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No Effects of Successful Bidirectional SMR Feedback Training on Objective and Subjective Sleep in Healthy Subjects

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Abstract There is a growing interest in the application of psychophysiological signals in more applied settings. Unidirectional sensory motor rhythm-training (SMR) has demonstrated consistent effects on sleep. In this study the main aim was to analyze to what extent participants could gain voluntary control over sleep-related parameters and secondarily to assess possible influences of this training on sleep metrics. Bidirectional training of SMR as well as heart rate variability (HRV) was used to assess the feasibility of training these parameters as possible brain computer interfaces (BCI) signals, and assess effects normally associated with unidirectional SMR training such as the influence on objective and subjective sleep parameters. Participants (n = 26) received between 11 and 21 training sessions during 7 weeks in which they received feedback on their personalized threshold for either SMR or HRV activity, for both up- and down regulation. During a pre- and post-test a sleep log was kept and participants used a wrist actigraph. Participants were asked to take an afternoon nap on the first day at the testing facility. During napping, sleep spindles were assessed as well as self-reported sleep measures of the nap. Although the training demonstrated successful learning to increase and decrease SMR and HRV activity, no effects were found of bidirectional training on sleep spindles, actigraphy, sleep diaries, and self-reported sleep quality. As such it is concluded that bidirectional SMR and HRV training can be safely used as a BCI and participants were able to improve their control over physiological signals with bidirectional training, whereas the application of bidirectional SMR and HRV training did not lead to significant changes of sleep quality in this healthy population.

Keywords Sleep · Military · BCI · Biofeedback · Neurofeedback · Training · Heart rate variability

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Introduction

Neurofeedback (NFB) has been in use since the 1960s in clinical settings for revalidation purposes, more recently, due to technical improvements and new computer technology, it is geared towards non-clinical domains for prevention purposes or improvements of performances in applied domains (Hammond 2007). For that reason, there is a need for more solid theoretical and methodological sound experimentation and scientific evidence to test and validate the NFB applications as reliable methods in order to help advance this field (Gruzelier et al. 2006; Gruzelier 2014). Therefore, the underlying motivation to conduct the current study was to test the most beneficial NFB method on

a sufficiently measurable variable such as sleep quality, in order to develop an adequate self-paced intervention in the domain of high risk professions. Military, police officers and fire fighters are often forced to operate in high risk environments and are, therefore, exposed to a significant amount of stressors during their professional career (e.g., Binsch et al. 2015). Insufficient quality and duration of sleep during missions and shift work can lead to sleep disorders and insomnia (e.g., Peterson et al. 2008), which is associated with negative daytime performance (e.g., Morin et al. 2006). Therefore, it is important to decrease or reduce insomnia symptoms personnel in high risk professions.

One of the most promising approaches that may increase sleep quality are NFB applications involving the training of the sensory motor rhythm (SMR) that have been studied in multiple settings. Clinically, unidirectional SMR enhancement training has been reported to have effects in ADHD (Monastra et al. 2005; Arns et al. 2009; Lofthouse et al. 2012) and epilepsy (Sterman 2000; Tan et al. 2009). SMR feedback training has also improved cognitive performance in healthy subjects; Egner and Gruzelier (2001) showed a positive effect of SMR training on attention using a continuous performance task. Furthermore, Vernon et al. (2003) showed that SMR feedback training is associated with a slight improvement of working memory and attentional processing. A number of studies have shown that SMR training also transfers to the sleeping state, this was first reported by Sterman et al. (1969) using cats as subjects. In particular, SMR frequencies overlap with dominant oscillations in stage two sleep (i.e. stage of light sleep), called sleep spindles, which have the same topography and frequency as the SMR rhythm trained during wakefulness. Furthermore, it has been demonstrated that SMR enhancement neurofeedback induces and increases the occurrence of sleep spindles (Sterman et al. 1969; Hoedlmoser et al. 2008) as well as improves sleep parameters such as decreased sleep onset latency and increased sleep duration (Cortoos et al. 2010; Hoedlmoser et al. 2008; Arns et al. 2014). SMR training was applied to help patients with insomnia (Cortoos et al. 2010; Hoedlmoser et al. 2008). Also, in a healthy population, results showed it was possible to gain control over the SMR frequency with positive effects on quality of sleep; Hoedlmoser et al. (2008) demonstrated that after 10 SMR training sessions their participants showed an improvement in declarative learning, an increased number of sleep spindles during stage 2 sleep and a reduced sleep onset latency. Furthermore, it was recently hypothesized that activating and deactivating the reticular–thalamocortical–cortical sleep spindle circuitry would increase the synaptic strengths within that network (Arns et al. 2014, 2015). As a result the probability of future activation of this network would increase (Sterman and Egner 2006; Arns and Kenemans 2013), which explains the increased sleep density during sleep.

A second application that involves feedback of physiological activity is in the field of brain–computer interfacing (BCI). BCI is well-known as a technique based on the interaction between the brain and a device (i.e. computers). More specifically, the BCI technique uses electrophysiological signals extracted from the brain that enables the user to direct multidirectional and multidimensional activity, such as control of a cursor, a computerized language or speech program, and/or an motorized wheelchair without muscular activity or overt speech. Such control can be beneficial for patients with severe motor disabilities. For example, Birbaumer et al. (1999, 2007) combined the BCI technique with SMR–NFB and developed and validated a spelling device [thought translation device (TTD)] for patients suffering from amyotrophic lateral sclerosis (ALS) to improve their ability to interact with their social environment. The BCI–TTD bidirectional interface only required to select a certain topic from a list and to learn how to up- and down-regulate a courser in order to perform (i.e., select and edit) the communication that matches the corresponding intent of the individual through the route of electroencephalography (EEG). Other studies demonstrated that patients with spinal cord injuries and healthy users were able to provide point-to-point movements in motorized wheelchairs (Wolpaw and McFarland 2004), or participants learned to control helicopter flights in 3-dimensional space (Royer et al. 2010) by applying BCI multidirectional trainings to increase and decrease the amplitude of SMR (see also Yuan and He 2014 for an overview). As such, BCI bidirectional training methods are beneficial as the user get enhanced to control alternately the de- and increase of brain signal output *and* simultaneously also inhibiting brain activity (Ancoli and Kamiya 1978; Vernon et al. 2009). A bidirectional training which incorporates both enhancement and suppression may also enable a user to obtain a greater degree of voluntary control in less time.

Besides the positive effects of SMR–NFB, research has shown that increasing heart rate variability (HRV) using biofeedback (BFB) can have a positive effect on mental and psychological health, including a decrease in depression, anxiety, post-traumatic stress disorder (PTSS), medically unexplained syndromes, high blood pressure and an increase in lung function (Lehrer et al. 2000). Furthermore, Hansen et al. (2009) found a positive correlation of HRV performance on cognitive tasks and self-regulatory control with positive implications for the military domain. In summary, HRV–BFB has been applied and examined for many different clinical uses, including in patients with major depressive disorder (Hassett et al. 2007), hypertension (Del Pozo et al. 2004) and PTSD (Zucker et al. 2009), as well as in healthy people (Lehrer et al. 2003). However, the results of these studies are mixed. In patients with depression, clinical symptoms decreased in the BFB group (Hassett et al.

2007), whereas BFB for people with PTSD showed similar results compared to other, less intense relaxation techniques (Zucker et al. 2009).

As there is an indication that SMR neurofeedback has effects on objective and subjective sleep parameters in both healthy populations (Hoedlmoser et al. 2008) as well as in clinical populations (Cortoos et al. 2010; Arns et al. 2014), in this study we aimed to investigate BCI bidirectional NFB–SMR training (i) to investigate how well volunteers could control this activity, and (ii) to quantify the effects on sleep to further explore if clinical effects are also obtained with bidirectional as opposed to unidirectional SMR training. As a control variable BCI HRV–BFB training was used, as it was expected that volunteers could also learn to gain bidirectional control over HRV, and this training was expected to have more non-specific effects e.g. increase parasympathetic activity (Lehrer et al. 2000), thereby increasing the quality of sleep through relaxation. Concerning the bidirectional BCI training we hypothesized that this could be an efficient method that result in increased sleep spindle density and therefore in improved sleep in a healthy military population.

Method

Participants

A total of 62 participants, all military working at the Dutch Ministry of Defense, were invited for a screening consisting of the Holland Sleep Disorders Questionnaire (HSDQ; Kerkhof et al. 2013). 20 participants were excluded because they had a score above 2 on the HSDQ, suggesting a possible sleep disorder (mean score = 1.4, SD = 0.3; Kerkhof, 2013). The remaining 42 participants were matched and assigned to either NFB or BFB group. The assignment to the groups was based on gender, age, and HSDQ score. Of the remaining 42 participants, 16 participants were further excluded from the analysis because they were not able to attend the predefined number of 10 required training sessions (see Hoedlmoser et al. 2008), due to their preparation for a military mission in Africa. In total 26 participants (8 female) remained, aged between 21 and 52 years ($M = 32.46$, SD = 8.90). Of those 26 participants, 12 belonged to the HRV–BFB group and 14 to the SMR–NFB group. The study's protocol was approved by the Ethics Committee (TCPE) of the Dutch Research Institute for Applied Sciences (TNO).

Design

The treatment consisted of 7 weeks of feedback training, with one to three training sessions per week. To assess the effects of this training on sleep quality, pre- and post-tests were conducted including EEG measurements during an afternoon nap from 12:30 to 14:30 p.m. and several questionnaires out to asses subjectively perceived quality of sleep. In addition to these assessments, participants kept a sleep journal and wore an Actiwatch (Actiwatch Sleep & Activity Software V 5.32, Cambridge Neurotechnology) for the duration of 1 week, after the pre- and post-test.

Apparatus and Materials

The training sessions were conducted using Brainquiry PET EEG 4.0 (four channels) NFB equipment (Brainquiry B.V). The software was programmed in BioExplorer (CyberEvolution, Inc.).[1] Disposable electrodes were placed on EEG locations C3 and C4, referenced behind the left ear, on the mastoid. In addition, ECG electrodes were placed on the sternum and left clavicle (Ruehland et al. 2011). The sampling rate was 200 Hz and signals were low pass filtered at 1 Hz and high pass filtered at 41 Hz. In the SMR group, the power in the SMR frequency band (12–15 Hz) was calculated with Butterworth filter (Bianchi and Sorrentino 2007). For the HRV group, ECG signals were low pass filtered at 5 Hz and high pass filtered at 50 Hz to calculate HRV. During training, the thresholds were adjusted (SMR: steps of 0.5 µV and HRV: steps of 2.5 V). Both, SMR and HRV feedback was displayed on a 19″ computer screen (LCD Screen, 1920 × 1200 WUXGA Matte Wide, Dell©) to the participant. The exact processing and real-time artifact handling is described in detail in Kleinnijenhuis et al. (2008).

During the pre- and post-tests to assess sleep parameters the PET system was used again to measure only EEG with four channels, placed on locations C3, C4, F4, O2 which were referenced to the left mastoid (these channels were chosen in agreement with the AASM guidelines for polysomnography). Subjective sleepiness was assessed with the Pittsburgh Sleep Quality Index (PSQI; Buysse et al. 1989) and the Stanford Sleepiness Scale (SSS; Hoddes et al. 1973). The Groninger Sleep Quality Scale (GSQS; Mulder-Hajonides van der Meulen et al. 1980) was applied to measure the subjective perceived sleep after the pre- and post-test napping. Following the week of the pre- and post-test, a sleep diary was kept which included the GSQS and other items providing an indication of the total sleep time (TST), sleep onset latency (SOL), wake after sleep onset (WS), time in bed (TB) and sleep efficiency (TST/TB). Actigraphy was used to objectively assess sleep characteristics, total sleep time, activity, and fragmentation (Ancoli-Israel et al. 2003).

[1] For a more detailed explanation of the bidirectional screens, the exact processing and real-time artefact handling that were applied during the feedback training sessions see Kleinnijenhuis et al. 2008; Spronk et al. 2010.

Procedure

During the pre-test, participants received the briefing and signed the informed consent. The SSS and PSQI were rated. EEG measurements were collected using the PET system during an afternoon nap. After a nap of 120 min sleep, again the SSS and the GSQI were rated. After the pre-test, the selected participants had to fill-out a sleep diary every day for 1 week and they wore the Actiwatch. The participants were instructed to press the button on the Actiwatch every time they went to bed or went out of bed. The post-test procedure was similar to the pre-test, and ended with a debriefing of the treatment phase.

During feedback training sessions, the participants of both groups were trained to attain, and endure in, a certain range level of SMR or HRV activity, respectively. Each session started with the application of electrodes on the scalp and chest of the participant. The first time, participants were instructed on the functions of the various elements of the feedback window and the task requirements. Following Kober et al. (2013) who found that a 'Just do it' task instruction is most effective, a general explanation of BFB- and NFB was given; participants were not provided with a directed strategy to control the HRV or SMR. Participants were only told that up-regulation is associated with relaxation, and down-regulation is associated with effort.

The sessions lasted 1 h, including 25 min of preparation, 24 min of effective training and ca. 11 min of removing the electrodes and debriefing. The timeline of the experiment was scheduled equally for each participant. That is, the experiment lasted 10 weeks for each participant and started with the pre-test arranged in the initial 2 weeks. This period was followed by 7 weeks of training sessions, and ended with the post-test planned in the last week. Participants who started the experiment with the pre-test in the first week, started the training sessions in the following week, and ended the experiment also in the first days of the post-test week. The maximum latency time between pre-test and the initial training session lasted 7 days (including days of the weekend), and lasted a maximum of 6 days between the last training session and the post-test.

Feedback Training Task

Each training session consisted of four runs with a duration of 6 min (Fig. 1). During a run, 45 trials were presented; trials for the up-regulation and the down-regulation were mixed pseudo-randomly (Kleinnijenhuis et al. 2008; Spronk et al. 2010). In summary, (also see Fig. 1) a blue bar filled up slowly either upwards or downwards to indicate the direction of the trial. The feedback signal of the participants was shown in real-time on the screen i.e. either SMR or HRV in the form of a yellow bar on the feedback screen and a trial

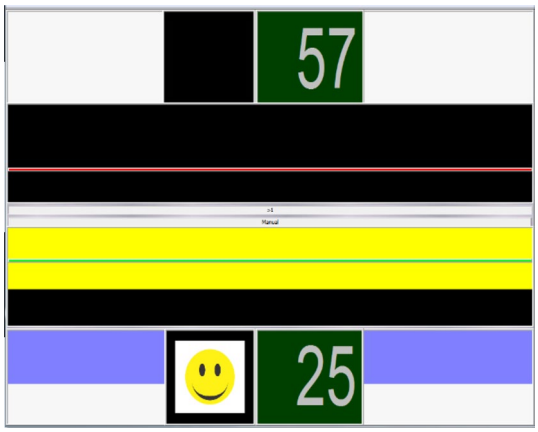

Fig. 1 Screenshot of the feedback training application as was presented to the participant. A Smiley and sound indicated a successful trial in which the yellow bar (either SMR or HRV activity) was beyond the threshold (green/red horizontal lines, 60 Hz update rate) for at least 300 ms. The numbers above and below on the screen represent the percentage of successful trials for up- and down regulation, respectively. These numbers were updated after every trial. Training was bidirectional and trials for up- and down-regulation were mixed randomly. (Color figure online)

lasted 7 s in which the participant had to regulate the signal in the desired direction. The inter-trail interval varied randomly between 1.5 and 3 s. The participant had to try and cross the threshold line that was indicated (red and green) for at least 300 ms to complete the trial successfully. If the trial was successful, visual feedback (smiley was shown and percentage of successful up- or down regulation was updated) and auditory feedback (sounds played over headphone) were provided. If the participant was unable to exceed the threshold line for more than 300 ms, the trial was unsuccessful and the percentage correct was lowered accordingly. The thresholds used for positive feedback were based on the achieved performance during each run. If, in one training session, three of the four runs scored 50% or higher, the threshold was increased one step upwards for the next training session. The thresholds were adjusted separately for upward/downward regulating e.g. a participant who achieved better scores in relaxation could have a higher threshold for upward regulation than for downward regulation. However, if a participant scored lower than 50% in six of the eight runs (over two training sessions) the threshold was decreased one step downward. Apart from these adaptations, the threshold values remained unchanged for the following training session.

In order to keep participants motivated, every 2 weeks a result list was published with top 10 performers. The point system was based on the combination of the number of runs and the number of levels the participants were able to regulate up or down. Participants deserved one point when the threshold was increased one step after a session. A deduction of one point occurred when the threshold was decreased one

step after a session. These points were added up to a score for all sessions. Because the SMR and HRV training groups had different threshold values, the top performers of the two groups were placed alternately on the list.

Analysis

Statistical analyses were performed using Statistical Package for the Social Sciences (SPSS, IBM® statistic software for Windows version 22.0.0). Please note that due to the operational setting of the military population, the number of completed trainings sessions varied between 11 and 21. In line with Hoedlmoser et al. (2008), only the datasets of participants that attended a minimum of 10 training session were analyzed. Twenty-six participants were able to attend the minimum of 10 or more sessions. All data of these participants were used for the analysis, including the data of all completed training sessions, the sleep data of the 2×120 min during the pre- and post-test, and all subjective data to analyze sleep quality. Kolmogorov–Smirnov tests were applied to test for normality of the distribution of the data. For all analyses, the significance level was set to $p < .05$.

Training Effect

Prior to the analyses of the training effect a training effect score was calculated per participant by using a standard z-transformation procedure. That is, the maximum obtained training level (α), the baseline level (β) at which the training started, the number of all completed training sessions (ω) and the number of steps (σ) that the participant needed to achieve α. These factors were used to examine the ratio (i.e. training effect score) between the level that the participant have achieved and the level that the participant could have achieve transferred into percentage $(\alpha - \beta)/((\omega - 1) \times \sigma) \times 100\%$. Consequently, the training effect data were analyzed by using a paired samples T-test for each group (SMR–NFB, HRV–BFB) separately on the training scores obtained during up- (relaxation) and down- (effort) regulation.

Pre- and Post-test

Sleep spindles were derived from the EEG during the pre- and post-test naps. They were determined automatically (13–15 Hz at C4) in the selected periods of sleep and verified by visual inspection. More specifically, sleep was defined as periods were alpha or theta power decreased relatively to the beginning of the nap. For the detection of the spindles a spindle threshold of 3 µV was used and the duration of the spindle should be between 0.5 and 2 s (Piantoni et al. 2013). From this data the total number of spindles and spindles per minute were derived. Artefacts were removed manually from the raw data during a semi-automatic process, i.e. after visual inspection for abnormalities (i.e., spindle threshold of 3 µV and spindle duration between 0.5 and 2 s; see also Piantoni et al. 2013) of the previous automatically detected data through the analyses of relative alpha (7.5–13.0 Hz) and theta power (3.5–7.5 Hz). To compare the sleep spindle/quality data between pre- and post-test generalized linear model (GLM) repeated measures analysis of variance (ANOVA) for both groups separately were conducted using a 2 test (pre-, post-) × 2 regulation (up-, down-) design. Greenhouse-Geisser correction was used in case of non-sphericity of the data. Pair-wise comparisons using Bonferroni correction (Kinnear and Gray 2000) were made to identify specific mean differences when appropriate. Partial eta squared (η_p^2) assessed the explained variance in the ANOVA models. Subjective ratings were analyzed using non-parametric techniques (i.e. Wilcoxon Matched-Pairs Signed-Ranks, Mann–Whitney *U*) with a within-subject factor (pre-test, post-test) and a between-subject factor (SMR–NFB vs. HRV–BFB).

Results

Training Effect

Participants in the HRV–BFB group completed on average 15 sessions (min. = 13, max. = 21, median = 14 sessions). Figure 2 shows the average correct achieved trials during up-regulation (i.e., relaxation, in %; black bars) and the average correct achieved trials during down-regulation (i.e., effort, in %; gray bars) of the HRV–BFB group.[2]

In addition, the average maximum obtained training level during up-regulation (relaxation) is presented by the green line and the average maximum obtained training level during down-regulation (effort) is presented by the red line. As such, Fig. 2 indicate that the HRV–BFB group was not able to achieve correct trails for both up- and down-regulation

[2] Figure 2 show all 18 HRV–BFB and Fig. 3 all 21 SMR–NFB training sessions for the sake of completeness. As stated earlier, due to the operational setting of the military population, the number of completed trainings sessions varied between 11 and 21 per participant. Therefore, starting from training session 11 for the SMR-NFB and 13 for the HRV-BFB groups the bars and lines in Figs. 2 and 3 show average data assessed from a decreasing number of participants. Note, the number of completed training sessions were not different between the groups, $t(24) = 1.38$, $p = .181$. Next, in both Figs. 2 and 3 the average percentage of successful trials and achieved training level for down-regulation (effort; grey bars and red line, respectively) were converted into negative numbers to show the results for up- (relaxation) and down- (effort) regulation for both groups in only two Figures.

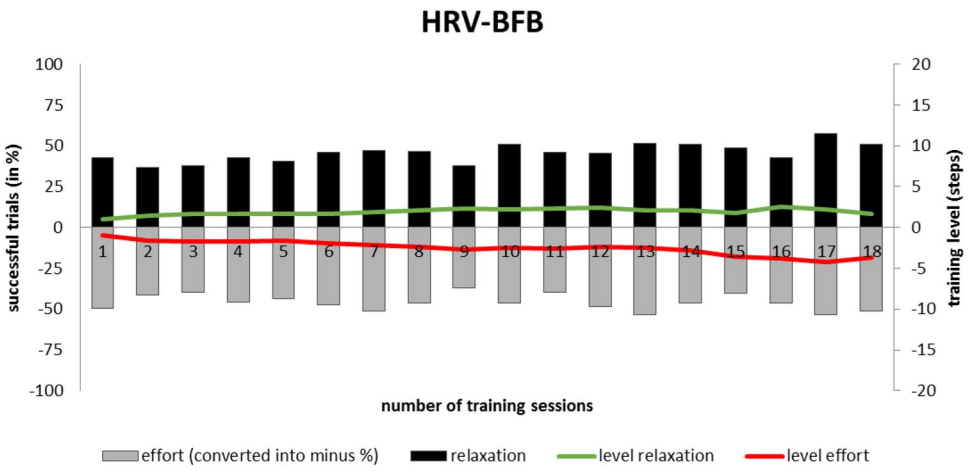

Fig. 2 Training performance in percentage successful trials per training session (1–18) and corresponding achieved training levels in steps for the HRV–BFB group

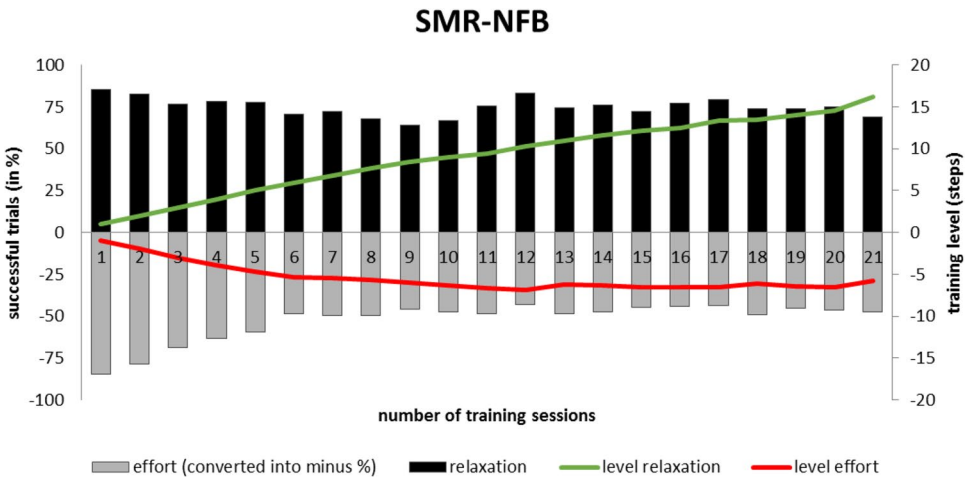

Fig. 3 Training performance in percentage successful trials per training session (1–21) and corresponding achieved training levels in steps for the SMR–NFB group

above or below the given threshold of 50%, respectively. Therefore, participants of this group were also not able to achieve higher or lower training levels during up- and down-regulation. The paired samples T-test on the training effect scores of the HRV–BFB group confirmed no achieved training performance as no significant difference was found between up-and down regulation, $t\,(11) = -.479$, $p = .641$. Participants of the SMR–NFB group completed on average 17 training sessions (min. = 11, max. = 21, median = 18 sessions; Fig. 3). In line with Figs. 2, 3 also shows the average correct achieved trials during up-regulation (i.e., relaxation, in %; black bars) and the average correct achieved trials during down-regulation (i.e., effort, in %; gray bars) of the SMR–NFB group. Also Fig. 3 shows the average maximum obtained training level during up-regulation (relaxation; green line) and the average maximum obtained training level during down-regulation (effort; red line). Thus, Fig. 3 shows that the SMR–NFB group obtained on average continuously correct trails above the 50% threshold during up-regulation (relaxation); hence, participants achieved also higher training levels.

During down-regulation (effort) the SMR–NFB group obtained on average successful trails above the 50% threshold during the first 12 training sessions followed by unvaried percentages of successful trials around the 50% threshold and a steady training level. The difference between up- and down regulation of the SMR–NFB group was significant as revealed by the paired samples T-test on the training effect scores, $t\,(13) = 8.382$, $p < .001$. The mean difference between the training effect scores indicate that participants in the SMR–NFB group were able to up-regulate (relax) much more as their training scores were much higher, $M = 81.21$, $SD = 20.10$, compared to when they tried to down-regulate, $M = 38.93$, $SD = 18.19$ (see also Table 1).

Sleep Spindles

The total nap duration that was analyzed after artifact rejection, ranged between 52 and 66 min and the total number of sleep spindles ranged between 718 and 1076. During the pre-test nap the mean number of spindles per minute was 16,9 ($SD = 2.1$) for SMR and 22.3 ($SD = 3.1$) for HRV. After

Table 1 Mean training effect scores in percentage with standard deviations (SD) of successful training for both up- (relaxation) and down-(effort) regulation during the training sessions and the corresponding mean training level in steps for both groups

Group	Up-regulation (relaxation)				Down-regulation (effort)			
	Training level		Training effect		Training level		Training effect	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
SMR–NFB	7.39 steps	2.00	81.21%	20.10	3.86 steps	.80	38.93%	18.16
HRV–BFB	9.17 steps	2.89	11.84%	8.15	9.79 steps	4.58	13.09%	11.83

the training session the mean number of spindles was 17.4 ($SD = 2.6$) for SRM and 22.8 ($SD = 3.9$) for HRV. The 2 test (pre-, post-) × 2 group (SMR–NFB, HRV–BFB) repeated measures ANOVA on the number of sleep spindles per minute revealed no significant main effect for test, $F(1, 24) = 0.2$, $p = .90$, $\eta_p^2 = 0.06$, no significant main effect for group, $F(1, 24) = 0.8$, $p = .38$, $\eta_p^2 = 0.13$, nor an interaction between test and group ($F(1, 24) = 0.9$, $p > .36$, $\eta_p^2 = 0.14$). In addition, the same ANOVA design on the total number of sleep spindles revealed also no significant main effect for test, $F(1, 24) = 0.6$, $p = .46$, $\eta_p^2 = .11$ no significant effect for group, $F(1, 24) = 2.4$, $p = .14$, $\eta_p^2 = 0.24$ and also no interaction between test and group ($F(1, 24) = 0.5$, $p = .47$, $\eta_p^2 = .10$).

Sleep Diaries and Actigraphy

Participants reported that they on average went to bed at 23:35 h and woke up at 07:16 h during the pre-test week. During the post-test week participants went to bed on average at 23:25 h and woke up at 07:13 h. Mean sleep onset latency was 13 min during the pre-test and 12 min during the post-test period. During the pre-test period participants had a sleep efficiency between 78.63 and 96.48% and during the post-test between 74.23 and 97.89%. Three 2 test (pre-, post-) × 2 group (SMR–NFB, HRV–BFB) repeated measures ANOVA on sleep onset latencies, time of going to bed and wake up time revealed no significant main effects for test, $Fs(1, 19) < .72$, $ps > .41$, no significant main effects for group, $Fs(1, 24) < 1.89$, $ps > .19$, and no interactions between test and group ($Fs(1, 24) < 1.13$, $ps > .26$). If anything, the two 2 test (pre-, post-) × 2 group (SMR–NFB, HRV–BFB) repeated measures ANOVA on 'minutes awake during night' and 'times awake during night' both revealed significant main effects for group, $F(1, 24) = 10.08$, $p = .005$; $\eta_p^2 = .35$, and $F(1, 24) = 4.72$, $p = .04$; $\eta_p^2 = 0.20$, respectively. The effects for test were not significant ($Fs(1, 24) < 0.5$, $ps > .52$), and no interactions between test and group were found ($Fs(1, 24) < 0.73$, $ps > .40$). Post hoc pair-wise comparisons on the significant group effects revealed that participants in the SMR–NFB group reported that they were on average 8 min longer awake when they woke up ($p = .006$), and on average 0.5 times more awake during the night ($p = .043$) compared to the HRV–BFB group. Also, the ANOVA's conducted on actigraphy parameters concerning actual sleep time, immobility percentage and moving minutes revealed no significant main effects for test and group ($Fs(1, 24) < 1.2$, $ps > .43$), nor interactions ($Fs(1, 24) < 0.71$, $ps > .34$). However, a Pearson product-moment correlation conducted in order to assess the relationship between the sleep diaries and actigraphy revealed a positive correlation for the pre-test ($r = .55$, $p = .027$) and post-test ($r = .63$, $p = .009$).

PSQI

During the pre-test, the PSQI median for participants in the SRM–NFB group was 4.0 (range 2.0–8.0) and for the participants in the HRV–BFB group the median was also 4.0 (range 1.0–8.0). In comparison with the post-test, the PSQI median for participants in NFB group was 3.5 (range 1.0–8.0) and for the participant in the BFB group the median was 3.0 (range 2.0–5.0). Non-parametric tests showed no significant effects on the PSQI from pre- to post-test and no significant effects between groups.

GSQS

The analysis showed no statistical significant differences of the subjective quality of sleep from pre- to post-test for the SMR group. Significant improved subjective quality of sleep ratings were found during the post-test compared to the pre-test for the BFB group ($N = 12$, $z = -2.395$; $p = .017$). There were no significant differences between the groups.

SSS Before and After Nap

Significant higher sleepiness scores were found after the nap in comparison with sleepiness scores before the nap, only during the post-test for both the SMR group ($N = 14$, $z = -3.357$; $p = .001$) and BFB group ($N = 12$, $z = -2.489$; $p = .013$). The analysis showed no significant group differences in sleepiness levels for both the pre-test and post-test.

Discussion

In this study, we investigated the feasibility of bidirectional SMR neurofeedback and HRV biofeedback training application and investigated (i) if participants were able to gain control over these parameters, and (ii) to investigate the effect of bidirectional training as opposed to unidirectional SMR training on sleep. Participants were able to learn to control their signals over the course of 10–21 training sessions. The neurofeedback (NFB) group showed that they were better able to up-regulate their SMR signal, than to down regulate their signal. In the biofeedback (BFB) group, this unidirectional preference effect was not found. For the BFB group, it was more difficult to achieve a higher threshold compared to the NFB group, it also seemed that the participants in the BFB group reached a ceiling effect earlier in the training. This might be explained by the differences in threshold step sizes, which, due to their nature of the physiological signals, cannot be made identical. Another explanation for the differences found in the learning curves was discussed by Vernon et al. (2009). They stated that there are natural limits to the increase and decrease of heart and brain activity in a certain frequency, and that it is unlikely that such activity can be increased ad infinitum. As an example, they relate to evidence that has indicated that alpha power NFB training cannot enhance alpha beyond that level seen at rest with eyes closed. Overall, all participants showed an increase in their scores on the feedback task showing that they are all able (to some degree) to learn to consciously control their physiological signals. This study also showed that it was feasible to execute the training in a military setting.

The sleep spindles derived from the EEG during pre- and post-training naps did not show any effect of the bidirectional training on sleep quality nor on sleep spindle density for both groups. Furthermore, analyses of sleep diaries at home, revealed no post-training differences on self-reported sleep variables. There was a minor effect when participants in the NFB group during the post-test 0.5 times woke up more often during the night therefore being awake for 8 min longer than the BFB group. However, no differences were found between the pre- and post-test, which also indicates that participants were not awake more often and/or longer due to training effects.

An improvement on subjective quality of sleep ratings was found on the GSQS after BFB (pre Md = 1.8 and post Md = 1.5). Under normal conditions—an unrestricted and undisturbed night's sleep—a score of 1–2 was found, so these averages stay within a normal range (Meijman et al. 1990). Results of the PSQI questionnaire, showed no significant improvement after BFB/NFB training. Before the training, both groups were, according to the PSQI, good sleepers. This may explain the lack of effect of the feedback training on sleep quality. For the post-training nap, higher sleepiness scores were found for both groups after the nap in comparison with sleepiness scores before the nap. This effect could be contributed to sleep inertia.

The present study has various strengths and limitations. The automated procedure for calculating the sleep spindle density could have limitations, since sleep spindles were not scored by a certified polysomnographer and the number of sleep spindle reported seem to be relatively high. On the other hand, this method has been used and published before, and it was identical for both groups. If expected systematic changes had occurred, they would become prevalent because of the within-subject comparison. Concerning the statistical power of the results, the sample size is similar in a comparable study (Cortoos et al. 2010), and even larger compared to another study with a similar design (Hoedlmoser et al. 2008). A power analyses was conducted on the effect size derived from Hoedlmoser study (2008). These analyses revealed a minimal sample size of 10 participants per group for the current experiment. Although, the current study had a higher sample size, the selected group of healthy participants were not sensitive for the treatment because they were good sleepers, indicated by low effect sizes of the sleep spindle data. Furthermore, the current study used on average 15 and 17 training sessions, while a number of comparable unidirectional studies only used ten trainings sessions to indicate effects of NFB (Hoedlmoser et al. 2008; Gruzelier et al. 2006; Gruzelier 2014; Schabus et al. 2014). This effort was specifically taken to ensure the bidirectional feedback training was long enough to be effective, in this study the bidirectional training was a new aspect. This could be the reason that no effects were observed on sleep. However, in earlier studies that applied bidirectional protocols, it was shown that participants obtained a greater degree of conscious control (Ancoli and Kamiya 1978; Vernon et al. 2009). Another addition within the current study was to use a ranking top ten list with the purpose to motivate the participants. Due to the ranking list, and the announcement of top performers frequently, in combination with the competitive spirit among the participants, the participants stayed motivated and involved throughout the training sessions.

For future studies, a next step in the usage of bidirectional training could focus on selection of a more sensitive group within the population e.g. with sleep disorders. Also, in the NFB group there was a tendency for less drop outs and more learning effects during the trial, making it more suitable for a self-paced intervention training. Participants in the NFB group were more motivated to train because they were aware of their improvements when reaching a higher threshold, which in fact they did achieve more often than the BFB group. Continuous developments in the hardware of physiological measurements could also decrease the intrusiveness of this training on daily activities e.g. dry electrodes would make it more acceptable

Table 2 Sleep quality descriptives

	Pre-test				Post-test			
	SMR–NFB		HRV–BFB		SMR–NFB		HRV–BFB	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Time to bed (hh:mm)	23:27	00:54	23:41	00:34	23:13	00:51	23:35	00:47
Wake up time (hh:mm)	07:14	00:30	07:19	00:44	07:23	00:48	07:04	00:22
Sleep onset latency (min)	16.4	16.8	10.3	6.5	16.2	14.3	9.1	5.6
Sleep efficiency (%)	89.02	5.95	90.48	3.61	87.60	6.92	92.22	3.51
Times awake	.86	.65	.47	.42	.89	.91	.25	.49
Minutes awake (min)	7.2	9.3	3.1	4.6	10.4	16.2	2.5	2.9
GSQS sleep diary (score)	1.93	1.24	1.79	1.30	2.19	1.72	1.49	.84

Table 3 Median scores (MdS) and ranges (minimum and maximum value) of PSQI, GSQS, SSS before sleep session and SSS after sleep session for each group and time of measurement

	Pre-test				Post-test			
	SMR–NFB		HRV–BFB		SMR–NFB		HRV–BFB	
	MdS	Range	MdS	Range	MdS	Range	MdS	Range
PSQI	4.0	2.0–8.0	4.0	1.0–9.0	3.5	1.0–8.0	4.0	2.0–5.0
GSQS	3.0	0.0–8.0	2.0	0.0–4.0	3.0	0.0–9.0	4.0	1.0–5.0
SSS before sleep session	3.0	1.0–4.0	3.0	1.0–4.0	2.0	1.0–3.0	2.0	1.0–3.0
SSS after sleep session	3.0	2.0–4.0	3.0	2.0–4.0	3.0	1.0–4.0	3.0	2.0–4.0

to train during working hours. Finally, further research should aim to make feedback training more context specific and attractive; the repetitive nature of the training that is needed to achieve results can also become quite boring (Tables 2, 3).

Summarizing, our findings illustrate that bidirectional SMR training is feasible i.e. high number of training repetitions and that extensive training of SMR was successful i.e. revealed training effects: participants were able to actively control their SMR frequency bidirectionally. However, opposed to studies using unidirectional uptraining of SMR, bidirectional SMR neurofeedback had no effects on sleep in this study, demonstrating that bidirectional training of SMR had no clinical effects. Possibly, the bidirectional training does not result in the same neuroplastic changes seen with unidirectional training, due to the constant changing contingencies (i.e. up- vs. down required), which can be desirable in BCI applications.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

References

Ancoli, S., & Kamiya, J. (1978). Methodological issues in alpha biofeedback training. *Biofeedback and Self-Regulation, 3*, 155–183.

Ancoli-Israel, S., Cole, R., Alessi, C., Chambers, M., Moorcroft, M., & Pollak, C. P. (2003). The role of actigraphy in the study of sleep and circadian rhythms. *Sleep, 26*, 342–392.

Arns, M., de Ridder, S., Strehl, U., Breteler, M., & Coenen, A. (2009). Efficacy of neurofeedback treatment in ADHD: The effects on inattention, impulsivity and hyperactivity: A meta-analysis. *Clinical EEG and Neuroscience, 40*, 180–189.

Arns, M., Feddema, I., & Kenemans, J. L. (2014). Differential effects of theta/beta and SMR neurofeedback in ADHD on sleep onset latency. *Frontiers in Human Neuroscience, 8*, 1019.

Arns, M., Heinrich, H., Ros, T., Rothenberger, A., & Strehl, U. (2015). Editorial: Neurofeedback in ADHD. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/fnhum.2015.00602.

Arns, M., & Kenemans, J. L. (2013). Neurofeedback in ADHD and insomnia: Vigilance stabilization through sleep spindles and circadian networks. *Neuroscience and Biobehavioral Reviews, 44*, 183–194.

Bianchi, G., & Sorrentino, R. (2007). *Electronic filter simulation & design*. New York: McGraw-Hill Professional, pp. 17–20.

Binsch, O., Banko, K., Veenstra, B. J., & Valk, P. J. L. (2015). Examining the relationship between mental, physical and organizational factors associated with attrition during maritime forces training. *Journal of Strength & Conditioning Research, 29*, 187–191.

Birbaumer, N., & Cohen, L. (2007). Brain-computer-interfaces (BCI): Communication and restoration of movement in paralysis. *Journal of Physiology, 579*, 621–636.

Birbaumer, N., Ghanayim, N., Hinterberger, T., Iversen, I., Kotchoubey, B., Kübler, A., et al. (1999). A spelling device for the paralysed. *Nature, 398*, 297–298.

Buysse, D. J., Reynolds, C. F. III, Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Psychiatry Research, 28*, 193–213. https://doi.org/10.1016/0165-1781(89)90047-4.

Cortoos, A., De Valck, E., Arns, M., Breteler, M. H., & Cluydts, R. (2010). An exploratory study on the effects of tele-neurofeedback and tele-biofeedback on objective and subjective sleep in patients with primary insomnia. *Applied Psychophysiology and Biofeedback, 35*, 125–134.

Del Pozo, J. M., Gevirtz, R. N., Scher, B., & Guarneria, E. (2004). Biofeedback treatment increases heart rate variability in patients with known coronary artery disease. *American Heart Journal, 147*, G1-G6.

Egner, T., & Gruzelier, J. H. (2001). Learned self-regulation of EEG frequency components affects attention and event-related brain potentials in humans. *NeuroReport, 12*, 4155–4159. https://doi.org/10.1097/00001756-200112210-00058.

Gruzelier, J. H. (2014). EEG-neurofeedback for optimising performance. In: A review of cognitive and affective outcome in healthy participants. *Neuroscience and Biobehavioral Reviews, 44*, 124–141.

Gruzelier, J. H., Egner, T., & Vernon, D. (2006). Validating the efficacy of neurofeedback for optimising performance. *Progress in Brain Research, 159*, 421–431.

Hammond, D. C. (2007). Neurofeedback for the enhancement of athletic performance and physical balance. *The Journal of the American Board of Sport Psychology, 1*, 1–9.

Hansen, A. L., Johnsen, B. H., & Thayer, J. F. (2009). Relationship between heart rate variability and cognitive function during threat of shock. *Anxiety, Stress, & Coping, 22*, 77–89. https://doi.org/10.1080/10615800802272251.

Hassett, A. L., Radvanski, D. C., Vaschillo, E. G., Vaschillo, B., Sigal, L. H., & Karavidas, M. K. (2007). A pilot study of heart rate variability (HRV) biofeedback in patients with fibromyalgia. *Applied Psychophysiology and Biofeedback, 32*, 1–10. https://doi.org/10.1007/s10484-006-9028-0.

Hoddes, E., Zarcone, V., Smythe, H., Philips, R., & Dement, W. C. (1973). Quantification of sleepiness: A new approach. *Psychophysiology, 10*, 431–436. https://doi.org/10.1111/j.1469-8986.1973.tb00801.x.

Hoedlmoser, K., Pecherstorfer, T., Gruber, G., Anderer, P., Doppelmayr, M., Klimesch, W., & Schabus, M. (2008). Instrumental conditioning of human sensorimotor rhythm (12–15 hz) and its impact on sleep as well as declarative learning. *Sleep, 31*, 1401–1408.

Kerkhof, G. A., Brouwer, A., Rijsman, R. M., Schimsheimer, R. J., & van Kasteel, V. (2013). Holland sleep disorders questionnaire: A new sleep disorders questionnaire based on the international classification of sleep disorders-2. *Journal of Sleep Research, 22*, 104–107. https://doi.org/10.1111/j.1365-2869.2012.01041.x.

Kinnear, P. R., & Gray, C. D. (2000). *SPSS for Windows made simple*. Hove: Psychology Press.

Kleinnijenhuis, M., Arns, M. W., Spronk, D. B., Breteler, M. H. M., & Duysens, J. E. J. (2008). Comparison of discrete-trial based SMR and SCP training and the interrelationship between SCP and SMR networks: Implications for brain-computer interfaces and neurofeedback. *Journal of Neurotherapy, 11*, 19–35.

Kober, S. E., Witte, M., Ninaus, M., Neuper, C., & Wood, G. (2013). Learning to modulate one's own brain activity: The effect of spontaneous mental strategies. *Frontiers in Human Neuroscience, 7*, 695. doi:https://doi.org/10.3389/fnhum.2013.00695.

Lehrer, P. M., Vaschillo, E., & Vaschillo, B. (2000). Resonant frequency biofeedback training to increase cardiac variability: Rationale and manual for training. *Applied Psychophysiology and Biofeedback, 25*, 177–191. https://doi.org/10.1023/A:1009554825745.

Lehrer, P. M., Vaschillo, E., Vaschillo, B., Lu, S. E., Eckberg, D. L., Edelberg, R., Shih, W. J., Lin, Y., Kuusela, T. A., Tahvanainen, K. U., & Hamer, R. M. (2003). Heart rate variability biofeedback increases baroreflex gain and peak expiratory flow. *Psychosomatic Medicine, 65*, 796–805.

Lofthouse, N., Arnold, L. E., Hersch, S., Hurt, E., & DeBeus, R. (2012). A review of neu-rofeedback treatment for pediatric ADHD. *Journal of Attention Disorders, 16*, 351–372.

Meijman, T. F., Thunnissen, M. J., & De Vries-Griever, A. G. H. (1990). The after-effects of a prolonged period of day-sleep on subjective sleep quality. *Work and Stress, 4*, 65–70.

Monastra, V. J., Lynn, S., Linden, M., Lubar, J. F., Gruzelier, J., & LaVaque, T. J. (2005). Electroencephalograpic biofeedback in the treatment of attention-deficit/hyperactivity disorder. *Applied Psychophysiology & Biofeedback, 30*, 95–111.

Morin, C. M., LeBlance, M., Daley, M., Gregoire, J. P., & Merette, C. (2006). Epidemiology of insomnia: Prevalence, self-help treatments, consultations, and determinants of help-seeking behaviors. *Sleep Medicine, 7*, 123–130. https://doi.org/10.1016/j.sleep.2005.08.008.

Mulder-Hajonides van der Meulen W. R. E. H., Wijnberg, J. R., Hollanders, J. J., DeDiana, I., & Hoofdakker, R. (1980). Measurement of subjective sleep quality. *Fifth European Congress on Sleep Research*, Amsterdam.

Peterson, A. L., Goodie, M. J. L., Satterfield, W. A., & Brim, W. L. (2008). Sleep disturbance during military deployment. *Military Medicine, 173*, 230–235.

Piantoni, G., Poil, S.-S., Linkenkaer-Hansen, K., Verweij, I. M., Ramautar, J. R., Van Someren, E. J. W., & Van Der Werf, Y. D. (2013). Individual differences in white matter diffusion affect sleep oscillations. *Journal of Neuroscience, 33*, 227–233.

Royer, A.,S., Doud, A.,J., Rose, M.,L., & He, B. (2010). EEG control of a virtual helicopter in 3-dimensional space using intelligent control strategies. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 18*, 581–589.

Ruehland, W. R., O'Donoghue, F. J., Pierce, R. J., Thornton, A. T., Singh, P., Copland, J. M., Stevens, B., & Rochford, P. D. (2011). The 2007 AASM recommendations for EEG electrode placement in polysomnography: Impact on sleep and cortical arousal scoring. *Sleep, 1*, 34, 73–81.

Schabus, M., Heib, D. P. J., Lechinger, J., Griessenberger, H., Klimesch, W., Pawlizki, A., Kunz, A. B., Sterman, B. M., & Hoedlmoser, K. (2014). Enhancing sleep quality and memory in insomnia using instrumental sensorimotor rhythm conditioning. *Biological Psychology, 95*, 126–134.

Spronk, D., Kleinnijenhuis, M., Luijtelaar, G., & Arns, M. (2010). Discrete-trial SCP and GSR training and the interrelationship between central and peripheral arousal. *Journal of Neurotherapy, 14*, 217–228.

Sterman, M. B. (2000). Basic concepts and clinical findings in the treatment of seizure disorders with EEG operant conditioning. *Clinical EEG (Electroencephalography), 31*, 45–55.

Sterman, M. B., & Egner, T. (2006). Foundation and practice of neurofeedback for the treatment of epilepsy. *Applied Psychophysiology and Biofeedback, 31*, 21–35.

Sterman, M. B., Wyrwicka, W., & Roth, S. R. (1969). Electrophysiological correlates andneural substrates of alimentary behaviour in the cat. *Annals of the New York Academy of Science, 157*, 723–739.

Tan, G., Thornby, J., Hammond, D. C., Strehl, U., Canady, B., Arnemann, K., & Kaiser, D. A. (2009). Meta-analysis of EEG biofeedback in treating epilepsy. *Clinical EEG and Neuroscience, 40*, 173–173.

Vernon, D., Dempster, T., Bazanova, O., Rutterford, N., Pasqualini, M., & Andersen, S. (2009). Alpha neurofeedback training for performance enhancement: Reviewing the methodology. *Journal of Neurotherapy, 13*, 214–227.

Vernon, D., Egner, T., Cooper, N., Compton, T., Neilands, C., Sheri, A., & Gruzelier, J. (2003). The effect of training distinct neurofeedback protocols onaspects of cognitive performance. *International Journal of Psychophysiology, 47*, 75–86.

Wolpaw, J. R., & McFarland, D. J. (2004). Control of a two-dimensional movement signal by a noninvasive brain-computer interface in humans. *Proceedings of the National Academy of Sciences of the U. S. A. 101*, 17849–17854.

Yuan, H., & He, B. (2014). Brain-computer interfaces using sensorimotor rhythms: Current state and future perspectives. *IEEE Transactions on Biomedical Engineering, 61*, 1425–1435.

Zucker, T. L., Samuelson, K. W., Muench, F., Greenberg, M. A., & Gevirtz, R. N. (2009). The effects of respiratory sinus arrhythmia biofeedback on heart rate variability and posttraumatic stress disorder symptoms: A pilot study. *Applied Psychophysiology & Biofeedback, 34*, 135–143.