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# EEG-neurofeedback training of beta band (12–22 Hz) affects alpha and beta frequencies – A controlled study of a healthy population

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ABSTRACT

The frequency-function relation of various EEG bands has inspired EEG-neurofeedback procedures intending to improve cognitive abilities in numerous clinical groups. In this study, we administered EEG-neurofeedback (EEG-NFB) to a healthy population to determine the efficacy of this procedure. We evaluated feedback manipulation in the beta band (12–22 Hz), known to be involved in visual attention processing. Two groups of healthy adults were trained to either up- or down-regulate beta band activity, thus providing mutual control. Up-regulation training induced increases in beta and alpha band (8–12 Hz) amplitudes during the first three sessions. Group-independent increases in the activity of both bands were observed in the later phase of training. EEG changes were not matched by measured behavioural indices of attention. Parallel changes in the two bands challenge the idea of frequency-specific EEG-NFB protocols and suggest their interdependence. Our study exposes the possibility (i) that the alpha band is more prone to manipulation, and (ii) that changes in the bands' amplitudes are independent from specified training. We therefore encourage a more comprehensive approach to EEG-neurofeedback training embracing physiological and/or operational relations among various EEG bands.

## 1. Introduction

One of the main goals of neuroscience is relating cognitive functions to neurophysiological processes. Assuming that these relationships are reciprocal and can be experimentally established by various recording methods, the alteration of a given pattern of physiological activity should result in corresponding specific changes in behaviour. Techniques such as transcranial magnetic stimulation and transcranial direct current stimulation have thus recently been developed to directly stimulate relevant cortical tissues. These techniques require specialised equipment and medical supervision. Therefore, simpler methods without the risk of negative side effects are in high demand for both scientific and clinical applications. One of the most promising techniques is EEG-based neurofeedback (EEG-NFB). During an EEG-NFB training session, participants are provided with external sensory stimuli representing the chosen parameter of their brain activity (e.g., the amplitude of oscillations in a particular frequency band). When the chosen parameter exceeds a predefined threshold, participants are provided with a reward - this procedure fulfils operant conditioning principles.

Even though its underlying mechanisms are far from being understood in full, EEG-NFB has been applied as a supportive treatment in a range of disorders, such as epilepsy (Sterman, 2000), ADHD (for review, see: Arns et al., 2009), and tinnitus (Hartmann et al., 2014). In healthy subjects, EEG-NFB is used with the expectation of behavioural and/or cognitive improvements (Reiner et al., 2014) and as a means of improving cognitive performance in elderly people (Staufenbiel et al., 2014; Wang and Hsieh, 2013). Despite numerous studies reporting behavioural improvements after EEG-NFB training (for review, see: Vernon, 2005), the method has received criticism due to the scarcity of physiological evidence supporting its effectiveness (Egner et al., 2004; Enriquez-Geppert et al., 2017; Rogala et al., 2016; Schabus et al., 2017), low replicability of study results, and the lack of widely acclaimed indices of training success (Dempster and Vernon, 2009). Thus, careful, systematic examination of the physiological basis of EEG-NFB and its efficacy in a kind of "baseline condition" (i.e., normal brain) is still needed in the field (for theoretical background see Ros et al., 2014).

The large diversity of protocols targeting various bands results from the belief that each frequency range is related to some specific cognitive

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functions. However, conventional taxonomy of EEG bands is arbitrary (but see Shackman et al., 2010), as their generators are largely unknown (e.g., rhythms generated by the same brain networks can fall into different bands and a particular frequency may reflect activation of different brain networks; Buzsáki, 2009). The usage of classifications of brain frequency bands is thus limited, but continues to be of practical importance. As such, all traditionally discriminated EEG bands have been used as a feedback source. Among other oscillatory frequencies, those of the beta band are a common target in EEG-NFB training. Several attempts were made to determine the efficacy of beta training in healthy population (12–15 Hz: Egner and Gruzelier, 2001; Egner et al., 2004; Gruzelier et al., 2014a, 2014b; Hoedlmoser et al., 2008; Kober et al., 2013; Paul et al., 2012; Reichert et al., 2015; Ros et al., 2010; Rostami et al., 2012; Vernon et al., 2003; Witte et al., 2013; 12–16 Hz: Berner et al., 2006; 12–18 Hz: Engelbregt et al., 2016; 15–18 Hz: Egner and Gruzelier, 2001; Egner et al., 2004; Ghaziri et al., 2013; Gruzelier et al., 2014a, 2014b; 12–20 Hz: Keizer et al., 2010; Staufenbiel et al., 2014). The beta band was earlier recognized as an attention carrier (Buschman and Miller, 2007; Wróbel, 2000, 2014), with specific local increases in amplitude during attentional tasks positively correlating with correct performance in animals and humans (Bekisz and Wróbel, 1993; Gola et al., 2013; Kamiński et al., 2012; Wróbel et al., 2007). Accordingly, the up-regulation of activity in this band has been tested in healthy population mostly to assess its effects on attention performance (Egner and Gruzelier, 2001; Egner et al., 2004; Logemann et al., 2010; Vernon et al., 2003). This method has also been implemented to boost athletic performance and preserve cognitive functions in the elderly (for review see: Gruzelier, 2014). Beta up-regulation training has also been attempted in more complex EEG-NFB training protocols as a supplementary treatment for patients with ADHD (for review see: Arns et al., 2009).

However, the ability of EEG-NFB to alter beta band amplitude is unclear. Studies reporting successful modification of beta amplitude (Vernon et al., 2003; Witte et al., 2013) were usually focused on its lower range (12–15 Hz, sensorimotor rhythm), adherent to the alpha band. Most of the relevant studies lack information regarding the influence of the training on the rest of the frequency spectrum, or provide information about frequency ratios only (e.g. Gruzelier et al., 2014a, 2014b; Vernon et al., 2003), precluding any statements regarding the physiological outcomes of training. Other beta band training experiments have at best been inconclusive in this respect, failing to report any EEG data (Ghaziri et al., 2013; Rostami et al., 2012). Indeed, one double-blind experiment on beta frequency training, including a sham feedback control, was discontinued before the scheduled time due to a lack of effect. The authors of this study neglected to report their training data, relying instead on pre-training and interim behavioural screening (Logemann et al., 2010). No amplitude increase was reported by Keizer et al. (2010), who used a beta up-regulation protocol.

We conducted an experiment aiming to increase/decrease beta1 band (12–22 Hz) amplitude using EEG-NFB. The present study focuses on EEG-NFB efficiency in beta manipulation and intends to complement the existing data implicating the beta band as an attention carrier by testing the causal relationship between the beta band and attention. We trained healthy young participants to voluntarily manipulate the amplitude of beta1 band oscillations recorded from the frontal and parietal leads. EEG-NFB efficiency was assessed by offline analysis of EEG data recorded during training sessions. We provide the results of between- and within-session analyses for the trained band as well as for the flanking alpha (8–12 Hz) and beta2 (22–30 Hz) bands. Additionally, we report outside training recordings, which provide us with the opportunity to examine the transfer of training effects. To assess training impact on attention before and after the training, we also administered a set of psychological attention tests.

## 2. Materials and methods

### 2.1. Participants

Thirty-two healthy male participants aged 22.34 ± 1.18 (mean ± SD) years took part in the study. The experiments were approved by the local ethics committee. All participants provided written informed consent for participation in the study. Nineteen participants received training aimed at increasing the amplitude of beta1 (12–22 Hz) oscillations (B+ group), while the remaining 13 participants received training to decrease the amplitude of this band (B- group). Both groups were exposed to all nonspecific factors of the training. Therefore, each group was the control for the other group.

### 2.2. EEG-neurofeedback protocol

The training sessions were performed using a customised version of the commercial system EEG DigiTrack Biofeedback (Elmiko Medical Sp. z o.o.; Warsaw, Poland). Each participant was assigned a unique personal code, which was automatically recognized by the program to initiate the appropriate group-dependent feedback protocol. Training sessions were conducted by hired professional neurofeedback trainers. In order to reduce possible nonspecific effects, trainers were instructed not to additionally motivate the trainees. Over a period of two months, subjects underwent 16 training sessions (one or two training sessions per week). During each session, subjects were seated in a chair in front of a 17-in. computer LCD screen at a distance of approximately 70 cm. Each session consisted of ten 3-min-long blocks. The session started after mounting of the EEG electrodes, which was followed by a 2-min resting period (baseline) intended to accustom the participants to the training situation and to record the non-training sample of the EEG signal (Fig. 1).

In both groups, the band chosen for training was defined as 12–22 Hz, otherwise referred to as the beta1 band. An amplitude threshold at higher frequencies (22–45 Hz) halted the presentation of the feedback stimulus if high-frequency artefacts were detected (i.e., when amplitude in this range exceeded 60 μV).

Feedback information was provided visually in the form of a shooting target and four moving green dots. The shooting target was present in the background, while the dots were sliding inwards and outwards along the vertical and horizontal axes depending on the changing EEG signal (Fig. 1). The dots were controlled by the value of beta1 band amplitude averaged across four training electrodes. When this amplitude changed in the intended direction, all dots moved simultaneously towards the centre. The trainer's display contained a bar plot of beta1 band amplitudes in a running window covering a period of thirty seconds (with bars representing 2-second-long overlapping frames, see Methods Section 2.3).

The threshold defining the required value of beta1 band amplitude was depicted as a horizontal line on the graph, which could have been adjusted manually by the trainers during the session. The threshold was held above (for B+) or below (for B-) the higher limit of the beta1 band amplitudes to provide a relatively constant rate of reward across subjects. We aimed to observe the genuine effects of feedback loop, by instructing the trainers not to manipulate threshold value unless participants consequently fail to receive any rewards. As reported by the trainers, threshold had to be manually adjusted, at some point during the training, for 4 subjects from B+ and 6 subjects from B- group. There were no differences in the results after exclusion of these participants.

The subject's goal was to make the green dots meet in the centre. Additional reinforcements were provided to boost the participants' motivation and to make the training more involving. The established threshold constituted a reference (100%) for the intermediate reward steps. If beta amplitude reached the value within the range 57% below (B+) or above (B-) the threshold, the display was complemented with black rings within the high-score area of the shooting target. When the