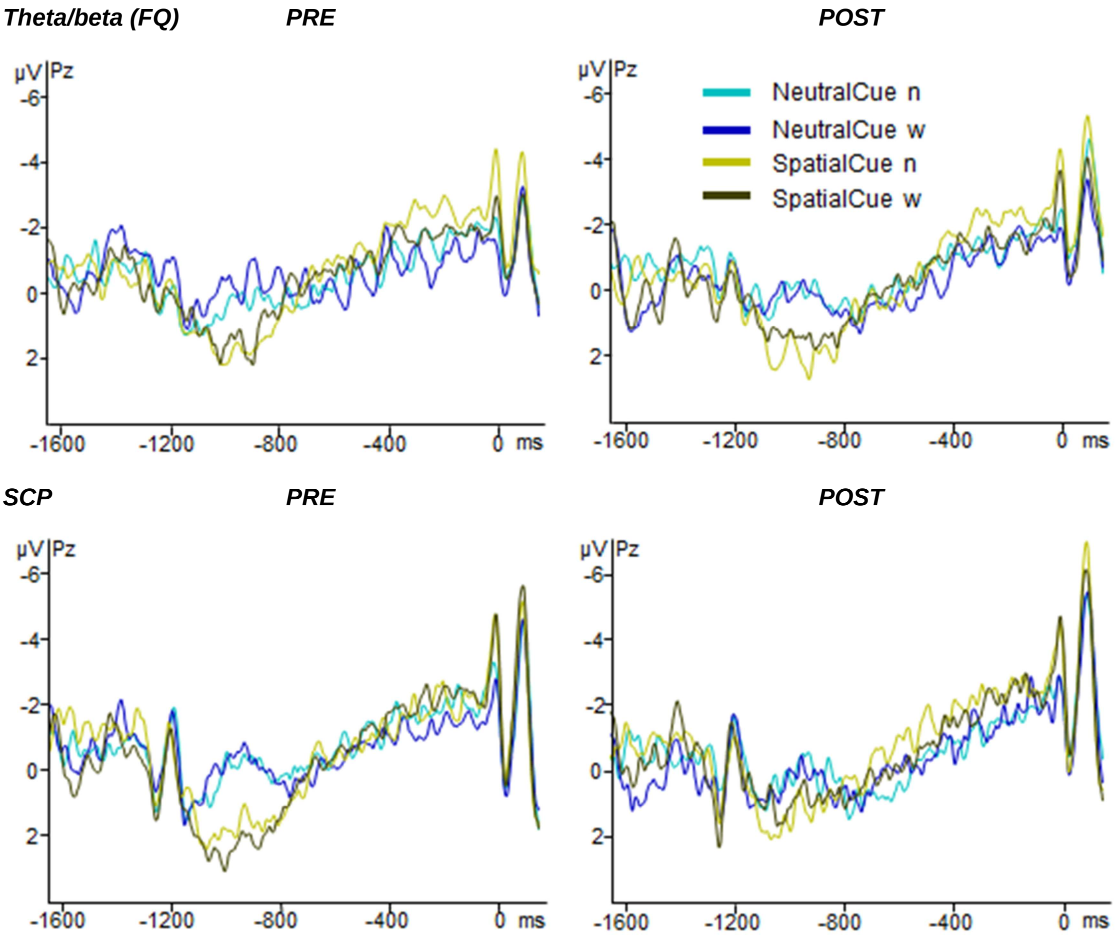
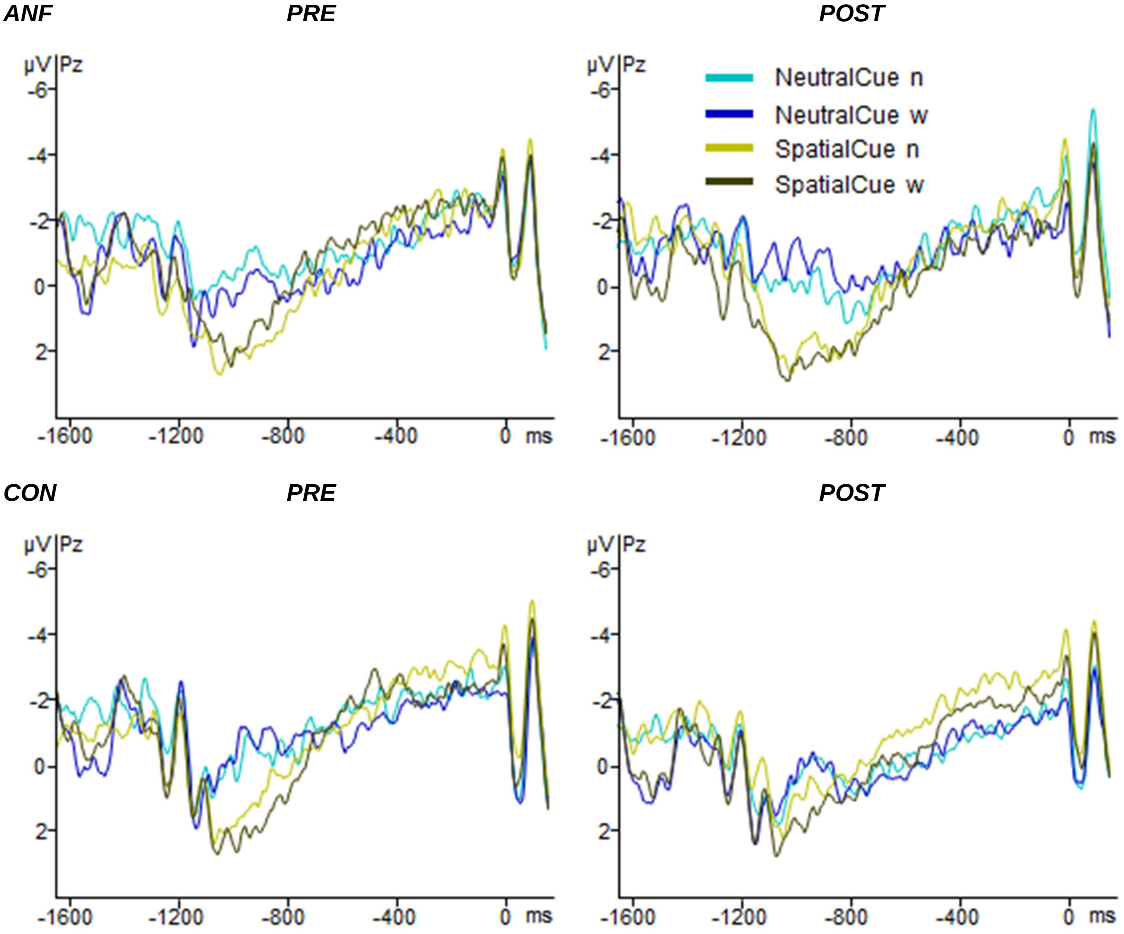


Figure 16. Cue-P3 amplitudes for the FQ and SCP group

Grand average ERPs (at Pz) during the preparation phase in the ANT are depicted for both pre- and post-assessment for the FQ and SCP groups in order to illustrate cue-P3 amplitudes. ERPs for NeutralCue and SpatialCue trials are shown separately for the NoStress and WithStress conditions. At -1400 ms a cue was presented, flanking fish appeared at -100 ms, and the target fish appeared at 0 ms. Cue-P3 amplitudes were determined as the largest peak within -1200 to -600 ms. FQ: theta/beta training group, SCP: slow cortical potential raining group, ANT: Attention Network Test.

STRESS × GROUP: *F*(3,57) = .84, n.s.).

Yet, no change in cue-P3 amplitudes (see Figure 16 and Figure 17) was observed from pre to post training in general (TIME: *F*(1,57) = .18, n.s.) or related to type of training (e.g. TIME × GROUP: *F*(3,57) = .14, n.s.). Even though an orienting effect was present at the level of cue-P3 amplitudes, orienting was not modulated by training as indicated by non-significant interactions of TIME × ORIENTING (*F*(1,57) = .85, n.s.) and TIME × ORIENTING × GROUP (*F*(3,57) = .2.13, n.s.).


ANF ***PRE*** ***POST***

CON ***PRE*** ***POST***

Figure 17. Cue-P3 amplitudes for the ANF and CON group

Grand average ERPs (at Pz) during the preparation phase in the ANT are depicted for both pre- and post-assessment for the ANF and CON groups in order to illustrate cue-P3 amplitudes. ERPs for NeutralCue and SpatialCue trials are shown separately for the NoStress and WithStress conditions. At -1400 ms a cue was presented, flanking fish appeared at -100 ms, and the target fish appeared at 0 ms. Cue-P3 amplitudes were determined as the largest peak within -1200 to -600 ms ANF: adaptive neurofeedback training, CON: control training group, ANT: Attention Network Test.

Effect sizes related to cue-P3 amplitudes[34] (see Table 10) in the NoStress condition revealed a small effect size for the FQ vs. CON group (FQ vs. CON: Cohen's $d = -.22$). In the WithStress condition small effect sizes were observed for the SCP vs. CON group (SCP vs. CON: Cohen's $d = -.25$) as well as for the ANF vs. CON group (ANF vs. CON: Cohen's $d = -.35$). All these effects were related to a decrease in P3 amplitudes in the respective NF group and a small increase in the CON group

Comparisons between NF groups revealed a small effect size in the FQ vs. SCP group in the NoStress condition (FQ vs. SCP: Cohen's $d = -.45$) and in the opposite direction in the WithStress condition (FQ vs. SCP: Cohen's $d = .30$). In addition, in the WithStress condition a small effect size was obtained for the FQ vs. ANF group (FQ vs. ANF: Cohen's $d = .41$).

4.3.2.3 Target-P3 amplitudes

Grand average ERPs related to target-P3 amplitudes in the different cue conditions are depicted in Figure 18 and Figure 19). For target-P3 amplitudes, a significant effect was obtained for ALERTING ($F(1,55) = 4.67$, $p < .05$, $\eta_p^2 = .08$) indicting an alerting effect at the level of target-P3 amplitudes which was related to larger amplitudes in the NoCue compared to the NeutralCue condition. No significant effect was observed for STRESS ($F(1,55) = .00$, n.s.) or for interactions including the factor STRESS (e.g. TIME × STRESS: $F(1,55) = .12$, n.s.; TIME × STRESS × GROUP: $F(3,55) = .55$, n.s.).

Target-P3 amplitudes (based on NoCue and NeutralCue trials) did not significantly change from pre to post training in general (TIME: $F(1,55) = .01$, n.s.) or related to type of training (TIME × GROUP: $F(3,55) = .18$, n.s.). Also for the alerting effect, no significant change was observed from pre to post training (TIME × ALERTING: $F(1,55) = 1.15$, n.s.; TIME × ALERTING × GROUP: $F(3,55) = .44$, n.s.).

Target-P3 analyses related to the orienting network revealed significant effects for ORIENTING ($F(1,55) = 24.16$, $p < .001$, $\eta_p^2 = .31$) which was related to larger target-P3 amplitudes in the NeutralCue compared to the SpatialCue condition. Stress did not significantly affect target-P3 amplitudes (STRESS: $F(1,55) = .07$, n.s.; e.g. TIME × STRESS: $F(1,55) = .04$, n.s.; TIME × STRESS × GROUP: $F(3,55) = .22$, n.s.).

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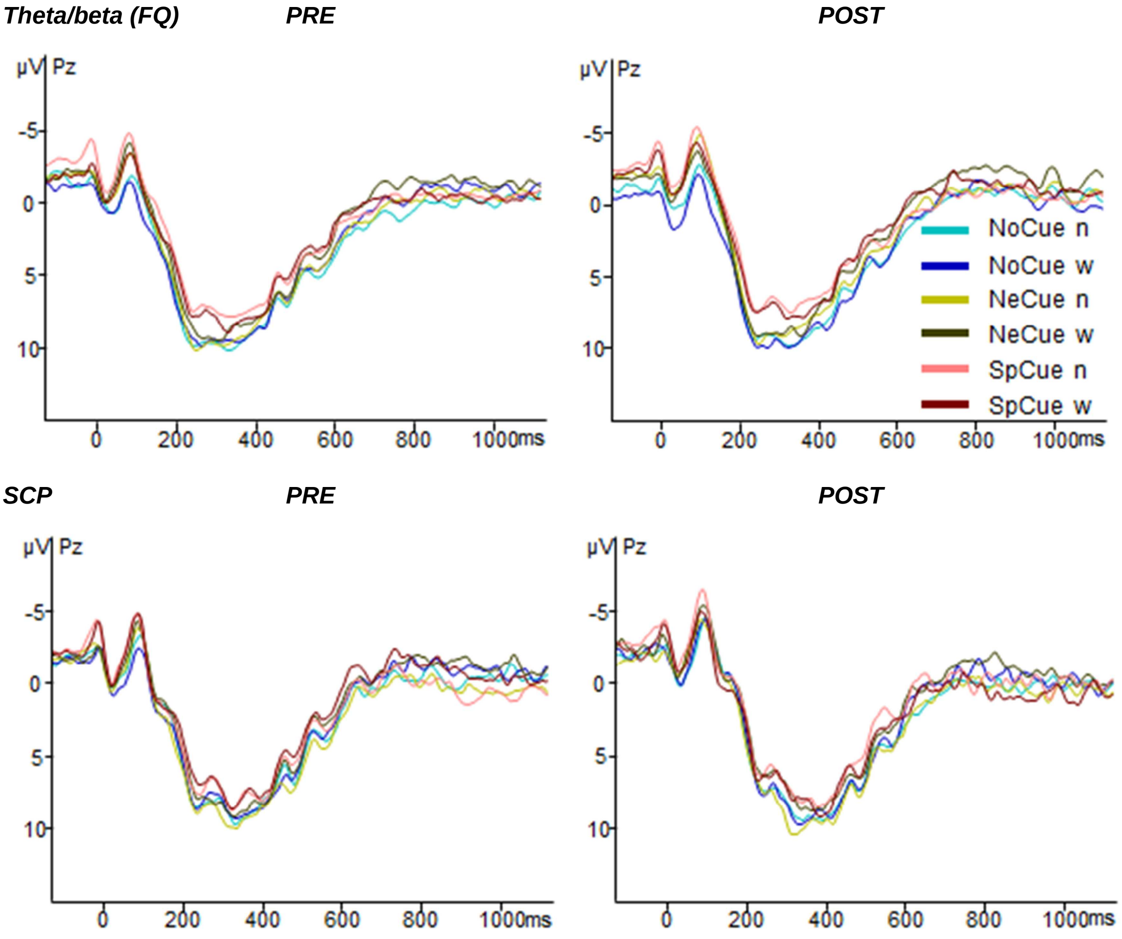
[34] Effect size calculations were based on the average of cue-P3 amplitudes of the NeutralCue and SpatialCue conditions, i.e. including all trials for which cue-P3 amplitudes could be calculated.


Theta/beta (FQ) *PRE* *POST*

SCP *PRE* *POST*

Figure 18. Target-P3 amplitudes for the three cue conditions (FQ, SCP)

Grand average ERPs (at Pz) during presentation of target stimuli in the ANT are depicted for both pre- and post-assessment for the FQ and SCP groups in order to illustrate target-P3 amplitudes. ERPs for NoCue, NeutralCue (NeCue) and SpatialCue (SpCue) trials are shown separately for the NoStress and WithStress conditions. Flanking fish appeared at -100 ms, and the target fish appeared at 0 ms. Target-P3 amplitudes were determined as the largest peak within 280 to 450 ms. FQ: theta/beta training group, SCP: slow cortical potential raining group, ANT: Attention Network Test.

No significant pre-post changes in target-P3 amplitudes (based on NeutralCue and SpatialCue trials) were observed in general (TIME: *F*(1,55) = .22, n.s.) or related to type of training (TIME × GROUP: *F*(3,55) = .61, n.s.). Also for the orienting effect, no significant change emerged from pre to post training (TIME × ORIENTING: *F*(1,55) = .00, n.s.; TIME × ORIENTING × GROUP: *F*(3,55) = .10, n.s.).

For target-P3 amplitudes related to the conflict network (see Figure 20 and Figure 21), no significant effects were observed for CONFLICT (*F*(1,60) = .79, n.s.), i.e. conflict network modulations were not present at the level of target-P3 amplitudes. No significant effect was observed for STRESS (*F*(1,60) = 1.56, n.s.) or for interactions including the factor STRESS and TIME (e.g. TIME × STRESS *F*(1,60) = .00, n.s.; TIME × STRESS × GROUP: *F*(3,60) = 1.01, n.s.).

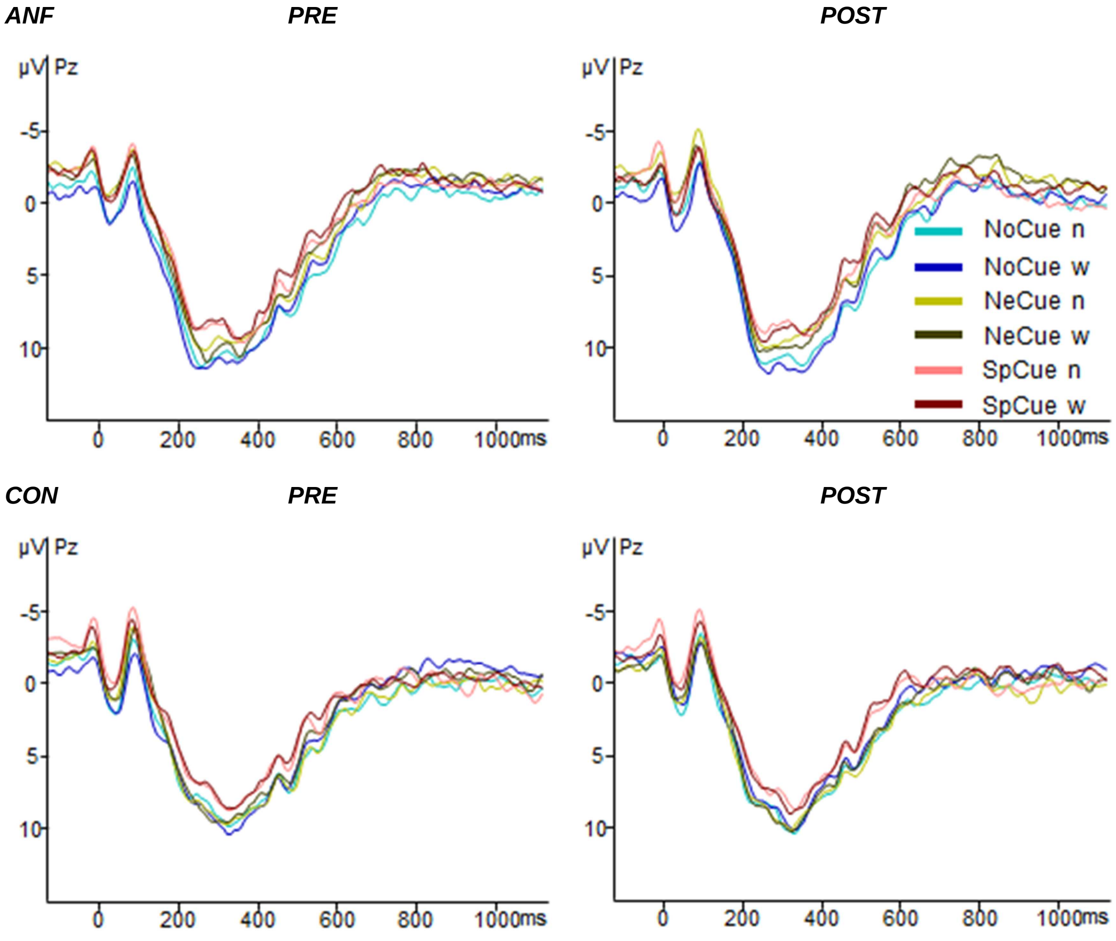
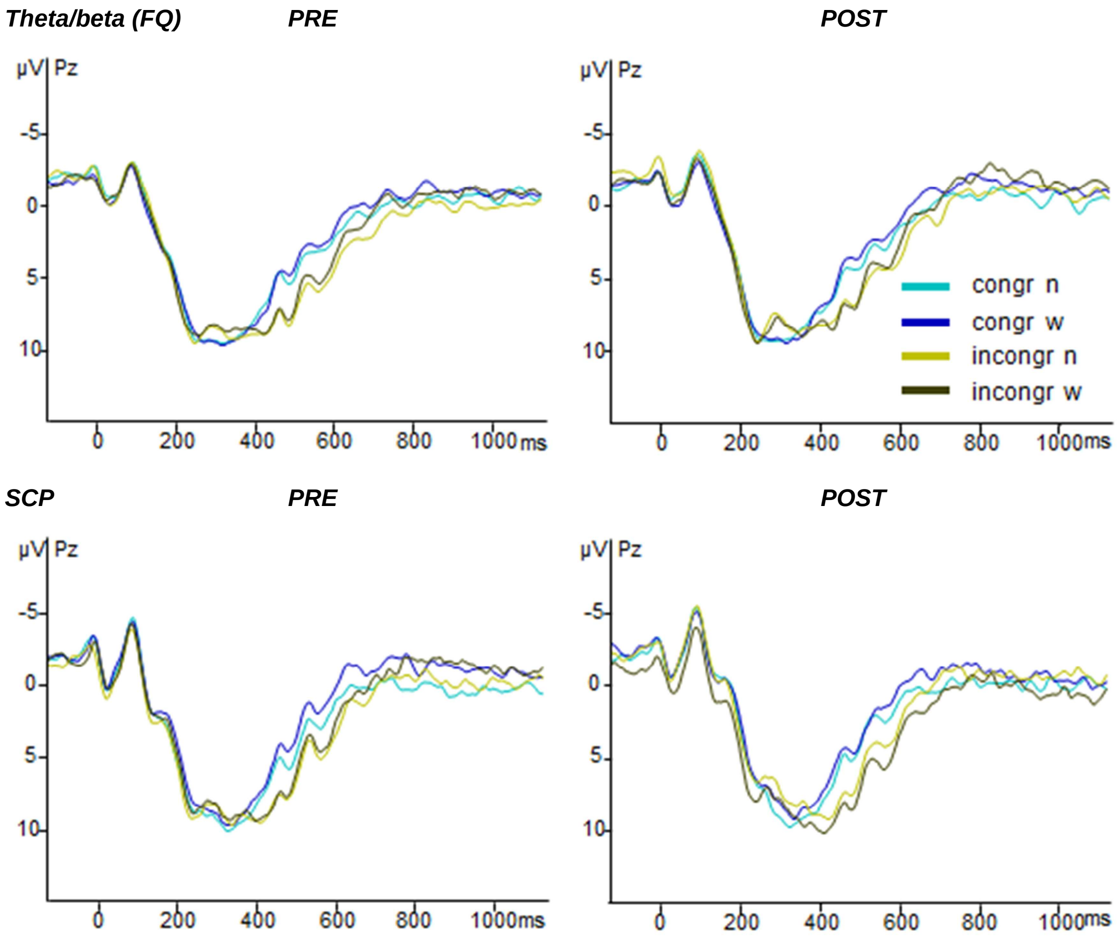


Figure 19. Target-P3 amplitudes for the three cue conditions (ANF, CON)

Grand average ERPs (at Pz) during presentation of target stimuli in the ANT are depicted for both pre- and post-assessment for the ANF and CON groups in order to illustrate target-P3 amplitudes. ERPs for NoCue, NeutralCue (NeCue) and SpatialCue (SpCue) trials are shown separately for the NoStress and WithStress conditions. Flanking fish appeared at -100 ms, and the target fish appeared at 0 ms. Target-P3 amplitudes were determined as the largest peak within 280 to 450 ms. ANF: adaptive neurofeedback training group, CON: control training group, ANT: Attention Network Test.

Target-P3 amplitudes (based on congruent and incongruent trials) did not significantly change from pre to post training in general (TIME: *F*(1,60) = .14, n.s.) or related to type of training (TIME × GROUP: *F*(3,60) = .17, n.s.). No conflict effect was present in the data as reported above, and also no significant change in the conflict score was observed from pre to post training (TIME × CONFLICT: *F*(1,60) = .56, n.s.; TIME × CONFLICT × GROUP: *F*(3,60) = .74, n.s.).

In summary, these results indicated that target-P3 amplitudes did not significantly change from pre to post training in general (no significant effects for TIME) or depending on the type of training (no significant interactions of TIME × GROUP). Furthermore, attention network modulations of target-P3 amplitudes were present for the alerting and orienting network (significant effects for ALERTING and



Theta/beta (FQ) PRE POST

SCP PRE POST

Figure 20. Target-P3 amplitudes in congruent / incongruent conditions (FQ, SCP)

Grand average ERPs (at Pz) during presentation of target stimuli in the ANT are depicted for both pre- and post-assessment for the FQ and SCP groups in order to illustrate target-P3 amplitudes. ERPs for congruent (congr) and incongruent (incongr) trials are shown separately for the NoStress and WithStress conditions. Flanking fish appeared at -100 ms, and the target fish appeared at 0 ms. Target-P3 amplitudes were determined as the largest peak within 280 to 450 ms. FQ: theta/beta training group, SCP: slow cortical potential training group, ANT: Attention Network Test.

ORIENTING), but not for the conflict network (no significant effect for CONFLICT). However, these network modulations were not observed to change with training (no significant interactions of TIME × ALERTING/ ORIENTING/ CONFLICT or TIME × ALERTING/ ORIENTING/ CONFLICT × GROUP) while analyses related to the conflict network have to be considered with care due to the missing target-P3 modulations related to the conflict network.

For effect size measures related to target-P3 amplitudes please refer to Table 10.

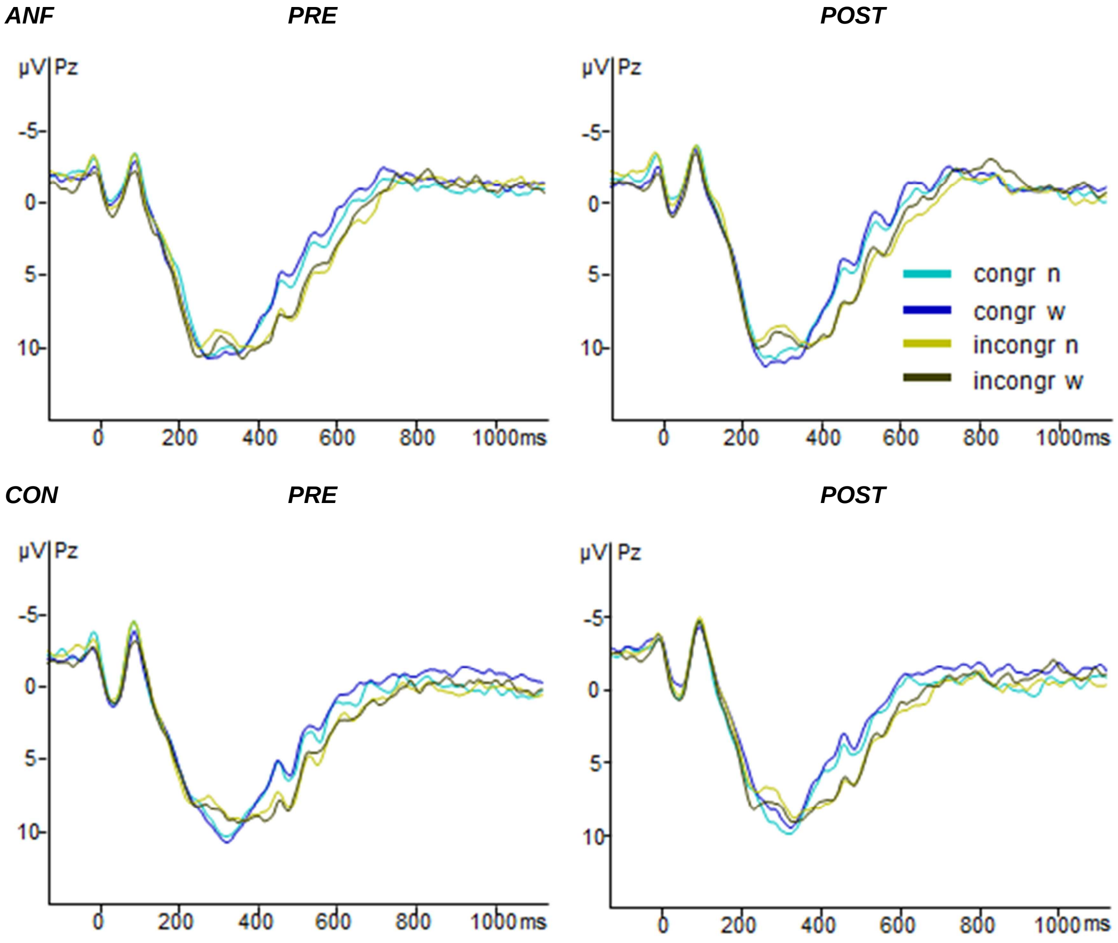


Figure 21. Target-P3 amplitudes in congruent / incongruent conditions (ANF, CON)

Grand average ERPs (at Pz) during presentation of target stimuli in the ANT are depicted for both pre- and post-assessment for the ANF and CON groups in order to illustrate target-P3 amplitudes. ERPs for congruent (congr) and incongruent (incongr) trials are shown separately for the NoStress and WithStress conditions. Flanking fish appeared at -100 ms, and the target fish appeared at 0 ms. Target-P3 amplitudes were determined as the largest peak within 280 to 450 ms. ANF: adaptive neurofeedback training group, CON: control training group, ANT: Attention Network Test.

4.3.3 TMS

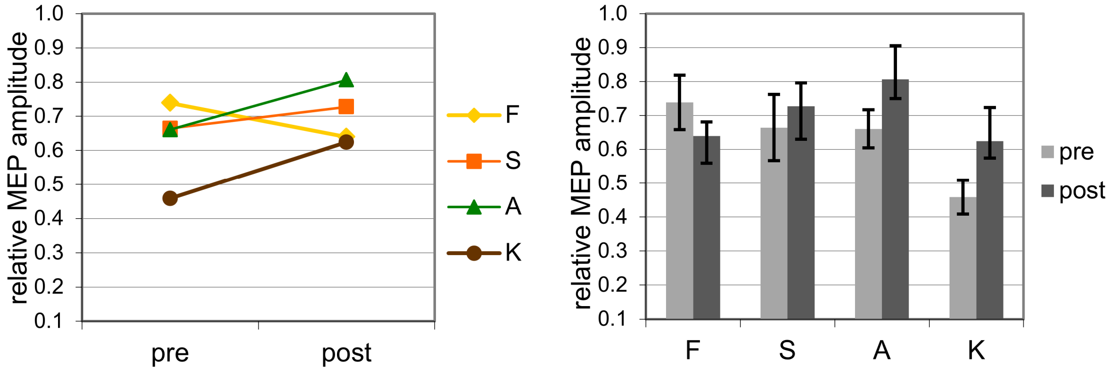
Due to the TMS incident and related precautionary measures (see 3.1.1 Screening interview and assessments) the TMS measurement was only performed in 53 subjects. Out of these subjects, data quality of pre- and post-assessments of 43 subjects was sufficient to include them in further data analysis (FQ: n = 11, SCP: n = 10, ANF: n = 12, CON: n = 10) while three outliers (see 3.2.4.1 General information on statistical analysis) were additionally excluded (see Appendix C).

The repeated measure ANOVA calculated for the SICI measure (see Figure 22) resulted in a trend for TIME ($F(1,36) = 3.13$, $p < .10$, $\eta_p^2 = .08$) which tended to be related to an increase of relative MEP amplitudes from pre to post, i.e. a decrease of

SICI. Furthermore, a trend was obtained for the interaction of TIME × GROUP ($F(3,36) = 2.41$, $p < .10$, $\eta_p^2 = .17$).

Post-hoc tests based on pairwise comparisons revealed significant interaction effects for the FQ compared to the ANF group (TIME × GROUP for FQ vs. ANF: $F(1,20) = 5.06$, $p = .036$, $\eta_p^2 = .20$) as well as for the FQ compared to the CON group (TIME × GROUP for FQ vs. CON: $F(1,17) = 5.49$, $p = .032$, $\eta_p^2 = .24$). No significant interactions were obtained for the other pairwise group comparisons (TIME × GROUP for FQ vs. SCP: $F(1,17) = 1.93$, n.s.; TIME × GROUP for SCP vs. ANF: $F(1,19) = .59$, n.s.; TIME × GROUP for SCP vs. CON: $F(1,16) = .86$, n.s.; TIME × GROUP for ANF vs. CON: $F(1,19) = .03$, n.s.). After applying Holm-Bonferroni correction to correct for multiple testing, post-hoc tests no longer revealed significant results as smallest $p > .05 / 6$.

SICI



ICF

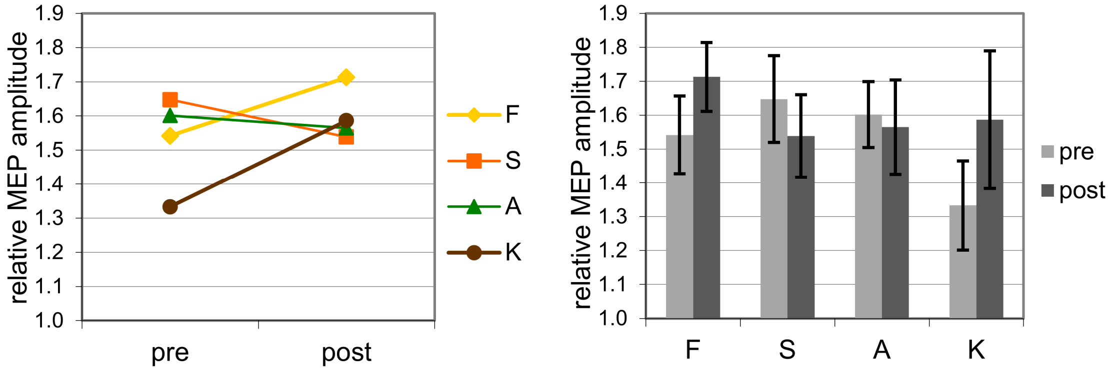


Figure 22. TMS measures SICI and ICF

The mean value of SICI (top) and ICF (bottom) at pre- and post-assessment is depicted for each group. Right: error bars are included. SICI: short-interval intracortical inhibition, ICF: intracortical facilitation, F: theta/beta training group, S: slow cortical potential training group, A: adaptive neurofeedback group, C: control training group.

While no significant effect was observed for GROUP ($F(3,36) = 1.51$, n.s.) in the present analysis, a trend for group differences emerged in the analysis of the SICI pre assessment data which was performed to check for pre training group differences (GROUP for pre training data: $F(3,36) = 2.58$, $p < .10$, $\eta_p^2 = .18$).

Post-hoc tests based on pairwise comparisons revealed significant group differences between the FQ and CON group ($t(17) = 2.95$, $p = .010$), and between the ANF and CON group ($t(19) = 2.58$, $p = .018$), as well as a trend for group differences between the SCP and CON group ($t(16) = 1.88$, $p = .079$) at pre assessment. These effects were related to a larger SICI in the CON group at pre assessment, i.e. smaller relative MEP amplitudes. No significant results were obtained for the comparison of the other groups (FQ vs. SCP: $t(17) = .58$, n.s.; FQ vs. ANF: $t(20) = .81$, n.s.; SCP vs. ANF: $t(19) = .04$, n.s.). After performing a Holm-Bonferroni correction of p-values post-hoc tests no longer revealed significant results as smallest $p > .05 / 6$.

Effect sizes at the level of SICI (see Table 11) indicated a large effect in the FQ compared to the CON group (FQ vs. CON: Cohen's $d = |1.08|$) and a small effect in the SCP compared to the CON group (SCP vs. CON: Cohen's $d = |.44|$).

Table 11

Effect sizes (Cohens' d) based on TMS measures

	FQ_CON	SCP_CON	ANF_CON	FQ_SCP	FQ_ANF	SCP_ANF
SICI	|**1.08**|	|.44|	|.08|	**|.65|**	|**.96**|	|.34|
ICF	|-.17|	**|-.78|**	**|-.64|**	**|.64|**	|.49|	|.-18|

Note. Effect size measures (Cohen's *d*) are depicted for SICI and ICF assessed by TMS for the comparison of pre-post change scores between groups. Positive values of effect sizes indicate a larger increase (or smaller decline) of the respective measure in the group mentioned first compared to the group mentioned second. Black numbers indicate small effect sizes, black bold numbers medium effect sizes, and black bold underlined numbers large effect sizes, while grey numbers indicate no effect. Effect sizes are depicted in brackets since it is not clear a change in which direction constitutes an improvement.TMS: transcranial magnetic stimulation, SICI: short-interval intracortical inhibition, ICF: intracortical facilitation, FQ: theta/beta training group, SCP: slow cortical potential training group, ANF: adaptive neurofeedback group, CON: control training group,

The comparison between neurofeedback groups revealed a medium effect size for the FQ compared to the SCP group (FQ vs. SCP: Cohen's $d = |.65|$) and a large effect size for the FQ compared to the ANF group (FQ vs. ANF: Cohen's $d = |.96|$).

Regarding ICF (see Figure 22), no significant change from pre to post training was observed (TIME: *F*(1,36) = 1.02, n.s.; TIME × GROUP: *F*(3,36) = 1.41, n.s.).

Effect sizes for this ICF measure (see Table 11) revealed medium effects for the SCP and ANF groups compared to the CON group (SCP vs. CON: Cohen's *d* = |-.78|; ANF vs. CON: Cohen's *d* = |-.64|).

The comparison of neurofeedback groups related to the ICF measure indicated a medium effect size in the FQ compared to the SCP group (FQ vs. SCP: Cohen's *d* = |.64|) and a small effect size in the FQ compared to the ANF group (FQ vs. ANF: Cohen's *d* = |.49|).

4.4 Assessments during the course of training

4.4.1 Satisfaction with life situation

No difference between groups was observed related to the satisfaction with their life situation (satisfaction with life averaged over all groups: *M* = 4.12, *SD* = 1.00; *F*(3,69) = 1.09, n.s.; see Table 12).

Table 12

Satisfaction with life situation

	M ± *SD*
FQ	4.06 ± 1.10
SCP	4.23 ± .83
ANF	4.35 ± .90
CON	3.78 ± 1.14

Note. The mean score (and *SD*) of the self-report measure satisfaction with life situation averaged over all training sessions is depicted for each group. Ratings are based on a 7-point rating scale ranging from zero (*not content at all*) to six (*very content*). FQ: theta/beta training group, SCP: slow cortical potential training group, ANF: adaptive neurofeedback group, CON: control training group.

4.4.2 Evaluation scales

Evaluation scales (see Table 13) assessed after the last training session showed no difference between groups related to their ratings on how strong they experienced the effect of their training on attention (GROUP: *F*(3,68) = .88, n.s.) and well-being (GROUP: *F*(3,68) = .40, n.s.) to be. Furthermore, satisfaction with the training did not differ between groups (GROUP: *F*(3,68) = .22, n.s.).

Table 13

Evaluation scales

	Attention	Well-being	Satisfaction
FQ	2.32 ± 1.16	2.79 ± .63	2.18 ± .27
SCP	2.21 ± .85	2.84 ± 1.01	2.26 ± .28
ANF	2.35 ± 1.11	2.47 ± 1.01	2.06 ± .32
CON	2.00 ± 1.00	2.94 ± .90	2.11 ± .27

Note. The mean score (and *SD*) of the dimensions attention, well-being, and satisfaction of the evaluation scales is depicted for each group. Larger scores indicate higher experienced effects of training on attention, well-being, or satisfaction with training. FQ: theta/beta training group, SCP: slow cortical potential training group, ANF: adaptive neurofeedback group, CON: control training group.

4.5 Self-regulation abilities in theta/beta and SCP training

4.5.1 Self-regulation abilities in theta/beta training

For the FQ group the theta/beta ratio in the course of training is depicted in Figure 23. For the theta/beta ratio no significant effect was obtained for the theta/beta ratio from the beginning to the end of training (theta/beta ratio pre: *M* = 1.72, *SD* = .31, theta/beta ratio post: *M* = 1.75, *SD* = .34; *t*(16) = -1.05, n.s.).

For good performers (based on the theta/beta ratio, see Table 14), a significant effect was observed for cluster 4 of the Brown Scale (good performers' change score: *M* = -.44, *SD* = 1.24; bad performers' change score: *M* = .75, *SD* = 1.04; *t*(15) = -2.14, *p* =

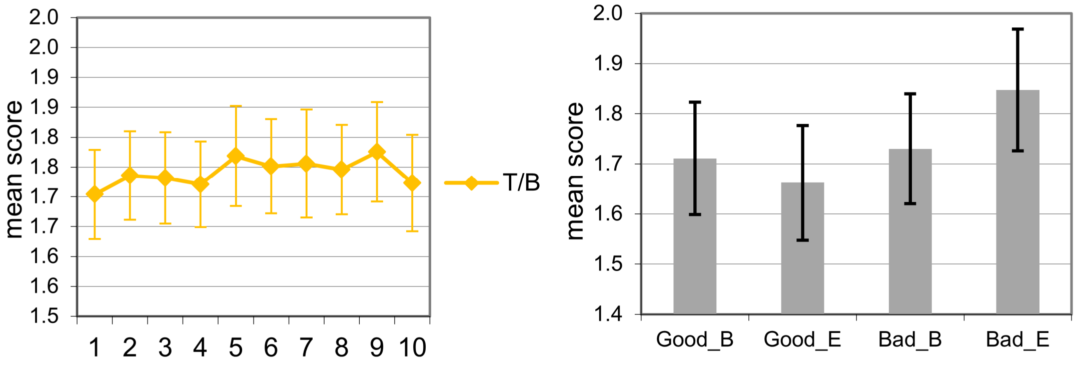


Figure 23. Theta/beta ratio in the course of theta/beta training

Left: The mean theta/beta ratio (and standard error) is depicted for the first to tenth theta/beta training session (averaged over all blocks per session). Right: Mean theta/beta ratio (and standard error) for good and bad performers for the beginning (B) of training (average of first 2 sessions) and the end (E) of training (average of session 9 and 10). T/B: Theta/beta ratio.

.03, Cohen's *d* = 1.05) which was related to an improvement in managing frustration and modulating emotions in good performers compared to bad performers.

Furthermore, good performance was significantly associated with a decrease in fatigue ($t(12) = -2.14$, $p = .03$, Cohen's $d = 1.14$) as measured by the POMS[35] (good performers' change score: $M = -5.14$, $SD = 7.34$; bad performers' change score: , $M =$

Table 14

Good / bad performers in theta/beta training: self-report and darts measures

	Change ($M_{post} - M_{pre}$)		*t*-test:		Effect size
	Good performers	Bad performers	*t*-value (df)	*p* one-sided	Cohen's *d*
Brown Scale					
Total score	-1.44 ± 5.10	.63 ± 5.42	-.81 (15)	.22	
Cluster 1	-.11 ± 1.27	.25 ± 1.83	-.48 (15)	.32	
Cluster 2	-.11 ± 1.76	-.25 ± 2.38	.14 (15)	.45	
Cluster 3	.11 ± 2.37	.25 ± 2.38	-.12 (15)	.45	
Cluster 4	-.44 ± 1.24	.75 ± 1.04	-2.14 (15)	.03*	1.05
Cluster 5	-.89 ± 1.69	-.38 ± .74	-.83 (15)	.21	
POMS					
Dejection	-1.00 ± 12.64	2.13 ± 15.07	-.45 (14)	.33	
Fatigue	-5.14 ± 7.34	3.00 ± 6.90	-2.14 (12)	.03*	1.14
Displeasure	-.78 ± 9.78	-2.13 ± 4.19	.38 (15)	.36	
Vigor	-1.00 ± 5.66	-5.75 ± 4.98	1.78 (14)	.05*	.89
Darts					
NoStress	.12 ± 1.15	.17 ± .58	-.12 (15)	.45	
WithStress	.12 ± .62	.47 ± .74	-1.05 (15)	.16	

Note. Results of the good / bad performer analysis based on regulation abilities in theta/beta ratio are depicted. For each measure, the mean change score (and *SD*) is listed for the group of good and bad performers, and *t*-test statistics are presented. Significance is assumed if $p \leq .05$ (one-sided, marked with *) and when correcting for multiple testing significance is assumed if $p \leq .01$ (one-sided, marked with **).

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[35] For the analysis of the POMS measure, despite further reducing already small sample sizes in the self-regulation bases analysis, extreme outliers had to be removed from the analysis in order to receive reliable results. Without removing outliers, the following results would have been obtained for good compared to bad performers in the FQ group for fatigue ($t(14) = -2.77$, $p = 0.01$) and for vigor ($t(15) = 1.85$, $p = 0.04$) which would have pointed towards an even stronger advantage for good compared to bad performers.

3.00 , *SD* = 6.90). Regarding vigor, a significant advantage was observed for good compared to bad performers (good performers' change score: *M* = -1.00, *SD* = 5.66; bad performers' change score: *M* = -5.75, *SD* = 4.98; *t*(14) = 1.78, *p* = .05, Cohen's *d* = .89) which was related to a smaller decrease in vigor from pre to post assessment in good performers. Yet, after correcting *p*-values for multiple testing none of the described effects remained significant (as *p* > .01).

The analysis of associations between FQ self-regulation abilities and pre-post change in cue- and target-P3 amplitudes yielded the following results (see Table 15). No significant difference between good and bad performers was observed for the pre-post change in cue-P3 amplitudes in both the NoStress (NeutralCue: *t*(12) = .77, n.s.; SpatialCue: *t*(12) = .20, n.s.) and WithStress condition (NeutralCue: *t*(12) = .74, n.s.; SpatialCue: *t*(12) = -1.05, n.s.).

Table 15

Good / bad performers in theta/beta training: ERP measures in the ANT

	Good performers	Bad performers	*t*-test: *p* one-sided	Effect size (Cohen's *d*)
Cue-P3				
NeutralCue, NoStress	.10 ± 1.41	-.51 ± 1.51	.23	
NeutralCue, WithStress	.61 ± 1.10	-.17 ± 2.68	.24	
SpatialCue, NoStress	-.10 ± 1.11	-.28 ± 2.26	.42	
SpatialCue, WithStress	-.47 ± 2.28	.88 ± 2.51	.16	
Target-P3				
NoCue, NoStress	-.50 ± 1.82	.59 ± 4.80	.27	
NoCue, WithStress	-.93 ± 2.51	1.68 ± 3.65	.06	
NeutralCue, NoStress	-1.28 ± 1.49	-.49 ± 3.51	.31	
NeutralCue, WithStress	-1.84 ± 2.59	1.66 ± 3.95	.05*	-1.05
SpatialCue, NoStress	-2.16 ± 2.17	.96 ± 2.33	.01**	-1.38
SpatialCue, WithStress	-1.99 ± 2.13	.55 ± 2.33	.02*	-1.14

Note. Results of the good / bad performer analysis based on regulation abilities in theta/beta ratio are depicted for ERP measures (cue- and target-P3) assessed during the ANT. For each measure, the mean change score (and *SD*) is listed for the group of good and bad performers, and *t*-test statistics are presented. Significance is assumed if *p* ≤ .05 (one-sided, marked with *) and when correcting for multiple testing significance is assumed if *p* ≤ .01 (one-sided, marked with **).

Regarding target-P3 amplitudes, no significant differences were observed between good and bad performers in the NoCue condition (NoStress: *t*(13) = -.62, n.s.; WithStress: NoCue: *t*(13) = -1.65, n.s.) and in the NeutralCue-NoStress condition (*t*(13) = -.52, n.s.). However, in the NeutralCue-WithStress condition (*t*(13) = -1.92, *p* = .05, Cohen's *d* = -1.05) as well as in the SpatialCue condition (NoStress: *t*(13) = -2.62, *p* = .01, Cohen's *d* = -1.38; WithStress: *t*(13) = -2.18, *p* = .02, Cohen's *d* = -1.14) significant differences between good and bad performers related to pre-post changes in target-P3 amplitudes were observed. These effects were related to pre-post target-P3 amplitude decreases in good performers and increases in bad performers. However, when adjusting the significance level to $p \leq .01$ only the effect in the SpatialCue-NoStress condition remained significant.

4.5.2 Self-regulation abilities in SCP training

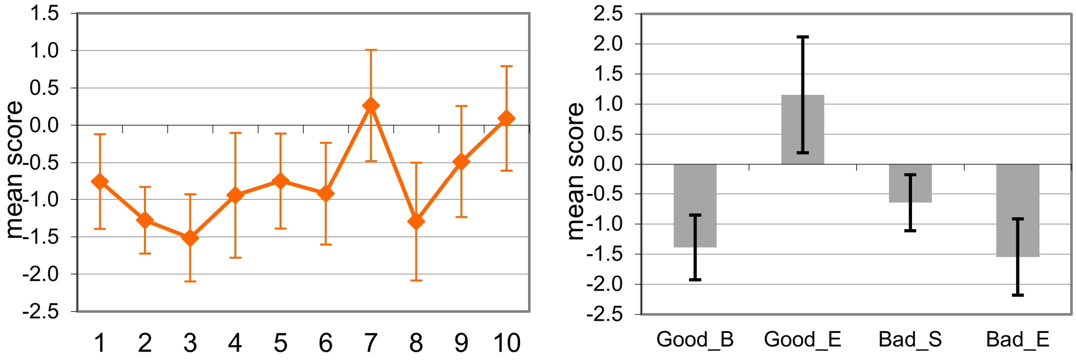

Figure 24. SCP differentiation in the course of SCP training

Left: The SCP differentiation (and standard error) is depicted for the first to tenth SCP training session (averaged over all blocks per session). Right: Mean SCP differentiation (and standard error) for good and bad performers for the beginning (B) of training (average of first 2 sessions) and the end (E) of training (average of session 9 and 10).

For the SCP group the differentiation in the course of training is illustrated in Figure 24. A trend was obtained for an increase in differentiation from the beginning to the end of training (differentiation_pre: *M* = -1.02 µV, *SD* = 1.43 µV, differentiation_post: *M* = -.20 µV, *SD* = 2.63 µV; *t*(15) = -1.40, *p* < .10, Cohen's *d* = .32).

Table 16

Good / bad performers in SCP training: self-report and darts measures

	Change (M_{post} – M_{pre})		*t*-test:		Effect size
	Good performers	Bad performers	*t*-value (df)	*p* one-sided	Cohen's *d*
Brown Scale					
Total score	-5.50 ± 6.12	-1.13 ± 2.17	-1.91 (14)	.05*	.95
Cluster 1	-.75 ± 1.49	.00 ± 1.20	-1.11 (14)	.14	
Cluster 2	-1.75 ± 3.01	-.38 ± 2.39	-1.01 (14)	.17	
Cluster 3	-2.50 ± 2.00	.00 ± 1.07	-3.12 (14)	.004**	1.56
Cluster 4	.38 ± 1.19	-.50 ± 1.07	1.55 (14)	.07	
Cluster 5	-.88 ± 1.73	-.25 ± 1.04	-.88 (14)	.20	
POMS	-				
Dejection	6.71 ± 10.59	-.38 ± 5.29	-1.50 (13)	.08	
Fatigue	-6.43 ± 7.85	1.88 ± 4.82	-2.51 (13)	.01**	1.27
Displeasure	-4.00 ± 4.10	1.71 ± 4.46	-2.39 (11)	.02*	1.33
Vigor	-2.14 ± 4.98	-.88 ± 4.79	-.50 (13)	.31	
Darts					
NoStress	-.12 ± .33	-.06 ± .33	-.39 (14)	-.35	
WithStress	.42 ± .65	.29 ± .60	.43 (14)	.34	

Note. Results of the good / bad performer analysis based on regulation abilities in SCP differentiation are depicted. For each measure, the mean change score (and *SD*) is listed for the group of good and bad performers, and *t*-test statistics are presented. Significance is assumed if $p \leq .05$ (one-sided, marked with *) and when correcting for multiple testing significance is assumed if $p \leq .01$ (one-sided, marked with **).

Good performance (based on the differentiation measure, see Table 16) was related to a significantly stronger reduction from pre to post in the total score of the Brown Scale (good performers' change score: $M = -5.50$, $SD = 6.12$; bad performers' change score: $M = -1.13$, $SD = 2.17$; $t(14) = -1.91$, $p = .05$, Cohen's $d = .95$) as well as in Brown Scale subscore 3 (good performers' change score: $M = -2.50$, $SD = 2.00$; bad performers' change score: $M = .00$, $SD = 1.07$; $t(14) = -3.12$, $p = .01$, Cohen's $d = 1.56$), which is associated with regulation of alertness, sustaining effort and processing speed.

Table 17

Good / bad performers in SCP training: ERP measures in the ANT

	Good performers	Bad performers	*t*-test: p one-sided	Effect size (Cohen's d)
Self-regulation: Differentiation				
CNV: NeutralCue, NoStress	-3.61 ± 2.09	-1.94 ± 2.70	.13	
CNV: NeutralCue, WithStress	-1.09 ± 1.53	-1.37 ± 2.43	.41	
CNV: SpatialCue, NoStress	-4.01 ± 1.67	-3.00 ± 2.32	.20	
CNV: SpatialCue, WithStress	-2.06 ± 1.10	-2.49 ± 2.76	.36	
Self-regulation: Negativity				
CNV: NeutralCue, NoStress	-3.79 ± 1.63	-1.69 ± 2.95	.07	
CNV: NeutralCue, WithStress	-1.89 ± 2.02	-.26 ± 1.18	.07	
CNV: SpatialCue, NoStress	-4.41 ± 1.57	-2.43 ± 1.93	.04*	1.13
CNV: SpatialCue, WithStress	-3.20 ± 1.64	-.89 ± 1.28	.01**	1.57

Note. Results of the good / bad performer analysis based on regulation abilities in SCP differentiation as well as SCP negativity are depicted for ERP measures (CNV) assessed during the ANT. For each measure, the mean change score (and *SD*) is listed for the group of good and bad performers, and *t*-test statistics are presented. Significance is assumed if $p \leq .05$ (one-sided, marked with *) and when correcting for multiple testing significance is assumed if $p \leq .01$ (one-sided, marked with **).

Furthermore, based on the POMS measure[36], good performers showed a significantly stronger reduction of fatigue from pre to post than bad performers (good performers' change score: M = -6.43, SD = 7.85; bad performers' change score: M = 1.88, SD = 4.82; $t(13) = -2.51$, p = .01, Cohen's d = 1.27). In addition, displeasure decreased significantly from pre to post in good compared to bad performers (good

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[36] For the analysis of the POMS measure, despite further reducing already small sample sizes in the self-regulation based analysis, extreme outliers had to be removed from the analysis in order to receive reliable results. Without removing outliers, the following results would have been obtained for good compared to bad performers in the SCP group for displeasure ($t(13) = -2.59$, $p = 0.01$), which would have pointed towards an even stronger advantage for good compared to bad performers.

performers' change score: *M* = -4.00, *SD* = 4.10; bad performers' change score: *M* = 1.71, *SD* = 4.46; *t*(11) = -2.39, *p* = .02, Cohen's *d* = 1.33).

When adjusting the significance level to $p \leq .01$ due to multiple testing, both the effect for subscore 3 of the Brown Scale and the effect for fatigue remained significant.

The analysis of associations between SCP self-regulation abilities and pre-post change in CNV amplitudes yielded the following results (see Table 17). No significant effect was obtained for the pre-post change in CNV amplitudes in good compared to bad performers based on the differentiation measure of self-regulation both for the NoStress (NeutralCue: *t*(10) = -1.21, n.s.; SpatialCue: *t*(10) = -.88, n.s.) and WithStress condition (NeutralCue: *t*(10) = .24, n.s.; SpatialCue: *t*(10) = .37, n.s.).

In the analysis based on negativity regulation abilities a significant effect was observed in the SpatialCue condition which indicated a larger CNV increase from pre to post in good compared to bad performers in both the NoStress (SpatialCue: *t*(10) = -1.97, *p* = .04, Cohen's *d* = 1.13) and WithStress condition (SpatialCue: *t*(10) = -2.62, *p* = .01, Cohen's *d* = 1.57) while only the effect of the WithStress condition also remained significant for the corrected significance level of $p \leq .01$. For the NeutralCue condition no significant difference between good and bad performers was observed (NoStress: *t*(10) = -1.59, n.s.; WithStress: *t*(10) = -1.60, n.s.).

5 Discussion

In the present study, the effects of a theta/beta neurofeedback training, a training of slow cortical potentials, and an adaptive neurofeedback training in ‘healthy’ adults were examined compared to a control training (randomized group assignment, *n* = 73). One motivation behind the present study was the effective application of two of the studied protocols in children with ADHD, without a full understanding of the mechanisms mediating an effective training. The present study set out to shed more light on the neuronal mechanisms underlying a successful NF training. The control training was implemented to delineate specific NF effects from unspecific effects, related to repeating measurements or practicing cognitive strategies in daily life situations.

In addition, the study aimed at examining the effects of NF on well-being and mood as a potential new field within the realm of peak performance training, where previous studies have mainly focused on performance measures. Furthermore, the effectiveness of adaptive NF was to be examined in the context of peak performance training. The reason for examining the adaptive NF training was that it is a NF method that is spreading and is being applied more and more in clinical practices for the treatment of a wide spectrum of psychiatric disorders, but without good scientific evidence.

Independent of training type, the following pre-post training effects were observed.

On the behavioral level, pre-post improvements were observed in the domains action orientation, self-access, and in tendency for attention, while vigor decreased and otherwise no effects on well-being / mood were present.

On the performance level, participants showed faster and more constant responding in the ANT, improved working memory as well as improved motor skills in a game of darts.

At the level of resting EEG measures, an increase in theta and alpha activity were observed as well as a tendency for an increase in beta activity. These EEG findings most likely indicate that at post assessment participants were more relaxed and possibly slightly more focused during a resting state. Overall, no training effects on the ERP measures (cue-P3, target-P3, and CNV amplitudes) as measured during the ANT were obtained. TMS measures indicated a tendency for a decrease of SICI.

With respect to NF training, these findings point towards unspecific results, probably due to repeated assessment as well as non-specific factors related to attending a training session and developing cognitive strategies.

Concerning the specific effects of NF training mainly based on effect size measures, the following pattern resulted.

Self-ratings of attention revealed only a very slight advantage for the NF groups. NF trainings also had a somewhat more positive effect on well-being / mood, perceived stress, and personality characteristics. More specifically, NF was associated with reducing deactivation; the most pronounced effect on mood and perceived stress was obtained for the ANF group; overall, the SCP and ANF groups were observed to profit more than the theta/beta group; and theta/beta training was associated with a slightly more pronounced increase in action orientation.

At the performance level, training-related differences between groups were not very prominent and mostly only present in one out of several task conditions. The only somewhat more pronounced result was faster responding in an attention-demanding task which was observed after theta/beta training. In addition, a very slight advantage in motor skills was obtained for the control training group.

Regarding the neuronal mechanisms underlying NF training, an increase in CNV amplitudes after all NF trainings indicated an improved resource allocation during cognitive preparation after NF. Based on self-regulation measures during negativity trials, a tiny hint for a specific effect of SCP training on increasing CNV amplitudes was observed. A similarly tiny hint for a specific effect of theta/beta training was observed, with a successful reduction of the theta/beta ratio being associated with decreased target-P3 amplitudes. In addition, an increase of alpha activity (at Pz) was observed after ANF training. Moreover, with respect to motor system excitability, theta/beta training was associated with an increase in both SICI and ICF which might possibly constitute a specific effect.

In the following, these results will be discussed in more detail and put in context to previous research.

5.1 The sample

With a training period of 27 months, some effort was made to include a reasonable number of subjects in the study. The final sample, on which further analyses were based, comprised 73 adults who were randomly allocated to four training groups. Thus, the group sizes of the present study were somewhat larger than in most previous peak performance studies in healthy adults. In these studies, mostly only between 20 and 30 subjects were recruited and allocated to two to three experimental groups (e.g. Egner & Gruzelier, 2004; Logemann et al., 2010; Ros et al., 2009). However, such peak performance studies were able to show some specific effects related to particular NF trainings protocols, suggesting that despite small sample sizes, these studies are meaningful.

Nevertheless, with between 17 and 19 subjects per group, the overall sample size of the present study was still rather small. To give a comparison, for the controlled multi-center neurofeedback study of Gevensleben et al. (Gevensleben, Holl, Albrecht, Vogel, et al., 2009) a sample size of about 100 children with ADHD was estimated to be necessary for being able to display significant differences of medium effect size between two experimental groups (NF vs. computerized attention training). The present study could not be conducted as a multi-center study. But quite some effort was made to nevertheless include an acceptable number of subjects in the study. When seen in the context of other peak performance studies, this was achieved.

The present study was conducted in ‘healthy’ adults and not in children with ADHD for the following reasons. Based on the concept of peak performance training, the employed NF protocols are also indicated for the training in healthy adults. Pre and post assessments were very comprehensive and therefore not well suitable for children with ADHD. Most notably, the adaptive NF training has not yet been scientifically established, wherefore it seemed more adequate to first examine this training protocol in adults. Moreover, it was assumed that a larger and more homogenous sample could be obtained when performing the study with ‘healthy’ adults.

Nevertheless, one advantage of a clinical sample in comparison to ‘healthy’ adults might have been that it may have left more room for improvement. In the present study, where most participants were university students who can be assumed to display relatively good performance, this room for possible improvements may have been rather small.

However, finding healthy adults that were interested and had enough time resources proved more difficult than expected. Among others, university students, the main target group, proved to have very tight time schedules. In addition, payment for participation in the study was too low to attract subjects who purely participated for money. Based on the study design, it was good that subjects hardly participated for monetary reasons. Thus, those subjects who participated were mostly interested and intrinsically motivated. Yet exactly this last aspect proved to pose a difficulty as well.

Volunteers who showed interest in the study often also experienced difficulties in daily life situations and hoped to improve their situation by participating in the study. Beyond the 33 volunteers that were excluded from participation in the study after the screening interview (see 3.1.1 Screening interview and assessments), there had been many more interested volunteers. However, they had to be excluded before a screening appointment was made due to an existent psychiatric diagnosis or clinically noticeable feeling and behavior. Still, for those subjects who were included in the study, a rather large standard deviation was observed for GSI scores (assessed with the SCL-90). This indicated that subjects with rather high overall psychological distress (but still within the norm) were included in the study (see 3.1 Participants – Screening and final sample). This was due to the procedure that free training places were rather allocated to subjects with such higher scores than left vacant. Therefore, the sample included more subjects with some kind of subclinical psychic symptomatology than originally intended. This might be an advantage and disadvantage at the same time. On the one hand, it may have left more room for improvements and on the other hand, it increased the heterogeneity of the sample and introduced uncontrolled factors. However, an analysis of the data including only subjects without such a noticeable symptomatology yielded a similar result pattern (see 3.2.4.1 General information on statistical analysis). For this reason, the composition of the sample should not have influenced the results in a certain way but is rather an indication for a lifelike sample.

Group assignment was performed randomly and resulted in groups that showed comparable results based on screening and pre-assessment measures. Groups were comparable regarding their age, estimated IQ and satisfaction with their life situation. Yet for the GSI score of the symptom checklist – a measure of overall psychological distress – significant group differences were obtained. However, these group differences did not remain significant when post-hoc tests were corrected for multiple comparisons by means of Holm-Bonferroni correction. At pre-assessment, only for the TMS measure SICI, a trend for pre-training differences was observed between groups. Also here, when correcting post-hoc tests by means of Holm-Bonferroni correction, group differences no longer remained significant. A single measure, the dejection scale of the EWL-N, revealed significant group differences in the repeated measure ANOVA applied in the analysis of pre-post training effects (sign. effect for GROUP). These were related to significantly higher dejection in the CON compared to the ANF group even after applying Holm-Bonferroni correction. Yet for the dejection scale of the POMS, no such group differences were observed. Thus, the described data indicate that random group assignment resulted in comparable groups, and the minor group differences described above will be considered in the discussion of the results.

Overall, mainly the rather small sample size constituted a limitation for the statistical data analysis by limiting statistical power. In addition, Holm-Bonferroni correction, which was applied to correct for multiple comparisons in post-hoc tests, is a rather strict method and it remains to be discussed in how far it is appropriate for these data. For these reasons, effect size measures will be reported in addition. Results based on effect size measures will be discussed if at least medium effect sizes were obtained, which can be considered meaningful especially when they were accordant to the hypotheses. Nevertheless, interesting findings which are based on these effect size measures have to be considered with care and need to be further examined in a larger sample in future studies.

5.2 The control training

A further important aspect concerning the design of the study is the control training. As outlined in the introduction (see 1.4.3 Specificity of training effects and the design of a control training), there is controversy about the choice of the appropriate control training. In the present study, it was decided to include a control training in order to control for effects related to practice and motivation due to repeated measurement and the usage of cognitive strategies (as will be discussed below). The control training was not designed to parallel the NF trainings regarding the amount of training time.

This was done for various reasons. One reason was that, as the training was performed in ‘healthy’ adults, there was no established training available which could have been used as a control training. The development of such a training would have been a time-consuming and non-trivial task. Another reason was the controlled design implemented in the study by Gevensleben and colleagues (Gevensleben, Holl, Albrecht, Vogel, et al., 2009), which had preceded the present study. They had applied two of the three NF protocols used in the present study (theta/beta and SCP training) in children with ADHD and had used an elaborate control training in combination with a large sample. The results of this large controlled study indicated stronger reductions in symptomatology after NF training compared to the control training (medium effect size).

Thus, the advantage of two of the three NF protocols applied in the present study has already been observed, albeit in children with ADHD and not in ‘healthy’ adults. In addition, the aim of the present study was to gain further insights into the specific neuronal mechanisms underlying different NF training protocols. This is a different focus, although nevertheless, the control training was used to differentiate specific from unspecific training effects and in this way to provide information on differential effects related to particular NF protocols.

A placebo training was not used as a control condition for the present study for the following reasons. As discussed in the introduction, including a placebo training group may have negative effects on NF performance. As one aim of the present study was to examine the effects of an adaptive NF training in comparison to theta/beta and SCP neurofeedback training, the inclusion of a placebo group was considered a confounding variable. Furthermore, in parallel to the present study the effects of a placebo SCP training in comparison to a real SCP training were examined in a study with healthy adults in Göttingen (for a brief description of preliminary results see 1.4.3 Specificity of training effects and the design of a control training). Their results are to be compared to the results of the present study. Currently, regarding the results of this study performed in Göttingen, the effectiveness of the training in terms of associations between regulation abilities and behavioral data remains to be analyzed. This analysis will be important for judging the specific effects of SCP training in healthy adults. Thus, unfortunately, at the present moment no conclusions can be drawn based on the comparisons of the present study with the study performed in Göttingen regarding potential unspecific training effects, which might be unmasked by their placebo training group. However, the missing comparison to a placebo training group is not the main critical point of the present study, as will be outlined in the further discussion.

In the present study, the subjects of the control group (like the subjects of the three NF groups) also practiced cognitive strategies in the context of transfer tasks during training as well as during everyday situations at home. In addition, the participants of the control group also applied their strategies in achieving an attentional state during post assessment in a similar way as participants of the NF groups. In this way, these unspecific training effects of developing a cognitive strategy and practicing its application in everyday situations, which is a process that attracts conscious perception to one’s own state, were controlled for. Additionally, self-access was observed to increase from pre to post training, but no relevant differences between the control group and the NF groups were observed. Thus, NF did not lead to increased self-access compared to the control training and therefore, increased self-access cannot account for the advantages observed for the NF groups (see discussion below).

The control training was shorter (shorter number of sessions and shorter duration of sessions) as it was designed to parallel the transfer parts of the NF sessions. For this reason, it was not able to control for unspecific training effects related to the amount of time spent for training as well as the direct feedback on one’s own mental state received during NF sessions. These remain aspects that also might have affected the more positive effects observed for the NF groups. Yet when looking at the evaluation scales assessed after the last training session, no differences between groups were observed regarding their satisfaction with the training or their rating on how strongly they experienced the effect of their training on attention and well-being. These findings cannot rule out the constraint mentioned before, but they provide a hint that the control training was similarly well accepted as the NF trainings and was perceived as similarly effective.

5.3 Effects of neurofeedback training protocols on attention, working memory, and motor skills

Regarding attention as assessed by self-report measures, the following results were obtained. For the Brown Scale, a trend for an increase in attention from pre to post was observed which was however not significantly related to specific training groups (no significant interaction of TIME × GROUP). Effect size measures only revealed small effects which were in favor of the NF groups but which cannot be considered as relevant results.

In addition, for the subscale concentration of the EWL-N, a significant TIME × GROUP interaction was obtained. Post-hoc tests indicated that this effect was related to a larger increase in concentration in the ANF compared to the CON and theta/beta groups (Cohen’s *d*: large effect sizes), and a tendency for a larger increase in the SCP compared to the CON and theta/beta groups (Cohen’s *d*: medium effect sizes). These group differences no longer remained significant after correcting for multiple comparisons. However, since large and medium effect sizes were obtained and because the stronger improvement in attention in the ANF and SCP groups compared to the control group was conform to the hypotheses, these findings were considered relevant.

Taken together, based on one of the two described self-report measures (EWL-N), effect sizes revealed larger increases in concentration in the ANF and SCP groups compared to the CON group. Hence, some support was obtained for H1. However, no advantage of a pre-post change of concentration was observed in the theta/beta compared to the CON group. Thus, with respect to the theta/beta group, H1 was not supported. Also the second measure of attention (Brown Scale) revealed no support for H1. For this measure, no advantages regarding pre-post improvement of attention were observed for any of the NF groups compared to the CON group.

When seen in the context of other studies, the assessment of self-report measures of attention is not a very common procedure in peak performance NF studies in healthy adults. In these studies, assessments were rather based on performance measures of attention-demanding tasks. As such measures were also assessed in the present study, any results concerning these measures will be outlined in the discussion below.

In contrast, regarding studies of NF training in children with ADHD, behavioral measures including attention / inattention which are assessed based on parent ratings constitute an important measure. Advantages of different NF protocols in reducing symptoms of inattention have been observed in a variety of studies in children with ADHD as indicated by the large effect size obtained for inattention in the meta-analysis conducted by Arns et al. (2009). However, there are also studies in which no advantage of NF was obtained with respect to the improvement of symptoms of inattention in these children (e.g. Holtmann et al., 2009). In a way, these findings on children with ADHD are not directly comparable to studies in healthy adults as the former’s symptomatology of inattention leaves considerably more room for possible improvements.

As the present study was motivated by the application of NF in children with ADHD, also here, self-report measures of attention were applied. The Brown Scale was selected as a measure of attention as it allows for a good distinction of different aspects of attention. Its main application is the assessment of symptoms of inattention in adults with ADHD. The purpose for which it was used in the present study was for assessing whether NF protocols were able to lead to improvements in attentional domains in ‘healthy’ adults which are also relevant for adults with ADHD. A further reason for the selection of this measure was to allow comparability to the placebo-controlled NF study conducted in Göttingen (see 1.4.3 Specificity of training effects and the design of a control training). The second measure of attention, the EWL-N, had mainly been chosen in order to assess well-being / mood. The subscale concentration of this self-report measure was therefore used as a supplementary measure.

Overall, the effects of NF on attention as assessed by self-report measures were rather small, which might be related to the following aspects. The Brown Scale was a self-report measure designed to display deficits in attention as observed in adults with ADHD, as outlined above. Items of this measure covered a wide range of aspects related to attention, which was the reason why this measure had been selected. However, it turned out that the four-point rating scale did not differentiate well in the peak performance range. This may have led to ceiling effects, as overall relatively good attentional abilities were observed in all groups as indicated by relatively low scores. Hence, this may partially explain the missing effect for the theta/beta compared to the CON group: visual inspection indicated that the subjects of the theta/beta group showed the lowest scores in the Brown Scale (i.e. the highest attentional abilities) at pre assessment (even though pre-training group differences were not significant according to the ANOVA calculated). Furthermore, the advantage of the SCP and ANF groups compared to the theta/beta group regarding pre-post improvements in concentration may also partially be explained in this way. Visual inspection indicated better pre-assessment scores in the theta/beta group while post-assessment values lay in the same range as for the SCP and ANF groups.

Also with respect to the subscale concentration of the EWL-N measure, the rating of “applicable” vs. “not applicable” did not allow for a good gradual differentiation of attentional capabilities in the peak performance range. Nevertheless, it was able to display some effects.

To conclude, for evaluating training effects on attentional abilities in the peak performance range, self-report measures combining differential aspects of attention (as assessed by the Brown Scale) in combination with a rating scale, which allows for more gradual distinctions of attentional abilities, would be desirable.

As a next step, the results of the performance measures assessed during an attention-demanding task, in the present study during the ANT, will be discussed.

With respect to the number of hits, no significant improvements were observed from pre to post training. However, with nearly 100% correct responses on average, overall task performance in all groups was very good. Thus, there was hardly room left for training-related improvements. Following the preceding study on children with ADHD (Wangler et al., 2011), the same ANT version has been used in the present study. As this ANT version had been designed for children, the task was not a difficult task for ‘healthy’ adults. Thus, the very high number of hits observed in the present study was an expected finding.

Nevertheless, based on effect size measures, increased performance from pre to post in the CON and theta/beta groups compared to the ANF group in the NoStress condition was indicated by medium effect sizes. However, these findings were not very robust in the sense that they were only observed in the NoStress and not in both conditions. In addition, visual inspection of the data suggested best performance in the ANF group at pre assessment (although the ANOVA for pre-assessment data revealed no significant effects for GROUP). Together with the overall very good performance in this task, the relevance of these effects remains questionable.

In summary, attentional performance in the ANT as measured by the number of hits was not observed to be improved from pre to post in the NF groups compared to the CON group. Hence, with respect to the number of hits, H8 was not supported. Overall, the more interesting measures were RT and the variability of RT which will be discussed in the following.

RT was observed to decrease from pre to post assessment, i.e. response speed increased. A tendency for group-specific pre-post changes in RT was indicated by a trend for the TIME × GROUP interaction. Post-hoc tests revealed that this tendency was mainly related to a larger decrease in RT in the theta/beta compared to the CON and SCP group. However, these results were no longer significant after correction for multiple testing. At the level of effect size measures, small to medium effects were obtained for pre-post RT measures in the theta/beta compared to the CON group. Thus, improved performance from pre to post was observed in the theta/beta compared to the CON group, as indicated by a larger decrease in RT in the theta/beta group. This faster responding in the theta/beta group compared to the CON group as an indicator of improved performance in an attention-demanding task provided support for H1. However, the pre-post increase in response speed was not more pronounced in the ANF and SCP groups compared to the CON group. Hence, with respect to ANF and SCP training, H1 was not supported.

In addition, for the direct comparison of RT changes between NF groups, effect size measures revealed the following results. A larger pre-post increase in response speed was observed in the theta/beta compared to the SCP group as indicated by effect sizes at the boundary between medium and large effects. To a lesser degree (small to medium effect sizes), response speed also increased more from pre to post in the ANF compared to the SCP group.

In summary, the clearest result was the larger increase in response speed in the theta/beta compared to the CON and SCP groups. This result may on the one hand indicate a specific effect related to self-regulation abilities acquired during theta/beta training. Theta/beta training aimed at training sustained attention. An increased ability in participants of the theta/beta group to attain this state of sustained attention, while performing the ANT at post assessment, may have been displayed in faster responses. On the other hand, the larger increase in response speed may also be related to the way the theta/beta training was designed. In theta/beta training, a few long self-regulation trials (5 to 10 minutes) were performed in a session with feedback animations that were not very diversified. In this respect, theta/beta training was very similar to the ANT task which also consisted of longer trials (about 5 minutes each) during which always the same kind of stimuli were presented, i.e. the task was also not very diversified. In contrast, SCP training consisted of many short trials (several seconds long). Thus, the more similar design of the trials in theta/beta compared to SCP training may explain the advantage in RT measures in the theta/beta training group. A similar explanation regarding continuous long trials may also account for the comparably marginal result obtained for the ANF compared to the SCP group.

The decrease in the variability of reaction times from pre- to post-assessment did not differ for the different training groups and therefore rather constituted an effect related to repeated task performance.

Concerning the attention networks which constituted the more specific measures of the ANT, the results were rather marginal. While no pre-post change was observed for the alerting network, both the orienting and conflict scores decreased from pre to post assessment independent of the training group. The pre-post decrease of these scores, in combination with reduced RTs, indicated overall improved orienting and conflict processing at post assessment. Effect size measures related to the attention networks revealed no relevant advantages (Cohen's *d* < .50) for any NF compared to the control group. That is, no larger improvements related to the attention networks on the performance level could be observed in the NF groups compared to the control group. Hence, in this respect H8 was not supported by the present data.

When considering effect size measures, for the comparisons between NF groups one result was obtained related to the alerting network. A stronger increase in alerting, i.e. a stronger decrease in the alerting score, was observed in the SCP compared to the ANF group in the WithStress condition (medium effect size). This may indicate a small advantage in maintaining an alert state in the absence of a warning stimulus in the SCP compared to the ANF group. Possibly, this may be associated with negativity trials trained in the SCP group where subjects trained to achieve a state of increased excitation related to response preparation. However, this results needs to be seen in the context of the other performance measures. Effect size measures for RTs had revealed a slight advantage for the ANF compared to the SCP group regarding pre-post increase in response speed. Thus, the improved alertness after SCP compared to ANF training was not related to improved overall performance. Considering in addition that this advantage in alerting in the SCP group was only observed for a single condition (WithStress) and only in comparison to one other group (ANF), it constitutes a rather minor finding. Overall, orienting and conflict processing were improved at post assessment independent of training group, but no clear advantage of any NF protocol related to these attention network measures at the performance level was observed.

So far, the only other NF study in which the ANT has been applied for assessing training effects was the study by Gevensleben and colleagues (Gevensleben, Holl, Albrecht, Vogel, et al., 2009) which was performed in children with ADHD (ANT data of this study were published in Wangler et al., 2011). Their analysis had revealed pre-post improvements in performance for all parameters (hits, RT, variability of RT, alerting, orienting, and conflict) independent of training group (NF, control). In this respect, their results were very comparable to the results of the present study. Also in the present study, pre-post improvements were observed for most measures (RT, variability of RT, orienting, and conflict) independent of training group. The only exception was formed by the trend for the TIME × GROUP interaction in the RT analysis in the present study. In addition, in the present study, no overall improvement in the number of hits was obtained, which can be attributed to the generally very good performance, as discussed above.

The attention network measures were the specific measure of the ANT. But neither in the present study performed in ‘healthy’ adults nor in the study by Wangler and colleagues (Wangler et al., 2011) performed in children with ADHD, robust specific effects of NF training have been observed. Instead, overall improvements were reported, which most likely were mainly related to repeated task performance.

Beyond the realm of NF, the ANT has been applied in a different kind of training study by Tang and colleagues (Tang et al., 2007) performed in Chinese students. ANT network measures were examined after five days of 20-minute integrative meditation training compared to a group performing relaxation training. At post assessment, no change was observed in the alerting and orienting networks, but an improvement in the conflict network was revealed in both groups. In addition, a stronger improvement in the conflict network was obtained in the meditation group, which the authors considered a specific finding. However, similarly as it is an important aspect of NF studies whether the self-regulation of the trained parameters was learned, the question can be posed in how far these Chinese students succeeded in achieving the intended meditative state. However, this question cannot be answered for the study by Tang and colleagues (Tang et al., 2007). The other approach in NF studies for disentangling specific from unspecific training effects is the design of a comparable control training. This was the approach chosen in Tang et al.’s (2007) study, where they implemented a relaxation training as control training. But, as no specific information on the design of this relaxation training was provided in their paper, it cannot be judged in how far this constituted an appropriate control condition. Also, as basic performance measures (hits, RT, and variability of RT) were not presented, which would have indicated whether overall performance was comparable in both groups, it remains difficult to judge the specificity of the reported effects.

In summary, it remains to be examined in how far the concept of the attention networks and their implementation in the ANT are a useful measure for examining the effects of NF training. On the other hand, it has to be acknowledged that the child version may have been a too simple task for ‘healthy’ adults and that self-regulation abilities were not very pronounced in the present study, both of which constitute limitations.

Regarding the basic performance measures, comparisons can be made to other NF studies which have employed different tasks to assess the effects of NF training on performance in attention-demanding tasks.

In a study by Doppelmayr and Weber (2011), healthy adults either performed an SMR (12-15 Hz), a theta/beta (theta: 4.5-7.5 Hz, beta: 17-21 Hz), or a control training. Faster reaction times were observed in simple and choice reaction time tasks for the SMR group compared to the other groups. The authors considered this finding a specific effect for SMR training. A difficulty in comparing their results to the results of the present study is posed by the differently designed NF protocols. In the present study, the beta band ranged from 13 to 20 Hz and thereby overlapped with both the SMR and the beta band in the study by Doppelmayr and Weber (2011). In this respect, the larger decrease in RT in the theta/beta compared to the CON and SCP groups observed in the present study may be considered, to some degree, in line with the faster reaction times in the SMR group reported in their study.

In addition, Egner and Gruzelier (2004) reported faster reaction times in a sustained attention task after beta NF training (15-18 Hz) which was not observed in a control group. Their results may be seen in line with the faster RTs after theta/beta training in the present study. However, as Vernon (2005) pointed out, their finding of reduced reaction times after beta training may also be related to a speed-accuracy tradeoff. Vernon (2005) concluded that the finding of Egner and Gruzelier (2004) therefore cannot be clearly interpreted as improved performance. In this respect, Egner and Gruzelier’s (2004) findings are not line with those of the present study. Furthermore, Egner and Gruzelier (2004) also had observed reduced reaction time variability in a sustained attention task after SMR but not after the control training. In contrast, in the present study, no group-specific reductions of reaction time variability were observed but rather an overall improvement independent of training group. Moreover, the specificity of findings reported in Egner and Gruzelier’s (2004) study has to be considered with care due to limitations in statistical procedures and results not being similarly observed for both sustained attention tasks applied in their study.

One further study, the study by Ros and colleagues (2009) which was performed in microsurgeons, may be relevant to mention in this context. In comparison to a waiting list control group, surgical task time was observed to be reduced after SMR training, among others. For the SMR group, surgical task time was associated with the desired EEG changes observed during SMR training, which provides some evidence for the specificity of this effect. In addition, a tendency towards reduced overall performance time was reported after alpha/theta training compared to a waiting list group (Ros et al., 2009). However, the reaction time measures of the tasks described in the studies mentioned above and surgical task time are not really comparable measures, for which reason the findings of this study have to be considered with care in the context of a discussion of NF effects on reaction time measures.

To sum up, at a precise level, due to differences in the NF protocol design of all three studies, the specificity of training effects on reaction times cannot be clearly entangled. Nevertheless, it can be concluded that SMR protocols are associated with improved reaction time measures, while observations of faster RTs vs. reduced RT variability were not completely consistent. Also, for NF protocols including a beta band, associations with faster RTs were reported, except for the study by Doppelmayr and Weber (2011) in which a rather high beta band (17-21 Hz) was used.

However, these studies also pointed out that the precise selection of a frequency band to be trained may affect training outcomes. This is precisely what the discussion about specificity of NF protocols is about and which opens up a whole realm of possible further NF research.

As to working memory, performance improved from pre to post training but no advantages were observed for one of the NF groups compared to the control group. Hence, H7 was not supported.

However, effect size measures revealed a larger improvement (medium effect sizes) in the theta/beta compared to the SCP group in the overall measure as well as in the ANF compared to the SCP group in the lower load condition. As these effects were only observed for certain conditions, the advantage of the theta/beta and ANF groups over the SCP group was not very pronounced. Yet when considering this rather minor finding, it may be seen in the following way. The advantage of the theta/beta over the SCP training group might be due to the fact that the state of sustained attention which was trained in theta/beta training was more applicable to the working memory task than the momentary activation trained in the negativity trials of the SCP training. A similar explanation may also hold for the somewhat larger improvement in the ANF compared to the SCP group.

In summary, as these effects were at the low range of medium effect sizes, were only observed for certain conditions and not in comparison to the control group, they constitute a minor result.

The present findings may even be set in context to the following studies. A study in healthy adults conducted by Rainer and colleagues (Rainer, Camenisch, Esselen, & Jäncke, 2007) comprised a low beta training (12-15 Hz), an SCP training and a temperature biofeedback training group. Their results differed from those of the present study in that no overall pre-post improvement in working memory performance was observed for their task, even though one might have expected improvements due to repeated task performance. A further difference was posed by their findings based on pre-post effect size measures which revealed improvements in each of the two NF groups (SMR and SCP) but not in the temperature feedback group (but only regarding a special aspect of the task, i.e. omission errors). In contrast, in the present study, an advantage of theta/beta over SCP training was observed. However, due to the different calculation of effect size measures and the different kinds of working memory tasks used, comparability remains limited.

The effects of NF training in healthy adults on working memory were also studied by Vernon and colleagues (2003). The SMR training group learned the desired neuroregulation and in addition showed improved performance in a semantic working memory task, in contrast to a theta enhancement and a control training group. Very similarly, also in the study by Doppelmayr and Weber (2011), only the SMR group learned the desired neuroregulation and at the same time improved their spatial rotation abilities (which can be considered a working memory task) in contrast to a theta/beta and a control group. These studies indicated clearer advantages of a specific NF training protocol, in both cases SMR training, with respect to working memory performance than the present one. At the same time, their results may be seen partly in line with the slight advantage observed for the theta/beta compared to the SCP training in the present study, considering the overlap of frequency bands of the SMR and theta/beta training as discussed above. Nevertheless, comparability remains limited due to the different kinds of working memory tasks and NF protocols used.

Motor skills as measured by darts performance were observed to increase from pre to post assessment. However, the type of training had no profound effects on darts performance. Effect size measures may have suggested a slight advantage of the CON compared to the NF groups. But only one effect size measure revealed a medium effect which indicated a stronger improvement in the CON compared to the SCP group in the NoStress condition. Visual inspection suggested that this result was possibly related to performance tending to be worse in the CON group at pre assessment. In addition, according to visual inspection, the highest scores were observed at both pre and post assessment in the SCP group (even though statistically, both the ANOVA calculated for pre-assessment data and the ANOVA calculated to assess pre-post effects did not reveal significant effects for the between-subject factor GROUP).

The overall slight advantage of the CON group might be explained in the following way. For the subjects of the CON group, the game of darts was more in focus as they came to every second training session in order to practice their strategy while playing darts. Although the number of darts games was exactly the same in all groups, the subjects of the NF groups performed the darts game[37] as the last part of an about two hour-long training session. Hence, besides the game of darts being more in focus in the control group, the subjects of the NF groups may also have been more tired when practicing the game of darts as a transfer task. This aspect constitutes a disadvantage in the design of the control training.

In addition, a shortcoming of the coding of darts scores has to be considered. Darts which had missed the darts board were coded as missing values. Also, darts that hit the darts board but fell down while the subject was still in the process of throwing further darts (i.e. before the darts scores were written down) were coded as missing values. Instead, only the latter case should have been marked as a missing value while

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[37] in every second training session starting from the 5th training session.

the first case should have been coded as score zero. However, darts hitting the board and falling down before the score could be written down had not been anticipated when designing the game of darts. This procedure was the same in all groups, but nevertheless it cannot be ruled out that it may have affected the results.

In summary, when considering the darts results obtained, no advantages of NF training compared to CON training were observed and hence no support was provided for H5. The results rather suggested a slight advantage of the CON group.

Concerning performance in the WithStress conditions of the ANT and game of darts, the results will be discussed below. But in a first step, it will be assessed wether the WithStress compared to the NoStress condition exerted modulating effects on performance.

In the ANT, subjects made significantly more correct responses in the NoStress compared to the WithStress condition. This finding may indicate that the WithStress condition was the more difficult task. In addition, shorter RTs and a smaller variability of RT were observed in the WithStress condition. Altogether, the lower number of correct responses in combination with faster responses in the WithStress condition may also be seen as a speed accuracy trade-off rather than being an indicator for task difficulty. Moreover, a stronger decrease in the variability of RT was obtained for the NoStress condition. This may be seen in line with the higher variability of RT in the NoStress condition which may have left more room for improvements. While overall darts performance was not significantly modulated by the WithStress condition, a trend towards a stronger improvement in darts performance from pre to post in the WithStress condition was observed. These results provided evidence that the WithStress condition exerted some modulatory effects on performance in both tasks, while effects were more pronounced in the ANT. But it has to be acknowledged that the WithStress condition had less modulatory effects on performance than expected.

However, the hypothesis of improved performance at post assessment in the NF groups compared to the control group under stress was not supported by the ANT and darts data. Only regarding RTs in the ANT, medium effect sizes were obtained for the theta/beta compared to the CON as well as compared to the SCP group in the WithStress condition. However, the described larger reduction in RT in the theta/beta group compared to the CON and SCP groups in the WithStress condition was also observed in a comparable way for the NoStress condition.

The only other relevant effect (Cohen's $d \geq .50$) observed for the WithStress condition was a medium effect for alerting in the SCP compared to the ANF group, which was not observed in the NoStress condition.

Hence, with respect to the working memory and darts performance in the WithStress condition, neither a clear advantage in pre-post performance improvements was obtained for any NF compared to the control group nor for the ANF compared to any other group. Hence, H6 was not supported.

Overall, the results obtained for the effects of NF training on attention, working memory and motor skills can be summarized in the following way. One has to acknowledge that, despite the comprehensive discussion presented above, the advantages obtained for the NF groups were very limited. Overall, response speed and the variability of responses in an attention-demanding task, working memory performance and darts performance were observed to improve significantly from pre to post assessment independent of type of training. In addition, tendencies for group-specific pre-post changes were observed for RTs in the ANT and for concentration (trends for TIME × GROUP).

Regarding effect size measures, the following slightly more differential results pattern was obtained. The only somewhat more pronounced effect was faster responding in the theta/beta compared to the CON and SCP groups. All other effects were mainly based on a single condition and therefore the results presented in the following are to be considered with caution. ANF as well as SCP training was associated with improved attention compared to the CON and theta/beta groups but only according to one out of two self-report measures. Alertness under stress was slightly improved after SCP compared to ANF training. Overall working memory performance was improved after theta/beta compared to SCP training. For lower working memory load, improved performance was observed after ANF compared to SCP training. Motor skills rather slightly improved in the CON group compared to the NF groups.

Limiting factors besides the rather small sample size may have been lacking specific self-report measures of attention suitable for the peak performance range, using the child version of the ANT which may have been a too easy task for 'healthy' adults, shortcomings in the design of darts performance scoring, and above all the low self-regulation abilities acquired in the NF groups (self-regulation abilities could only be measured for the theta/beta and SCP groups but not for the ANF group), as will be discussed below.

However, as these measures were not the focus of the present study, the reported findings have to be considered in the context of the further results which will be discussed in the following subchapters.

5.4 Effects of neurofeedback training protocols on well-being / mood, perceived stress, and personality characteristics

Concerning well-being / mood, perceived stress, and personality characteristics as assessed by self-report measures, ANOVAs revealed the following pre-post effects independent of training group: a significant increase in action orientation (HAKEMP), a significant increase in self-access (self-access questionnaire), and a decrease in vigor (POMS). Regarding the effects of training type, the only relevant TIME × GROUP interaction revealed a tendency towards a stronger decrease of deactivation in the NF groups compared to the control group (EWL-N).

However, based on effect size measures for pre-post changes in relation to the control group, the overall pattern of the results suggested an advantage for the NF groups: if effects were observed, they were in favor of the NF groups. That is, to some degree the employed NF protocols had a stronger effect on improving well-being / mood, perceived stress as well as personality characteristics than the control training. Thus, based on these effect size measures, support for H2, H3, and H6 was obtained.

Concerning effect size comparisons between NF protocols, on a descriptive level, somewhat more effects were observed for the ANF and SCP groups compared to the control group than for the theta/beta compared to the control group. The direct comparison of NF protocols revealed several advantages of the ANF compared to the theta/beta group (medium to large effects) with respect to well-being / mood and perceived stress. Similarly, some hints for advantages in these domains were also observed in the SCP compared to the theta/beta group (small effect sizes), while the single more pronounced advantage of SCP over theta/beta training (medium effect) was obtained for self-access. The direct comparison of the ANF and SCP groups revealed some advantages for each group rather than favoring one over the other. In summary, these findings suggest a somewhat stronger effect of ANF and SCP training compared to theta/beta training on well-being / mood and perceived stress.

In the following, the effects obtained based on these effect size measures are to be discussed in more detail.

The ANF was the only group for which in comparison to the control group, an effect of medium size had been obtained in the subscale mood of the EWL-N, which was the most direct measure of mood employed. For the SCP compared to the CON group, a small effect size was revealed while there was no effect for the theta/beta compared to the CON group. Similarly, a large effect size was obtained for the ANF compared to the theta/beta group, an almost medium effect size for the SCP compared to the theta/beta group and a small effect size for the ANF compared to the SCP group. These effect size measures related to the subscale mood provided small hints for the strongest improvements in mood in the ANF group, followed by the SCP group compared to the theta/beta and CON groups. This pattern of results was in line with the hypothesis (H2) of largest effects on mood in the ANF group and second-largest effects in the SCP group.

A pattern of results very similar to the pattern for mood emerged for perceived stress. Medium, small, and no effects were observed for the comparison of ANF vs. CON, SCP vs. CON, and theta/beta vs. CON, respectively. Direct comparisons between the NF groups revealed a medium effect for ANF vs. theta/beta and small effects for SCP vs. theta/beta and ANF vs. SCP. These effect size measures suggest the strongest reduction in perceived stress in the ANF group, followed by the SCP group compared to the theta/beta and CON groups providing some support for H6.

Concerning action orientation, the effects of NF training have not been as strong as expected. The medium effect observed in the theta/beta compared to the CON group for improved prospective action orientation may be seen in combination with a large effect related to decreased deactivation in the theta/beta vs. CON group after training. Taken together, they may indicate that after theta/beta training, subjects were better able to activate themselves and start sorting things out. Getting those things done that are relevant for the moment were difficulties reported by several participants during the screening interview. However, the effect sizes for direct comparisons of neurofeedback groups had neither revealed effects for prospective action orientation nor for deactivation. Rather, deactivation was reduced after all NF trainings compared to CON training (medium to large effects), and small effects suggested a slightly improved action orientation also after SCP and ANF compared to CON training. Thus, it remains questionable whether this finding represents an effect specific for theta/beta training.

The medium to large effects for reduced deactivation observed in the NF groups compared to the CON group may indicate that participants were better able to activate themselves. This ability may well be a non-specific effect related to self-regulation training, as it was comparable in all NF groups. The difference to the control group may be related to the more extensive self-regulation training during NF training, which may have been more effective than the application of cognitive strategies practiced during a smaller amount of time in the CON group. However, these findings are in contrast to the overall reduced vigor observed at post assessment. On the other hand, in a way the observation of reduced vigor at post assessment independent of training group is not surprising. All participants made a large effort, despite their busy schedules, to participate in this very comprehensive and time-consuming study. Thus, at post assessment they may well have been happy to have some more time available instead of feeling vigorous to start the next thing.

Taken together, based on effect size measures, these data suggest that NF to some extent can positively affect well-being / mood as well as perceived stress and personality characteristics. Positive effects on well-being / mood and perceived stress were somewhat more pronounced in the ANF and SCP groups. In addition, in line with the hypotheses, the most pronounced results regarding mood and perceived stress were obtained for the ANF group. However, the results on these domains were much less pronounced than expected, especially for the ANF group. Limitations of the results presented were also constituted by slightly more pronounced psychological distress (SCL-90) in the CON group (however, group differences were no longer significant after Holm-Bonferroni correction) as well as significantly higher dejection in the CON compared to the ANF group. These group differences between the CON and NF groups may have been associated with the less pronounced effects on well-being / mood in the CON compared to the other groups. Also, the CON training chosen which was not designed to completely parallel the NF trainings may have played a role here.

Thus, the most interesting effects are constituted by the small hints for differential effects between the NF groups. ANF and SCP training were associated with somewhat more pronounced effects on well-being / mood compared to the theta/beta group. The clearest effects on mood and perceived stress were observed in the ANF group (even though effects were still rather small), while SCP training was associated with a somewhat more pronounced increase in self-access. In addition, for the SCP and theta/beta group, results will be discussed in the context of self-regulation abilities (see discussion below).

So far, the positive effects of NF on mood were only reported in a study on alpha/theta NF training in adults with high withdrawal scores (Raymond, Varney, et al. 2005). In comparison to a mock feedback group, improvements in mood were associated with alpha/theta neurofeedback training, while no changes on personality were observed. According to the authors, participants of the mock feedback group did not know that they received mock feedback. In addition, subjects of the alpha/theta group showed improved regulation skills within sessions, albeit not across sessions. Taken together, the authors attributed the improved mood findings to the genuine feedback received in the alpha/theta group. It would have been interesting if results on associations between alpha/theta regulation and mood measures had been presented. For the data of the present study, such association measures will be discussed in a following chapter (see 5.5.4 Neuronal mechanisms: Self-regulation in the theta/beta and SCP group).

In contrast, in a study by Boynton (2001), no advantage on well-being was observed after NF compared to a control training. In another study (Allen et al., 2001), increasing right relative to left frontal alpha activity had effects on self-reported affect, in contrast to training frontal alpha asymmetry in the opposite direction. However, this effect was mainly related to a decrease in positive affect in the latter training group instead of to an increase in the former training group. In addition, this effect was only observed for happy but not for sad films, and unprovoked mood, which was assessed after each training session, was not associated with the direction of training. Thus, this study does not provide convincing evidence of positive effects on mood related to frontal alpha asymmetry training, in either direction.

Overall, little research has been conducted regarding the effects of NF trainings on well-being / mood in healthy adults. All of the described studies have used a training protocol including frequencies in the alpha range. Also in the ANF group in the current study, one of the training protocols was based on the alpha band. However, the protocol of training parietal alpha synchrony was different from the ones employed in the studies described above. Prominent alpha activity can be seen in the context of a state of relaxed wakefulness (see 1.1.1 Electroencephalogram (EEG) and mental states / behavior). Both the alpha/theta training and the alpha synchrony training performed in the ANF group target the training of a relaxed state with closed eyes. As regulation abilities could not be analyzed for the ANF group (see 3.2.3.3 Self-regulation abilities in theta/beta and SCP training), it remains unresolved to what degree the self-regulation of alpha synchrony may have mediated the more pronounced effects on mood and perceived stress observed in the ANF group. The increase in alpha activity observed after ANF training (see 5.5.2 Neuronal mechanisms: Resting EEG) may suggest that alpha synchrony training may have mediated the positive effects on mood and perceived stress in the ANF group. However, particularly the training at temporal sites was expected to be related to positive effects on mood. As different training protocols were included in the training of the ANF group, the specific effects related to the different protocols could not be disentangled.

Currently, the effects of self-regulation on mood in healthy adults are also being examined in real-time fMRI-based NF studies – where self-regulation is based on BOLD responses in specific emotion-related target areas. So far, these studies have particularly focused on the effects of self-regulation associated with the processing of negative affect (Caria, Sitaram, Veit, Begliomini, & Birbaumer, 2010; Johnston, Boehm, Healy, Goebel, & Linden, 2010). Such studies showing positive associations of BOLD response and negative affect are interesting because they illustrate the feasibility of rt-fMRI applications of emotion regulation. Additionally, they may find application in persons experiencing an inability to have emotional involvement, e.g. psychopaths (Caria et al., 2011).

However, for applications in healthy adults and peak performance fields, the more interesting domain would be learning to reduce negative affect or increase positive affect / mood. An rt-fMRI study with a focus on positive mood was performed by Johnston and colleagues (Johnston, Linden, et al., 2010). Participants (*n* = 17) trained to up-regulate the BOLD signal in individually determined target areas for positive emotions (prefrontal cortex, insula, medial temporal lobe). A control group (*n* = 10) received no feedback. The participants receiving feedback attained reliable self-control of these emotion-areas but they were not accompanied by clear changes in self-reported emotions. The authors discussed that using healthy participants and performing only a single session in the not-so-pleasant scanning environment may have prevented the detection of rather subtle mood changes.

In summary, so far, research on the effects of NF training on well-being / mood, perceived stress, and / or personality characteristics in 'healthy' adults is a field comprising only several studies circumscribed above. Previous studies have used NF protocols including the alpha band and also in the NF training of the ANF group, a form of alpha NF has been applied. To my knowledge, the present study was the first to study the effects of theta/beta and SCP neurofeedback training on well-being / mood in 'healthy' adults. No profound effects of NF training on the described domains have been observed in the present study. Nevertheless, based on effect size measures, some advantages could be observed for the NF groups which were somewhat more pronounced in the ANF and SCP groups regarding well-being / mood and perceived stress. Further research is needed to examine in how far different NF protocols are able to positively affect well-being / mood, perceived stress, and / or personality characteristics in healthy adults. Also, the emerging field of rt-fMRI for emotion regulation is a promising approach.

5.5 Neuronal mechanisms underlying neurofeedback

5.5.1 Neuronal mechanisms: Event-related potentials

One of the main results regarding the neuronal mechanisms underlying the different NF protocols studied was based on CNV measures during the ANT. Although merely a statistical trend was observed for group-specific pre-post changes in CNV amplitudes, this effect lay in the range of a medium effect size ($\eta_p^2 = .12$) and can therefore be considered relevant. Post-hoc tests revealed stronger increases in CNV amplitudes from pre to post in the three NF groups compared to the CON group, for which amplitudes rather decreased. When correcting for multiple comparisons, solely the difference between the theta/beta and CON group remained significant. However, as effect sizes for all three pair-wise comparisons lay in the range of large effects ($\eta_p^2 > .14$), they can be considered relevant findings. Regarding pre-post changes in CNV amplitudes, all three NF groups were very comparable. This was indicated on the one hand by the large effects obtained for the comparison of each NF to the control group as described above. On the other hand, this was indicated by post-hoc tests having revealed no significant results for the direct comparison of NF groups. The result of larger pre-post increases in CNV amplitudes in the NF groups compared to the control group was in line with H10.

However, no larger increase in CNV amplitude was observed in the SCP group compared to the other groups, and in this respect H10 was not supported. According to the close relation between the CNV and SCPs, from a theoretical perspective one would expect SCP training to have the strongest effect on CNV amplitudes compared to other NF protocols. So far, to my knowledge, there exists only one study in which the effects of both SCP and theta/beta training on CNV amplitudes have been examined (Wangler et al., 2011). In this study, which was performed in children with ADHD, a pre-post increase in CNV amplitude was observed to be specific for SCP training.

Based on this finding, the same specificity of SCP training was expected in ‘healthy’ adults. However, it has to be considered that in children with ADHD, reduced CNV amplitudes have been observed (Banaschewski et al., 2003; Sartory, Heine, Müller, & Elvermann-Hallner, 2002). This may leave more room for improvement, and SCP training may act in a way to ‘normalize’ CNV amplitudes. In this respect, findings in children with ADHD may not be directly transferable to SCP training in ‘healthy’ adults. One further aspect that may be relevant in this context is that the visual inspection of the CNV data of the present study suggested the largest CNV amplitudes at pre assessment in the SCP group (even though no statistically significant group differences at pre assessment were observed). In this respect, the pre-post increase of CNV amplitudes in the SCP group may be considered rather good: despite slightly higher pre-training CNV amplitudes, for participants of the SCP group a comparable increase in CNV amplitudes was observed as for the other two NF groups.

Moreover, a small hint for a possibly specific effect of SCP training on increasing CNV amplitudes in the present study comes from the analysis of self-regulation abilities. For participants who belonged to the group of good performers regarding self-regulation during negativity trials, the pre-post increase of CNV amplitudes in SpatialCue trials was observed to be larger than for bad performers. This may be considered a small hint for a specific effect related to SCP training. However, as such an association was not observed for the other cue conditions and also not for the self-regulation analysis based on differentiation abilities, it is a very small hint.

Furthermore, it needs to be considered that so far, only few studies have examined the effects of SCP training on CNV amplitudes, and even less have also used a well-controlled design. For instance, one study in children with ADHD (Heinrich et al., 2004) reported increased CNV amplitudes after SCP training in contrast to a waiting list group. This finding is comparable to the results of the present study of a larger increase in CNV amplitudes in the NF groups in comparison to the CON group. Yet due to the limitations posed by a waiting list control group, inferences regarding the specificity of the effect remain limited. In another study in which SCP training was compared to a group therapy in children with ADHD (Döhnert et al., 2008), CNV amplitudes were observed to decrease from pre to post training in both groups. However, this decrease was less pronounced in those children that successfully had learned SCP self-regulation. This may be seen as a small hint related to a specific effect for SCP training.

To sum up, to date the study by Wangler and colleagues (2011), which was performed in children with ADHD, has obtained the clearest results with respect to the specific effects of SCP training on CNV amplitudes. In the near future, the results of currently ongoing studies with well-controlled designs may provide further insights with respect to the specificity of effects (see 1.3.1 Clinical studies of neurofeedback).

With respect to theta/beta training, the pre-post increase in CNV amplitude in the theta/beta in comparison to the CON group contrasts with the findings reported by Wangler et al. (2011). In their study, they had not observed an increase in CNV amplitudes after theta/beta training, but only after SCP training. As discussed above, it remains a question in how far results observed in children with ADHD and ‘healthy’ adults are comparable. In addition, the question remains unresolved in how far this increase in CNV amplitude after theta/beta training is a specific or unspecific effect of theta/beta training. However, it may well be possible that this finding is an unspecific effect related to the design of theta/beta training which, in contrast to SCP training, consisted of a few long trials. As this has already been discussed in the context of the larger pre-post increase in response speed observed after theta/beta training, the reader is referred to that chapter for a further discussion (see 5.3 Effects of neurofeedback training protocols on attention, working memory, and motor skills). A similar explanation may hold for the effect in the ANF group.

Concerning attention network measures at the level of CNV amplitudes, neither was an overall pre-post improvement observed nor a pre-post improvement related to a specific type of training. This finding is in line with Wangler et al. (2011) where in the authors' opinion, also no training-related effects on the attention networks at the level of CNV amplitudes were observed.

Overall, these findings of a pre-post increase in CNV amplitudes in all three NF groups in comparison to the control group may indicate that these NF protocols enhance the allocation of attentional resources during the preparatory phases of an attention-engaging task. Based on the analysis of self-regulation abilities, small hints were observed which may possibly indicate a specific effect for SCP training on CNV amplitudes. Yet in order to delineate the specificity of the effects of these different NF protocols on allocating attentional resources during preparation, which is thought to be displayed in CNV amplitudes, further research is needed.

Regarding cue- as well as target-P3 amplitudes measured during the ANT, the following results were obtained. No significant effects of training or of type of training on both cue- and target-P3 amplitudes were observed. Also at the level of effect size measures, no relevant effects (Cohen's $d < .50$) were obtained for comparisons of pre-post changes between groups. Furthermore, analyses based on the attention networks at the level of cue- and target-P3 amplitudes did not reveal significant effects of training or type of training, either.

These results may be seen as contrasting Egner and Gruzelier (2001), who had observed increased P3 amplitudes after a combined SMR (12-15 Hz) and beta (15-18 Hz) training, and to Egner and Gruzelier (2004), who had observed increased P3 amplitudes after beta (15-18 Hz) training in healthy adults. However, in their second study, Egner & Gruzelier (2004) did not observe increased P3 amplitudes after SMR (12-15 Hz) training and in this respect, their findings may be seen in line with those of the present study. Yet due to the differences in training protocols, their results remain difficult to compare with the present study, where the beta band ranged from 13 to 20 Hz.

Nevertheless, findings of increased P3 amplitudes after beta training do not seem very robust. In the study by Egner and Gruezlier (2004), pre-post changes were analyzed based on t-tests and no ANOVAs including group as a factor were calculated, which has to be considered a limitation of their analysis. In addition, in the study by Wangler et al. (2011) which was performed in children with ADHD, a decrease in target-P3 was observed both in the NF (combined theta/beta and SCP training) and the control group. At the same time, performance in the ANT was observed to increase, which was interpreted as reflecting adaptation to the task.

For the theta/beta group, target-P3 amplitudes were also viewed in the light of self-regulation abilities acquired during training (based on the theta/beta ratio). This analysis to some extent revealed an association of good performance with reduced target-P3 amplitudes, while no such association was observed for cue-P3 amplitudes. This result was contrary to the expectation of finding increased target-P3 amplitudes after theta/beta training. However, as discussed above, the expectation of finding increased P3 amplitudes after theta/beta training is not well supported by the literature.

In addition, it also remains to be questioned in how far larger P3 amplitudes can be seen as indicators of improved processing abilities. For example, in the study by Wangler et al. (2011), the described pre-post decrease in target-P3 amplitude was larger for more intelligent children. In a similar way, in the discussion of their paper Howells and colleagues (Howells et al., 2010) report on a study which has observed repeated task performance to be associated with decreased P3 amplitudes. These findings suggest that in the context of repeated task performance, decreased target-P3 amplitudes may rather be desirable.

Taken together, the observed association of good performance in theta/beta training in the theta/beta group with reduced target-P3 amplitudes may be a very slight hint for a specific effect of theta/beta training. However, limitations for the interpretation of this result are the following: this association was not obtained for all cue conditions; such an association was not observed for cue-P3 amplitudes; and it remains unclear whether an increase or a decrease of target-P3 amplitudes would be desirable. Also with respect to self-regulation abilities, target-P3 findings are in contrast to Egner and Gruzelier (2001) who observed regulation abilities of SMR as well as beta training to correlate positively with increased P3 amplitudes.

To sum up, none of the NF training protocols exerted a profound effect on cue- or target-P3 amplitudes during the ANT. Also the attention networks effects at the level of cue- and target-P3 amplitudes were not altered due to training. Only the analysis of self-regulation abilities in the theta/beta group revealed a very small hint for an association of theta/beta training with target-P3 amplitude. Overall, when also considering literature, no convincing evidence exists to date for the effect of different NF protocols on P3 amplitudes during the performance of an attention-demanding task.

5.5.2 Neuronal mechanisms: Resting EEG

Eyes-open resting EEG measures revealed a significant pre-post increase in theta and alpha activity as well as a trend for beta activity independent of training group. This may be seen as a sign for the participants being more relaxed and possibly slightly more focused at post assessment. Resting EEG is the first measure subjects performed after electrodes were hooked up. At pre assessment, when everything was still new, they may have been tenser. At post assessment, they knew what to expect and therefore may have been able to be more relaxed.

Differential pre-post effects related to the type of training were obtained for the alpha-band as indicated by a significant TIME × ELECTRODE × GROUP interaction. Post-hoc tests calculated separately for each electrode revealed a significant result for Pz, which seemed to be related to a larger pre-post increase in alpha activity in the ANF group relative to the other groups. However, when correcting for multiple testing, this effect did not remain significant. Yet when considering effect size measures based on group comparisons of pre-post changes in alpha activity, the following pattern of results was obtained. Medium effect sizes indicated larger pre-post increases in alpha activity (Pz) in the ANF vs. CON group as well as in the CON vs. SCP group. This larger increase in alpha activity in the ANF group was also displayed in effect size measures related to the direct comparison between NF groups: large and medium effects sizes were obtained for the ANF compared to the SCP and theta/beta groups, respectively. This finding may constitute a differential effect for ANF training which is displayed at the level of effect size measures. The ANF training included an alpha synchrony training protocol which was performed at parietal electrode sites. The learned self-regulation of alpha activity may have allowed the subjects of the ANF group to achieve a relaxed state during resting EEG measurement where no attention was required. Unfortunately, self-regulation abilities could not be analyzed for the ANF group (see 3.2.3.3 Self-regulation abilities in theta/beta and SCP training). This would have made it possible to further clarify the specificity of this effect.

Concerning the theta (Cz) and beta (Cz) band, no relevant effects were observed for the NF groups compared to the CON group (Cohen's *d* < .50). For the theta band, the direct comparison between theta/beta and SCP groups revealed a medium effect size. This effect was related to a pre-post increase in theta activity in the SCP group, which was not observed in the theta/beta group. Thus, when considering these results with respect to the question whether theta/beta training in 'healthy' adults leads to differential effects in resting EEG measures, the following can be concluded. Theta/beta training did not lead to differential resting EEG changes in the trained frequency bands (theta and beta) at the trained electrode site (Cz). Effect size measures had only been analyzed for this trained electrode site. ANOVAs based on theta and beta activity measures (at Fz, Cz, and Pz) had also not revealed significant interaction effects (including the factors TIME and GROUP). Taken together, it can be concluded that in 'healthy' adults, theta/beta training did not exert profound differential effects on resting EEG activity in the theta and beta band, neither at frontal, nor central, nor parietal areas.

When looking at these results, the following quotation is of relevance: "Whether NF training affects spectral EEG measures in healthy subjects, who by definition display a spectral EEG composition within a 'normal' range in the first place, is currently not known." (Egner, Zech, et al., 2004, p. 2453). So far, there are only a few studies that have examined the effects of NF protocols comparable to theta/beta training on resting EEG measures. For example, Egner and colleagues (Egner, Zech, et al., 2004) examined the effects of a low beta training (12-15 Hz, at Cz, with theta inhibit band) in healthy adults on resting EEG measures. They observed some changes in resting EEG measures, but not in an expected way. The changes observed were not necessarily related to the frequency band trained, they were not consistent across their two experiments, and they were not observed at the site of training (Cz). For instance, effects observed in the low beta band indicated a decreased low beta activity even though the subjects trained to increase low beta. Moreover, these effects were observed at scalp locations other than the site of NF training. This topic was also addressed by Vernon (2005) and provides a good summary:

> An implicit assumption that permeates the neurofeedback literature and underpins current practice is that the training process will lead to changes in the EEG, which in turn produces changes in behaviour. However, it should be noted that the link between these components is not well established in either performance enhancement […] or the clinical literature […], especially with respect to predictable changes and correlations between changes and outcome variables. (p. 348, 352)

In summary, the present study does not provide any support regarding theta/beta training being associated with specific resting EEG changes. It also remains a question in how far it can be expected that a training in 'healthy' adults, which aims at enhancing attentional abilities, may lead to EEG changes in a resting state, which does not require attention. In addition, the resting EEG assessment very closely resembled the baseline measurement which was performed at the beginning of each theta/beta training session, during which subjects were asked to sit quietly without begin especially focused. This is different from the changes in alpha activity observed in the resting EEG after ANF training. The ANF training included a relaxation training. For the subjects, EEG assessment during a resting state may have been associated with a relaxed situation. Thus, resting state EEG assessment in this case may have reflected a situation which was related to a state trained during ANF training, namely relaxation.

In a next step, effects (based on effect size measures) related to theta activity are to be discussed in the context of SCP training. For the direct comparison between NF groups, effect size measures for the theta band (Cz) revealed medium effects for the SCP compared to the theta/beta and ANF group. These were related to a pre-post increase in theta activity (Cz) in the SCP compared to the other two groups. A similar tendency, i.e. a larger increase in theta activity (Cz) in the SCP group, was revealed compared to the control group (small effect size). The difference in the change of theta activity in comparison to the other NF groups described above may suggest a specific effect related to SCP training. However, as with respect to the CON group only a small effect size was obtained, it remains questionable in how far this finding is really specific for SCP training.

In addition, as outlined above, it is not clear in how far NF training in 'healthy' adults can be expected to modulate resting EEG measures. This holds especially when the mental state trained and the mental state required during resting EEG assessment do not match. In negativity trials of SCP training, subjects trained to achieve an activated state which is also associated with being prepared. This state does not match with the state during resting EEG assessment, where participants are merely required to sit still, which is not an attention-demanding situation. In contrast, during positivity trials, the subjects trained to achieve a relaxed state, which in comparison to the active state during negativity trials rather represents a deactivated state. This state may be somewhat related to a relaxed state in which participants may find themselves during resting EEG assessment. As relaxation is known to be associated with alpha activity (see 1.1.1 Electroencephalogram (EEG) and mental states / behavior), one may have expected to find increased alpha activity after SCP training, if any change in resting EEG measures could be expected at all.

Associations of pre-post increases in alpha activity with a reduced symptomatology have been reported after SCP training in children with ADHD. Gevensleben and colleagues (Gevensleben, Holl, Albrecht, Schlamp, et al., 2009) have described a pre-post increase in central alpha activity to be associated with behavioral changes (reduced ADHD symptomatology according to parent ratings) after SCP training. This association was mainly related to reduced symptoms of hyperactivity / impulsivity, rather than to reduced symptoms of inattention. Similarly, Döhnert et al. (2008) observed a tendency towards a correlation of increases in upper alpha activity (at Pz) and reduced impulsivity (parent ratings) after SCP training. However, the comparability of these findings in children with those in ‘healthy’ adults remains difficult for the following reasons. Increased alpha activity in these studies was mainly related to improved symptoms of hyperactivity / impulsivity instead of to attention, which is a relevant finding for SCP training in children with ADHD. Yet in ‘healthy’ adults, the focus of SCP training is clearly to improve attention, while in this context hyperactivity / impulsivity do not play an important role. In addition, in children with ADHD, the resting EEG assessment may have displayed a relevant situation, i.e. a situation which may be able to display effects of NF training. Resting EEG assessment required being quiet and sitting still, which is something children with ADHD, at least those with more pronounced symptoms of hyperactivity / impulsivity, experience difficulties with. A NF training in children with ADHD aims at improving both attention and hyperactivity / impulsivity. In this respect, it makes sense that changes in alpha activity were observed to be associated with improved hyperactivity / impulsivity.

Due to the aspects discussed, the comparability of these results in children with ADHD and ‘healthy’ adults remains very limited.

Overall, it remains questionable in how far resting EEG represents a relevant measure for examining the effects of NF trainings in healthy adults, at least if training focuses on increasing attentional abilities. In the present study, changes in resting EEG measures rather seemed to be related to participants in all groups being more relaxed during post assessment. The only more differential finding was observed in the alpha band: ANF training was related to increased alpha activity (Pz).

5.5.3 Neuronal mechanisms: TMS

A tendency for smaller SICI at post assessment was observed independent of training group, which was most likely an effect of repeated assessment. In addition, a differential effect of the type of training on pre-post change of SICI was observed. Post-hoc tests revealed that this effect was related to larger increases in SICI from pre to post in the theta/beta group compared to the CON and ANF groups. Even though this finding was no longer significant when correcting for multiple comparisons, due to the large effects obtained at the level of effect size measures, it may well be considered relevant. Also in comparison to the SCP group, effect size measures revealed a larger pre-post increase in SICI (medium effect) in the theta/beta group. Taken together, these results indicate that intracortical inhibition was increased after theta/beta training relative to all other training groups, where rather a pre-post decrease in SICI was observed. This pattern of results may suggest a specific effect of theta/beta training on increasing SICI.

However, it has to be considered that at pre assessment, a tendency for group differences of SICI was observed. These were related to larger SICI in the CON group compared to the NF groups at pre assessment. Although these differences were no longer significant after correction for multiple comparisons, they have to be taken into account when interpreting the results based on effect size measures. Thus, the difference in the pre-post change of SICI between the theta/beta and CON group remains difficult to interpret – also because SICI at post assessment in the theta/beta and CON group was factually the same.

Therefore, the more interesting finding is the difference in pre-post change of SICI between the theta/beta and ANF group. According to hypothesis 11, ANF training was not expected to affect motor system excitability. In this respect, for the analysis of SICI measures, the ANF group can be considered a control group. Similarly to the comparison of the theta/beta and CON group, also for the comparison of the theta/beta and ANF group, a large effect size was obtained, which was related to a pre-post increase of SICI in the theta/beta group in combination with a decrease in the ANF group. As there were no pre-training group differences in SICI between the theta/beta and ANF groups, this finding is better suited to suggest a potentially specific finding of an effect of theta/beta training on SICI. The similar pattern obtained for the theta/beta compared to the SCP group, albeit only in the dimension of a medium effect size, may provide further support for this possible interpretation.

Concerning ICF, even though no statistically significant results were obtained, based on effect size measures, medium effects were obtained which nevertheless may constitute relevant findings. Medium effects were observed for the CON compared to the SCP and ANF groups, which were related to a pre-post increase in ICF in the CON group compared to the other two groups. Visual inspection indicated the smallest ICF values in the CON group at pre assessment (even though no significant group differences in ICF were revealed at pre assessment). In addition, also based on visual inspection, factually similar ICF values were observed for the CON, SCP and ANF groups at post assessment. Thus, also regarding ICF, the findings obtained for the CON group remain difficult to interpret.

Regarding the effects related to the theta/beta group, a medium effect size was observed for the theta/beta compared to the SCP group and an almost medium (but nevertheless small) effect size for the theta/beta compared to the ANF group. These effects were related to a pre-post increase in ICF in the theta/beta compared to both other groups. This may possibly indicate a specific effect for theta/beta training.

As the SCP training protocol directly targets the regulation of cortical excitability, one may rather have expected to find a differential effect of SCP training on SICI and/or ICF. However, such an effect was not observed in the present data.

In summary, these data suggest that theta/beta training was associated with an increase in SICI as well as with an increase in ICF compared to the other two NF protocols. Such an effect, i.e. a “treatment” leading to an increase in SICI in combination with an increase in ICF, is a rare finding in the TMS literature. In a study by Kirschner and colleagues (2003), which was performed in healthy adults, methylphenidate was observed to increase both SICI and ICF. This is exactly the same pattern as that observed after theta/beta training.

This is an interesting finding for the following reasons. The motivation to use TMS assessments in order to examine the effects of NF training on motor system excitability was derived from the application of NF training in children with ADHD, for whom reduced SICI is commonly reported in the literature (e.g. Moll et al., 2002). Furthermore, methylphenidate is the psychostimulant drug which is most commonly applied as a treatment in children with ADHD. When administered in healthy adults, it exerted the above-described effects on motor system excitability, although according to the authors this was an unexpected finding which until then had not been observed in the literature. Thus, in ‘healthy’ adults theta/beta training was observed to have similar effects on motor cortex excitability as methylphenidate. However, the functional significance of the changes observed after theta/beta training remains unknown.

In contrast, in children with ADHD, methylphenidate has been reported to increase SICI while having no effects on ICF (Moll et al., 2002). Thus, it remains difficult to draw conclusions from the present study about the effects of theta/beta training on cortical excitability in children with ADHD.

So far, there is only one study in which the effects of NF training on motor system excitability have been examined (Ros et al., 2010). The authors reported an increase in corticospinal excitability (based on single pulse TMS) after training, but without differential effects for the two different NF protocols applied in healthy adults. No pre-post changes in SICI or ICF were observed. Only analyses based on t-tests revealed increased corticospinal excitability and decreased SICI in the alpha training group but not in the low beta training group.

The low beta training group of Ros et al.’s study (2010) may to some degree be considered comparable to theta/beta training. In contrast to the present study, no effects of low beta training on SICI or ICF were observed. However, it is difficult to compare the results of the two studies, as their design differed from that of the present study in various ways: TMS was performed before and after a single session of NF; NF protocols were alpha training or low beta (12-15 Hz) training; NF training was performed at C3, i.e. about at the position where TMS was applied; and they used no control group. Thus, their missing results related to effects of low beta training on TMS measures may also be related to the fact that they performed TMS after a single session of NF training. In order to observe the effects of NF training on behavior, a whole training schedule of NF sessions is needed, comprising an absolute minimum of about 10 sessions, better 20 to 30 sessions, or even more. Still, Ros and collaborators (2010) were able to observe some effects related to alpha training. Overall, it seems more interesting to examine motor system excitability after an extensive training schedule like in the present study.

Nevertheless, their design has a clear advantage over the present study in that they assessed TMS measures directly before and after a NF session. Yet similarly to resting EEG assessments, in healthy adults the functional significance of altered motor system excitability during a resting state remains debatable.

To conclude, to my knowledge this was the first study in which TMS measures were applied to assess the effects of theta/beta, SCP and ANF training in ‘healthy’ adults. The results possibly suggest a specific effect of theta/beta training on increasing both SICI and ICF. However, further studies including a larger sample and in which neuroregulation is better learned are needed, in order to examine whether this finding can really be considered specific for theta/beta training. In addition, in order to address the functional significance of NF-induced changes in motor system excitability, TMS measures should be assessed directly after a NF training session or even also during neuroregulation.

5.5.4 Neuronal mechanisms: Self-regulation in the theta/beta and SCP group

The analysis of self-regulation abilities is a method that further addresses the question of the specificity of NF effects. This is done by associating self-regulation abilities in the trained frequency band(s) with improvements at the behavioral, performance and / or neurophysiological level.

In the present study, for both theta/beta and SCP training, some associations between regulation abilities and behavior / neurophysiology were observed. However, these findings are far from being compelling. The main constraint of the present study is that for both theta/beta and SCP training, self-regulation was not sufficiently learned. These insufficient self-regulation abilities together with the small sample size may well be the main explanation why only few significant effects in favor of NF trainings were obtained in the present study. Nevertheless, a pattern slightly in favor of the particular NF protocols became visible. In this respect, it remains interesting to look at the associations of the self-regulation abilities and behavioral / neurophysiological findings of the present study. In the following, the results related to the self-regulation analysis, which was based on the comparison of good with bad performers, will be discussed. However, for the interpretation of the results, it needs to be considered that using a median split to divide each training group into good and bad performers resulted in very small group sizes.

Concerning theta/beta training as performed in the theta/beta group, the following pattern of results was obtained on the behavioral level. Good performance (based on the theta/beta ratio) was associated with reduced fatigue, less reduced vigor, and improved abilities to manage frustration and modulate emotions. At a statistical level, these findings were not very robust, as the results did not remain significant when *p* was adjusted for multiple testing. Yet at the level of effect size measures (Cohen's *d*), large effects were obtained for all three measures, which may be considered a relevant finding.

Reduced fatigue after theta/beta training is a finding that may be seen as fitting well with the theta/beta protocol. During training, several participants were observed to get tired in the course of training and especially during long self-regulation blocks, which lasted for ten minutes. Thus, during training these participants directly practiced the application of their self-regulation abilities to maintain a state of sustained attention even when they started to get tired, or to apply their self-regulation strategies to reacquire a state of sustained attention. Thus, the large effect sizes observed for reduced fatigue in good performers may possibly indicate that these participants were able to transfer their self-regulation abilities practiced during training to daily life situations.

This finding of reduced fatigue after theta/beta training may be related to the finding of a less pronounced reduction of vigor than in bad performers. At first glance, this result seems negligible, as no improvement in vigor was observed but only a less pronounced reduction. However, as discussed in a previous section, the pre-post decrease in vigor observed independent of group may have been related to the large effort subjects had made for participating in this time-consuming study. In this respect, the less pronounced reduction of vigor may be seen as a positive sign. Possibly, it is related to subjects feeling less tired which may increase their vigor or rather which may have prevented a stronger decrease in vigor.

The finding of their improved ability to manage frustration and regulate emotions was rather unexpected.

In addition, as already discussed in a previous chapter (see 5.5.1 Neuronal mechanisms: Event-related potentials), an association of good performance in theta/beta training with reduced target-P3 amplitudes during the ANT was also observed, even though this association was only significant for some of the ANT conditions.

Regarding SCP training, good performance (based on the differentiation measure) was associated with overall improved attentional skills, with improved regulation of alertness / sustaining effort and processing speed, as well as with decreased fatigue and decreased displeasure. All of these results were associated with large effect sizes (Cohen’s *d*), but when adjusting *p*-values for multiple comparisons, only the results for the improved regulation of alertness and reduced fatigue remained significant.

Reduced fatigue was a common finding for both SCP and theta/beta training. This finding may be explained in a similar way as the one for good performers in theta/beta training. The result that good performance in SCP training was associated with improved attentional abilities is conform to the expectations.

Moreover, as already discussed in a previous chapter (see 5.5.1 Neuronal mechanisms: Event-related potentials), an association of good performance (based on self-regulation of negativity trials during SCP training) with increased CNV amplitudes during the ANT has also been observed. However, this association was only obtained related to self-regulation abilities during negativity trials, but not with respect to the differentiation measure of self-regulation.

As interesting as the analysis of self-regulation abilities related to a particular NF protocol is, however, the more difficult it is to parameterize. So far, there is no standard how to measure self-regulation. In the following, several critical points with respect to the self-regulation analysis as used in the present study will be discussed.

A crux of the performed self-regulation analysis, which holds for both theta/beta and SCP training, is the following. Within the first two sessions, the duration of most self-regulation blocks was shorter than for the following sessions. The idea behind this design was to give the participants a chance to accommodate to the training protocols before increasing difficulty by increasing the duration of a self-regulation block. In the present self-regulation analysis, self-regulation during the first two sessions was compared to self-regulation during the last two sessions. Thus, self-regulation during shorter self-regulation blocks at the beginning of the training was compared to self-regulation during longer self-regulation blocks at the end of the training, and it was expected to observe improved self-regulation at the end of training. This is definitely not a good procedure. Therefore, it should be considered in all future studies that across training sessions, self-regulation blocks should be similarly designed in order to ensure pre-post comparability.

With respect to theta/beta training, self-regulation was analyzed relative to a baseline assessed at the beginning of a session, when subjects were comparably fresh and came from an active state of coming to the training. The session consisted of about 50 minutes of self-regulation and in total lasted for about two hours and was therefore rather exhausting. Thus, it remains questionable whether it is an acceptable procedure to measure self-regulation with respect to baseline assessment performed at the beginning of the training. In this respect, the theta/beta protocol used in another working group has the advantage that the baseline used for training is continuously updated (Leins et al., 2007). However, the theta/beta protocol of that group consisted of many short trials (10 seconds), while in the present study self-regulation was performed in long blocks (5 to 10 minutes). For this reason, the method of a continuously updated baseline was not applicable to the design of the theta/beta training in the present study. Another solution to this problem may be to acquire another baseline in the middle or at the end of a training session.

A further aspect related to self-regulation analyses performed relative to a baseline is that during baseline assessment the participant may not necessarily be in the desired state. For example, a participant may well have been concentrated during baseline assessment for theta/beta training, despite the instruction to be relaxed. During training, some subjects have reported that when they arrived for training, they had a lot on their mind which they could not easily stop thinking of. This cannot be reliably controlled for and thus baselines are not as objective measures as they may seem.

Regarding SCP training, the analysis was based on the mean amplitudes of negativity and positivity trials per self-regulation block, which did not include segments with artifacts recognized by the feedback software. However, if artifacts went unrecognized by the software, these data were included in the average. For future studies, it would be desirable to perform an offline artifact correction on a trial basis using an established EEG analysis software (e.g. VisionAnalyzer). In addition, such a method also allows for a distinct analysis of different time periods within a self-regulation trial instead of averaging over the whole period of 6 seconds. This procedure has been applied in a Master Thesis (Kleemeyer, 2010) and can be recommended for future studies.

In addition, using the method of median split to divide a NF group into a group of good and bad performers with respect so regulation abilities clearly has its limitations.

Moreover, it needs to be discussed in how far it can be expected that self-regulation abilities increase in the course of training. For example, for alpha/theta training, Raymond et al. (Raymond, Varney, et al., 2005) have observed improved self-regulation abilities within sessions, but no increase of self-regulation abilities across sessions. Vernon obtained a similar finding with respect to SMR training (Vernon et al., 2003; Vernon, 2005).

These limitations have to be considered with respect to the results obtained based on the self-regulation analysis of the present study. Furthermore, they also illustrate the complexity behind analyses of self-regulation measures. It remains the task of future research to establish methods that allow reliable measurements of self-regulation abilities. In addition, in order to allow for the comparability of findings across studies, it would also be desirable to establish a standard for self-regulation analyses.

However, despite the elaborate above discussion on the limitations of the employed self-regulation measures, overall it has to be acknowledged that self-regulation (theta/beta or SCP) was not learned sufficiently well during training in rather many subjects. Missing self-regulation abilities were also observed in other peak performance NF studies. For instance, in a study by Doppelmayr and Weber (2011) in healthy adults, only the SMR group was able to achieve self-regulation skills while the beta training group did not. Similarly, also Vernon and colleagues (2003) reported that only the SMR group, but not the theta enhancement group, acquired self-regulation skills. However, as was later argued by Vernon (2005), in his previous study the SMR group only achieved self-regulation within sessions, but no improvement across sessions was observed. In this way, Vernon et al.'s (2003) study is not comparable to the self-regulation analysis where a change in self-regulation in the first two sessions was compared to the last two sessions.

Thus, the most relevant question that has to be asked is why self-regulation was not learned sufficiently well during training in the present study. The following points may have counteracted a good acquisition of self-regulation skills.

One of the most relevant points may have been the small number of training sessions. NF training was performed in ten double sessions, each including about 50 minutes of neuroregulation. As a NF training usually comprises 25 to 50 training sessions (Heinrich et al., 2007), the small number of training sessions used in the present study is clearly a limitation. More training sessions may have enabled the participants to better learn the self-regulation of protocol-specific EEG parameters. Other NF studies in healthy adults comprising a smaller number of training sessions, report mixed results with respect to neuroregulation. For example, Vernon et al. (2003) reported that subjects learned the self-regulation of SMR after eight sessions of NF training. In contrast, the group performing a theta enhancement training was not able to acquire self-regulation abilities after these eight sessions.

In addition, training sessions of about two hours may have been too long. Practicing self-regulation in training blocks which aim at reinforcing an activated (negativity trials of SCP training) or focused state (theta/beta training) is an attention-demanding and exhausting process. In this respect, it may have been less tiring and thereby more effective to use a training schedule of 20 one-hour sessions instead of 10 double sessions. However, at least for those participants who had a longer way to come to the training sessions, doubling the number of training days might have reduced compliance.

Some of the participants had very busy time schedules and were already tired when coming to the training. This may not have been a beneficial state for acquiring self-regulation skills.

Another aspect, which is more applicable to SCP training, is related to artifacts. Both artifacts related to sweating during warm summer days as well as subjects arriving with a cold in winter have led to many invalid trials due to bad signal quality. Yet also apart from these especially difficult occasions, the trainer closely monitored the time course of the EEG and EOG signals to check them for artifacts. The trainer also observed the participant to detect small muscle and movement artifacts that may have influenced the feedback signal. If artifacts were detected which were not recognized as such by the software, feedback was provided to the participant that artifacts had been observed. This procedure of closely controlling for artifacts may have interfered with the participants’ practicing of self-regulation abilities.

Moreover, the participants were suggested to develop individual cognitive strategies in order to acquire self-regulation skills instead of merely focusing on the feedback signal. Mostly, these strategies were related to daily life situations in which the participant had experienced the desired state to be acquired during training. Whether such strategies are helpful for acquiring self-regulation abilities has not yet been studied. In a study in children with ADHD (Lansbergen, van Dongen-Boomsma, et al., 2011), the authors had discussed that the missing beneficial effects of NF in their study may have been related to the missing implementation of active learning strategies. In this respect, they have argued for the use of such strategies, but this remains speculative. In addition, the acquisition of regulation abilities by means of cognitive strategies may better enable participants to transfer this state practice during training to daily life situations. How well the transfer to daily life situations succeeded has not been evaluated in the present study and thus also this hypothesis remains a hypothesis.

Another interesting aspect, which is to be mentioned but without being further elaborated on, is predicting successful learning of a particular NF protocol (see Weber, Köberl, Frank, & Doppelmayr, 2011). This approach is motivated among others by the following aspects: the different NF training protocols available, the time and effort involved in performing such a comprehensive NF training, as well as the rather high number of non-responders (see Drechsler, 2011). Being able to predict the successful learning of self-regulation in a particular NF protocol at the level of an individual person may one day be used for choosing the appropriate treatment for a person. In this way, it may lead to more individualized NF training approaches.

In summary, first of all an important question which remains to be answered by further research is which aspects of a NF training benefit the acquisition of self-regulation abilities. Relevant aspects may be on the one hand the number and spacing of training sessions as well as their duration. On the other hand, the precise training procedure related to how to instruct subjects, whether to suggest the usage of cognitive strategies and how to best provide feedback to reinforce learning and prevent regulation via muscular artifacts remain important aspect so be resolved. In a next step, better and more standardized methods are needed to allow for a good parameterization of self-regulation abilities as well as predicting the successful learning of particular NF protocols.

5.6 The adaptive neurofeedback training

As outlined in the introduction (see 1.3.1.3 Clinical studies: adaptive neurofeedback training), various protocols of adaptive NF training based on the approach by Othmer and Othmer are being applied more and more in psychiatric practices over the world. The present study was the first study which set out to examine adaptive NF training protocols in a well-controlled design.

For various reasons (see 2.1 Research objective of the present study), the present study was conducted with ‘healthy’ adults and not with psychiatric patients, which is a difference to the main fields of application of the adaptive NF protocols. However, based on the peak performance rationale of NF, its application in healthy individuals is also reasonable.

Some further differences of the adaptive NF training protocols applied in the present study compared to the Othmers’ approach have to be acknowledged. In clinical practice, electrode sites from which the feedback signals for the NF training are derived are determined individually based on the specific pattern of symptoms of the patient to be trained. In the present study, the selection of training sites was based on the aim of implementing a peak performance training targeting attention and well-being. Thus, for all participants of the ANF group, the same training sites were used which was thought to be a sensible approach for the field of peak performance training. Furthermore, most adaptive training protocols start the training at sites T3-T4. This protocol was also implemented in the present study, which allows for a certain comparability with its application in clinical fields. The individual adjustment of frequency bands trained has been applied in a similar way as in clinical applications of adaptive NF training, i.e. no standardized frequency bands were used. Moreover, in order to parallel the training schedules of the other NF protocols used in the present study, a training session lasted for about two hours and consisted of about 50 minutes of neuroregulation. This is much longer than the duration of training sessions applied in practice. In addition, in the meantime the development of the adaptive NF training as applied by Othmer and Othmer has moved on to mainly training in the “infra-low” frequency range (Othmer, 2011) among others, and using multiple instead of wide band inhibits. The considerations outlined above have to be kept in mind for the evaluation of the adaptive training protocol as applied in the present study.

Overall, for the ANF group, positive training effects in the domains of attention, well-being / mood, and perceived stress were observed which were comparable to those of the theta/beta and SCP groups. In the domains mood and perceived stress, even a slight advantage over the other training protocols was observed. However, the effects fell behind expectations. As self-regulation could not be analyzed for the ANF group, it remains unclear in how far this constitutes a specific effect of ANF training. Effects may also well be related to participants in the ANF group, which in contrast to the other NF groups, explicitly performed a training protocol which they were told was intended to positively affect their mood. In addition, effects comparable to the other NF groups were observed for the ANF group on the neurophysiological level. Also after the ANF training in contrast to the control training, based on effect size measures, a pre-post increase in CNV amplitude was observed. In a similar way as for the results related to mood and perceived stress, also for the CNV findings the question of specificity remains unresolved.

A limitation of the results reported for the ANF training as applied in the present study may well be related to difficulties in the individual and adaptive adjustment of the reward frequency band. Training was started with the reward band adjusted to 12 to 15 Hz. Every two minutes, the subjects were asked to evaluate their current state on the dimensions mood, concentration, and relaxation. If ratings were not satisfyingly well, the reward frequency was adjusted based on the arousal assumption (see 1.2.3.3 Adaptive neurofeedback training).

However, while in some participants adjustment of the reward band worked well, it proved very difficult in others. In the latter participants, reward frequency was systematically changed every two minutes across the whole frequency spectrum in search for an optimal reward band. In some participants, this was successful and an optimal range could be determined. In other participants, it was temporarily successful but then ratings decreased again.

A general problem was that participants became very tired. This phenomenon was not specific to the ANF group, it was also observed in the other NF groups. It may well be related to the long duration of the training sessions which were squeezed in between the generally very busy time schedules of the participants. But in the ANF group, the observed tiredness may also be related to training too long in a non-optimal frequency band. A frequency band was trained for two minutes until the subjects were asked if they perceived a change (this procedure of asking every two minutes had been chosen for reasons of standardization). Thus, reward frequency was changed at the earliest after two minutes of training in this frequency band. If several non-optimal frequency bands were chosen in a row, this may have led to tiredness due to the enhancement of non-optimal frequencies. When the reward band was then changed towards a better fitting reward frequency, participants may have had difficulties to recognize it out of such a tired state.

Also in the SCP and theta/beta protocols, trainer impression during training was that neuroregulation was most difficult when participants were tired and that participants hardly succeeded in overcoming their tiredness by means of self-regulation abilities. Also regarding the transfer to daily life situations, many participants reported the most difficult situation being the transfer of their self-regulation abilities to situations when they were tired but needed to concentrate.

Moreover, some subjects also had difficulties in differentially perceiving and rating their current state. As the adjustment of the reward frequency band is based on the subjective ratings of participants, this posed a difficulty. Arousal assumptions can also be used to tackle the adjustments of reward bands (see 1.2.3.3 Adaptive neurofeedback training), but in 'healthy' adults where in this sense no symptoms are assessed and treated, this may have been more difficult and in turn less successful.

A further limitation regarding the comparability of the ANF trainings as applied in the present study to clinical applications of such training protocols may also be related to a difference in EEG recordings. Instead of basing feedback on a direct bipolar interhemispheric montage like T3-T4, EEG was recorded with bipolar montages in each hemisphere and feedback was based on the difference calculated from these signals. This procedure was chosen with the idea of being later able to analyze EEG measures in each hemisphere and thereby gaining insights into the neuronal processes underlying this training. Unfortunately, for technical reasons this analysis could not be performed and therefore such data are not available now.

One reason for performing the present study in 'healthy' adults and not in children with ADHD was also given by first testing the application of the ANF training in 'healthy' adults. The assumption was that they are better able to report on the perceived effects of training. Possible adverse effects of ANF training were not explicitly assessed, but the trainer impressions during training regarding this aspect can be summarized in the following way. As discussed above, tiredness was frequently observed in participants. It may have been somewhat more frequent in the ANF group, but as discussed above it was also perceived in the other groups. Apart from that, few participants complained of a headache. But it is difficult to say whether this was related to the reward band-based feedback or whether it was an unspecific effect related to an exertive and long training session. Also here, it was not only observed in the ANF group. As it was not systematically assessed, this discussion remains somewhat speculative.

But taken together, the impression is that no profound adverse effects were observed. With respect to adverse effects, the ANF training as applied in the present study provides no evidence arguing against the application in children with ADHD. In a study by Lansbergen and colleagues (Lansbergen, van Dongen-Boomsma, et al., 2011), in which individualized (but not adaptive) NF protocols were applied in children with ADHD, a systematic assessment revealed no adverse effects of NF. However, a difficulty for the application in children with ADHD may prove to be their often observed difficulties in self-evaluation. However, as adaptive training protocols are applied in this field (see 1.3.1.3 Clinical studies: adaptive neurofeedback training), this seems to be no hindrance. Nevertheless, the data obtained in the present study do not allow drawing conclusions on how effective adaptive training protocols may be in children with ADHD.

Overall, I still think that further development of NF training should move towards more individualized training protocols. In this respect, the ANF training approach is a very interesting one. In the present study, some advantages of ANF training compared to the control training group have been observed which were comparable to the other NF protocols. But, especially with respect to well-being / mood, the effects were much smaller than expected. However, when judging the ANF training based on the results of the present study, the above discussed differences to the Othmers' approach have to be kept in mind.

Further research in the field of neuroscience in the next decades may help to provide a clearer understanding of the brain mechanisms related to specific mental states and psychiatric conditions. Based on such findings, the individualization of protocols may stand on a better basis, and choices of training sites and reward frequency bands may be better grounded than at the present moment. Yet, seen from a therapeutic perspective the principle holds that what works counts. Thus, if the adaptive training approach proves effective in further well-controlled studies with patients with particular psychiatric diagnoses, the understanding of the underlying mechanisms may well come in a second step.

6 Summary and conclusion

The aim of the present investigation was three-fold. It set out to examine the effects of different neurofeedback protocols on well-being / mood, to evaluate the effects of an adaptive type of NF training, as well as to shed further light on the neuronal mechanisms underlying different NF protocols with respect to attentional processes (based on ERP measures) and motor system excitability (assessed by TMS).

Seventy-three 'healthy adults' were either allocated to a theta/beta training, an SCP training, an adaptive NF training, or a control training. Overall, with respect to specific results related to the NF protocols, the following pattern of results was obtained, mainly based on effect size measures. Some effects of NF training protocols on well-being / mood were observed, but the results were smaller than expected, especially with respect to effects on attention. All three NF protocols were associated with increased CNV amplitudes, i.e. improved resource allocation during cognitive preparation, which may have been specifically targeted by regulation abilities during negativity trials of SCP training. The association of reduced target-P3 amplitudes with successful theta/beta regulation may indicate less attentional resources needed for target stimulus evaluation. Motor system excitability changes after theta/beta training mimicked the results observed after a single dose of methylphenidate in healthy adults. The results obtained for the ANF group were comparable to those of the other NF groups, although the expected advantage on well-being / mood became only slightly visible. The effects of relaxation training in the ANF group may have been reflected in increased alpha activity observed after ANF training in a resting state.

A clear limitation of the present investigation is the still rather small sample size, even though it is in the larger range compared to other peak performance studies. This posed a limitation to statistical analyses due to associated relatively small statistical power. In addition, the sample was more heterogeneous than intended as quite some participants with rather high overall psychological distress (but still within the norm) have been included. This was the case, as it had proved much more difficult to find healthy adults who were interested and had enough time to take part in this comprehensive study than expected. An advantage of performing the study in a patient group would have been that it may have left more room for improvement. In addition, tasks used during assessment may not have been ideal to examine training effects. For example, using the ANT version designed for children may have been a too simple task when aiming at measuring peak performance. Also with respect to the assessment of EEG and TMS during a resting state, it is questionable in how far it can be expected that training effects are displayed at rest. For analyzing effects of NF training the peak performance domain it may be more suitable to assess performance in tasks more relevant to the participants, like it is being done for NF applications related to artistic performance (see e.g. Gruzelier, 2009). Moreover, despite the discussed constraints posed by the analysis methods, it has to be acknowledged that self-regulation was not sufficiently learned, although some small hints for possible specific training effects could be observed.

Overall, some effort was spent to include an acceptable number of participants in the study, and finally 73 ‘healthy’ adults had completed the training and could be included in the analysis. The investigation comprised three different kinds of NF protocols, which is not so commonly reported in literature. Even though not designed completely in parallel to the NF trainings, the study also included a control group which allowed controlling for some unspecific training effects. Assessments were performed on different levels and comprised self-report and performance measures, analysis of self-regulation abilities as well as ERP and TMS measurements. The present study was the first study to investigate motor system excitability after a comprehensive NF training schedule. In addition, it was the first study to examine the described kind of adaptive neurofeedback protocol in a more comprehensive study. The present investigation is also one of few in which effects of NF training on well-being / mood have been examined.

Future studies including larger sample sizes are needed to determine the specificity of the effects related to particular NF protocols as well as the latter’s effects on well-being / mood. Moreover, examining which factors mediate a more reliable acquisition of self-regulation skills, studying the effects of more individualized NF training protocols, as well as assessing motor system excitability during self-regulation can be considered relevant topics for future research.

7 References

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Appendix

A) Number of subjects: Self-report measures

	All *n*	FQ *n*	SCP *n*	ANF *n*	Control *n*
Brown Scale	69	18	18	18	15
POMS					
dejection	66	18	17	16	15
fatigue	66	16	18	15	17
displeasure	67	19	16	17	15
vigor	69	18	18	17	16
EWL-N					
concentration	69	18	19	17	15
deactivation	73	19	19	18	17
self-confidence	73	19	19	18	17
mood	73	19	19	18	17
sensitiveness	73	19	19	18	17
dejection	67	19	18	15	15
HAKEMP					
AOF	71	18	19	17	17
AOP	72	19	19	17	17
Self-access	68	18	17	16	17
PSS	63	19	15	13	16

Note. Number of subjects included in each analysis after removal of outliers and considering missing data. For a description of these self-report measures please refer to 3.2.3.1 Pre- and post-training assessments.

B) Number of subjects: Performance measures

	All *n*	FQ *n*	SCP *n*	ANF *n*	Control *n*
Darts	54	18	19	17	17
Working Memory	54	19	19	16	17
ANT					
Hits	65	17	16	17	15
RT/ RTV/ alerting/ orienting/ conflict	68	17	18	17	16

Note. Number of subjects included in each analysis after removal of outliers and considering missing data. For a description of these self-report measures please refer to 3.2.3.1 Pre- and post-training assessments.

C) Number of subjects: Neurophysiological measures

	All	FQ	SCP	ANF	Control
	n	*n*	*n*	*n*	*n*
Resting EEG					
Theta	67	17	17	16	17
Alpha	64	16	14	17	17
Beta	65	17	17	15	16
ANT					
CNV	61	18	14	16	13
Cue-P3	61	15	15	17	14
Target-P3 (alert., orient.)	59	16	14	16	13
Target-P3 (conflict)	64	17	17	16	14
TMS	40	10	09	12	09
Self-regulation	33	16	17	n.a.	n.a.

Note. Number of subjects included in each analysis after removal of outliers and considering missing data. For a description of these self-report measures please refer to 3.2.3.1Pre- and post-training assessments

D) ERP data assessed during the ANT: CNV

CNV	Pre		Post	
	NeutralCue n	SpatialCue n	NeutralCue n	SpatialCue n
FQ	-2.06 ± 1.95	-2.91 ± 1.57	-2.10 ± 1.38	-3.08 ± 1.78
SCP	-2.51 ± 1.57	-3.28 ± 1.20	-2.51 ± 1.51	-3.49 ± 1.20
ANF	-2.11 ± 1.73	-2.94 ± 2.23	-2.52 ± 1.53	-3.14 ± 2.29
CON	-1.85 ± 1.44	-3.16 ± 1.06	-1.46 ± 1.58	-2.34 ± 1.27

Note. Mean CNV amplitudes (and *SD*) for the different cue conditions (NoStress: n) at pre- and post-assessment for each group

.

CNV	Pre		Post	
	NeutralCue w	SpatialCue w	NeutralCue w	SpatialCue w
FQ	-1.48 ± 1.55	-2.41 ± 1.48	-1.78 ± 1.67	-3.26 ± 1.43
SCP	-2.01 ± 1.50	-3.36 ± 1.39	-2.65 ± 1.33	-3.75 ± 1.04
ANF	-1.68 ± 1.72	-3.37 ± 1.67	-1.85 ± 1.55	-3.22 ± 1.66
CON	-1.72 ± .76	-2.60 ± 1.38	-1.05 ± 1.40	-2.40 ± 1.07

Note. Mean CNV amplitudes (and *SD*) for the different cue conditions (WithStress: w) at pre- and post-assessment for each group

E) ERP data assessed during the ANT: Cue-P3

cueP3	Pre		Post	
	NeutralCue n	SpatialCue n	NeutralCue n	SpatialCue n
FQ	3.61 ± 1.55	4.85 ± 2.23	3.31 ± 1.59	4.70 ± 1.60
SCP	3.57 ± 1.95	4.74 ± 2.26	4.14 ± 1.79	4.68 ± 2.31
ANF	3.29 ± 2.23	5.51 ± 2.13	3.49 ± 2.53	5.32 ± 2.46
CON	3.45 ± 2.16	4.33 ± 1.92	4.00 ± 2.12	4.00 ± 1.96

Note. Mean cue-P3 amplitudes (and *SD*) for the different cue conditions (NoStress: n) at pre- and post-assessment for each group

.

cueP3	Pre		Post	
	NeutralCue w	SpatialCue w	NeutralCue w	SpatialCue w
FQ	3.54 ± 1.38	4.29 ± 2.27	3.64 ± 1.77	4.37 ± 1.60
SCP	3.52 ± 2.09	5.28 ± 3.09	3.83 ± 2.84	4.28 ± 1.99
ANF	3.94 ± 1.71	4.66 ± 2.34	2.68 ± 2.02	5.13 ± 2.54
CON	3.53 ± 1.77	4.77 ± 2.20	3.85 ± 2.00	4.49 ± 1.84

Note. Mean cue-P3 amplitudes (and *SD*) for the different cue conditions (WithStress: w) at pre- and post-assessment for each group

F) ERP data assessed during the ANT: Target-P3 (co-in)

Targ.-P3	Pre		Post	
	Congruent n	Incongruent n	Congruent n	Incongruent n
FQ	11.19 ± 2.80	11.03 ± 3.38	10.84 ± 3.07	10.64 ± 4.13
SCP	11.82 ± 2.97	11.37 ± 3.70	11.24 ± 3.81	10.84 ± 4.38
ANF	11.67 ± 4.05	11.57 ± 3.60	11.93 ± 4.29	11.60 ± 4.30
CON	10.93 ± 3.46	10.52 ± 2.74	11.52 ± 3.92	10.62 ± 2.85

Note. Mean target-P3 amplitudes (and *SD*) for the congruent and incongruent condition (NoStress: n) at pre- and post-assessment for each group.

Targ.-P3	Pre		Post	
	Congruent w	Incongruent w	Congruent w	Incongruent w
FQ	11.26 ± 3.53	10.82 ± 3.71	10.79 ± 2.69	10.80 ± 4.15
SCP	11.59 ± 3.31	11.34 ± 3.65	10.74 ± 3.65	11.89 ± 3.79
ANF	11.93 ± 3.88	12.13 ± 3.22	12.45 ± 4.42	12.13 ± 4.75
CON	11.47 ± 3.56	11.05 ± 3.70	10.61 ± 2.99	11.17 ± 2.22

Note. Mean target-P3 amplitudes (and *SD*) for the congruent (co) and incongruent (in) condition (WithStress: w) at pre- and post-assessment for each group.

G) ERP data assessed during the ANT: Target-P3 (cues)

Targ.-P3	Pre			Post		
	NoCue n	NeutrCue n	SpatCue n	NoCue n	NeutrCue n	SpatCue n
FQ	11.74 ± 3.31	11.75 ± 3.27	9.95 ± 3.18	11.61 ± 4.02	10.78 ± 3.36	9.09 ± 3.75
SCP	11.28 ± 3.64	11.53 ± 3.10	10.68 ± 2.83	11.59 ± 4.76	11.99 ± 5.07	10.70 ± 3.73
ANF	12.54 ± 3.84	11.59 ± 4.28	11.19 ± 3.30	12.89 ± 5.19	11.45 ± 4.44	10.90 ± 3.26
CON	10.67 ± 3.58	10.86 ± 3.35	9.66 ± 3.07	11.15 ± 3.07	11.17 ± 2.81	9.81 ± 3.29

Note. Mean target-P3 amplitudes (and *SD*) for the different cue conditions (NoStress: n) at pre- and post-assessment for each group.

Targ.-P3	Pre			Post		
	NoCue w	NeutrCue w	SpatCue w	NoCue w	NeutrCue w	SpatCue w
FQ	11.75 ± 4.17	11.27 ± 3.47	10.56 ± 3.01	11.67 ± 3.72	10.98 ± 3.54	9.56 ± 3.66
SCP	11.21 ± 3.42	11.26 ± 3.13	10.52 ± 3.28	11.63 ± 3.51	10.96 ± 3.74	10.87 ± 4.18
ANF	12.69 ± 3.87	12.27 ± 3.45	11.05 ± 3.72	13.45 ± 4.37	11.90 ± 4.52	11.00 ± 4.87
CON	11.12 ± 2.37	10.75 ± 3.04	9.67 ± 3.38	10.72 ± 2.99	10.95 ± 2.19	10.14 ± 3.29

Note. Mean target-P3 amplitudes (and *SD*) for the different cue conditions (WithStress: w) at pre- and post-assessment for each group.