Ecological validity of neurofeedback: modulation of slow wave EEG enhances musical performance

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Biofeedback-assisted modulation of electrocortical activity has been established to have intrinsic clinical benefits and has been shown to improve cognitive performance in healthy humans. In order to further investigate the pedagogic relevance of electroencephalograph (EEG) biofeedback (neurofeedback) for enhancing normal function, a series of investigations assessed the training's impact on an ecologically valid real-life behavioural performance measure: music performance under stressful conditions in conservatoire students. In a pilot study, single-blind expert ratings documented improvements in musical performance in a student group that received training on attention and relaxation related neurofeedback protocols, and improvements were highly correlated with learning to progressively raise theta (5–8 Hz) over alpha (8–11 Hz) band amplitudes. These findings were replicated in a second experiment where an alpha/theta training group displayed significant performance enhancement not found with other neurofeedback training protocols or in alternative interventions, including the widely applied Alexander technique. *NeuroReport* 14:1221–1224 © 2003 Lippincott Williams & Wilkins.

Key words: Alpha/theta training; EEG biofeedback (neurofeedback); Music performance; Theta activity

INTRODUCTION

Learned modulation of electrocortical activity has been used as a means of brain–computer communication [1] as well as for intrinsic clinical benefits associated with the enhancement and/or suppression of particular bandwidths of the electroencephalograph (EEG). For instance, the control of epileptic motor seizures through learned enhancement of the 12–15 Hz sensorimotor rhythm (SMR) over sensorimotor cortex, and through modulation of slow cortical potentials (SCPs), has been established in controlled studies [2,3]. Long-standing claims that hyperactivity disorder (HD) [4] and attention deficit hyperactivity disorder (ADHD) [5] respond to the attention-enhancing efficacy of training SMR along with other AC frequency components (such as 15–18 Hz; beta1) have recently been supported by comparisons with standard treatment with psychostimulants [6,7], and with waiting-list control subjects [8]. A further neurofeedback application, and subject of this report, has aimed to increase theta (5–8 Hz) over alpha (8–11 Hz) activity levels during a wakeful eyes-closed condition for the purpose of relaxation training, based on the association between theta activity and meditative states [9] as well as wakefulness-to-sleep transition [10]. This alpha/theta (a/t) training protocol has found promising applications as a complementary therapeutic tool in post-traumatic stress disorder (PTSD) [11] and alcoholism [12].

In the context of researching neurofeedback effects in healthy subjects, we have recently demonstrated that learned modulation of SMR and beta1 components can significantly enhance attention on behavioural and electrocortical performance measures [13,14], and that SMR training can enhance semantic memory performance [15]. When addressing the enhancement of normal function, however, statistically significant improvements on laboratory measures do not necessarily translate into any perceivable or relevant performance changes in real life tasks, nor do any such improvements have to be of consequence to mental and physical health. In order to establish whether neurofeedback protocols that target attention and relaxation processes could benefit healthy subjects to a meaningful degree on ecologically valid behavioural measures, we devised two studies investigating musical performance parameters in conservatoire students, as evaluated by expert judges in single-blind assessments. In experiment 1, a group of students was trained on the SMR, beta1, and a/t protocols and performance changes were compared to a no-training control group and a group receiving additional interventions. The differential contributions of the three neurofeedback protocols to music performance were assessed by correlating feedback-learning indices with performance change. In experiment 2, different neurofeedback protocols were trained in separate groups and performance changes were contrasted with comparison groups undergoing alternative interventions.

MATERIALS AND METHODS

In the first experiment, 36 students (22 females and 14 males; mean (±s.d.) age 20.9±1.36 years), and in the second study 61 students (43 females and 18 males, mean age 23.1±2.21 years), both from the Royal College of Music (London), volunteered for participation. Participants gave their informed consent, and the series of investigations received ethical approval from the Riverside Research Ethics Committee (ref. RREC 2224). In experiment 1, a group of students ($n=22$) was trained on two neurofeedback protocols (SMR and beta1) commonly used as tools for the enhancement of attention, and subsequent to this on a deep relaxation alpha/theta (a/t) protocol. A random subsample of this group ($n=12$) was additionally engaged in a regime of weekly physical exercise [16] and a mental skills training program derived from applications in sports psychology [17]. A third group consisted of a scholastic grade- and age-matched no-training control group ($n=14$). In experiment 2, a different cohort of students were randomly allocated to one of six training groups: alpha/theta neurofeedback ($n=8$), beta1 neurofeedback ($n=9$), SMR neurofeedback ($n=9$), physical exercise ($n=16$), mental skills training ($n=9$), or a group that engaged in Alexander technique training ($n=10$). The Alexander technique refers to a system of kinaesthetic education aimed at avoiding excessive postural tension, and constitutes the most widely practised behavioural training in professional orchestral musicians [18].

Before and subsequent to the training process, the students in both studies were assessed on two musical pieces of their own choice (approximate length 15 min), given in front of a panel of assessors internal to the Royal College of Music. The performances were video-taped, placed in a random order, and then assessed on 10-point scales adapted from a standard set of music performance evaluation criteria of the Associated Board of the Royal Schools of Music [19] (Table 1) by two expert judges in the first experiment, and three in the second. There were four different judges in all. These judges were external to the college and therefore did not know the students, and were blind as to the students' group membership and the order of performances. Prior to performances, participants were asked to complete Spielberger's state-anxiety inventory [20]. Unfortunately not all students complied with filling out the questionnaire, as some claimed it would make them more anxious.

Table 1. Correlations between musical performance change and a/t learning.

Overall quality	r = 0.47	$p=0.038$
Perceived instrumental competence	r = 0.5	$p=0.029$
Level of technical security	r = 0.39	$p=0.086$
Rhythmic accuracy	r = 0.65	$p=0.003$
Tonal quality and spectrum	r = 0.39	$p=0.14$
Musicality/musical understanding	r = 0.54	$p=0.017$
Stylistic accuracy	r = 0.58	$p=0.007$
Interpretative imagination	r = 0.48	$p=0.037$
Expressive range	r = 0.53	$p=0.016$
Communication	r = 0.55	$p=0.013$
Deportment	r = 0.45	$p=0.052$
Communication of emotional commitment and conviction	r = 0.51	$p=0021$
Ability to cope with emotional stress	r = 0.44	$p=0.052$

Music performance evaluation scales and Pearson product-moment correlation coefficients between change scores in music performance evaluation and the alpha/theta learning coefficient (a/t learning) for all subjects participating in neurofeedback training in experiment 1. Major evaluation categories are in bold type, with their associated sub-scales following below.

EEG biofeedback training in both studies was accomplished with a NeuroCybernetics (Encino, CA) EEG Biofeedback System and ProComp (Thought Technology Ltd; Montreal, Quebec) differential amplifier. Signal was acquired at 256 Hz, A/D converted and band-filtered to extract the beta1 (15–18 Hz), SMR (12–15 Hz), theta (4–7 Hz), and high beta (22–30 Hz) components. Band amplitude values were transformed online into audio-visual feedback representations. Operant contingencies determined that reward (points displayed on screen) was contingent upon increments in either beta1 (in the beta1 protocol) or SMR (in the SMR protocol) activity without concurrent rises in theta and high beta, relative to a 2 min pre-feedback baseline measure. The participants were instructed to let the continuous feedback guide them into maximising their point scores. In the a/t protocol, participants relaxed with their eyes closed and listened via headphones to auditory feedback representations of ongoing changes in relative theta (5–8 Hz) and alpha (8–11 Hz) power with respect to an eyes-closed relaxed 2 min baseline. The participants were instructed to relax deeply in order to achieve an increase in the amount of theta sound representation, while avoiding falling asleep. The operant contingencies of a/t feedback were thus aimed at inducing progressively high theta-to-alpha ratios under waking eyes-closed conditions.

An active scalp electrode was placed at C3 for Beta1, at C4 for SMR, and at PZ for a/t training (all according to the standard 10-20 system) with the reference electrode placed on ipsilateral, and the ground electrode on the contralateral earlobe, respectively. Impedance was kept below 5 kΩ, and artefact rejection thresholds were set individually for each participant so as to interrupt feedback during eye and body movements that caused gross EEG fluctuations. In the first experiment participants took part in 10 twice-weekly training sessions of SMR/beta1 feedback over the course of 5 weeks. Each session consisted of training both the SMR and the beta1 protocol for 15 min each, consisting of five 170 s feedback periods with 10 s breaks in between them. This training phase was followed by ten 15 min sessions of a/t training within a 5 week period. In the second experiment participants took part in ten 15 min sessions of their respective training protocols, carried out over the course of 6–8 weeks. The Alexander technique group engaged in fifteen 30 min sessions of one-to-one training, carried out weekly, and students participating in the physical exercise and mental skills groups had a similar amount of involvement.

In experiment 1, in order to tease apart the relations between individual neurofeedback protocols and changes in performance, learning-indices for each protocol were calculated. Relative success at SMR and beta1 feedback learning was defined by the number of 3 min periods within each session that participants managed to raise mean values in both absolute and relative power in the target band above the mean values of the preceding period. Relative power was defined as the mean power in the target band divided by the sum of mean power values in the target and both inhibit bands for a given 3 min period. These parameters have previously been shown to predict relative change in laboratory dependent measures [13]. Relative success at learning the alpha/theta protocol was defined by an a/t learning coefficient, whereby the success at elevating theta-to-alpha amplitude ratios within sessions was examined across sessions. This was expressed by the slope of regression across sessions of the correlation between t/a amplitude ratios and the number of 3 min periods within each session.

RESULTS

Experiment 1: While a 3 × 2 (training group × time of performance) mixed-effects ANOVA revealed no significant omnibus effects, exploratory within-group analyses documented that participants who had received only the neurofeedback training were judged to have improved their performance while no improvements were found in the other two groups, all of whom began with comparable level of performance. The neurofeedback group had marginally improved in particular on the criteria of overall quality ($t = -2.0$, $p < 0.05$), rhythmic accuracy ($t = -1.8$, $p = 0.05$), emotional commitment and conviction ($t = -2.8$, $p < 0.05$), and deportment with instrument on stage ($t = -1.9$, $p = 0.05$; one-tailed *p*-values). We then correlated neurofeedback learning-indices with changes in performance ratings for all 22 subjects (excluding the no-training control group), and found that learning success on the a/t protocol correlated significantly ($p = 0.007$–0.052) with improvements on 10 out of 12 of the musical evaluation criteria (Table 1). Neither SMR nor beta1 learning co-varied significantly with performance change. The improvements could not be attributed to anxiety, for a main effect on pre-performance anxiety levels showed that all three groups reported a similar reduction in anxiety between performances ($F(1,23) = 4.65$, $p < 0.05$). Pre-performance anxiety was not significantly correlated with any of the neurofeedback learning indices, nor with actual quality of performance.

Experiment 2: In support of the findings in experiment 1, planned comparisons showed that the a/t group displayed significant improvements, while neither the beta1 nor the SMR group exhibited any post-training performance changes. Similarly, students from the Alexander Technique, physical exercise, and mental skills training groups showed no post-training changes. In the a/t group, evaluation scores for musicality/musical understanding ($t(df = 7) = -3.23$, $p < 0.01$), stylistic accuracy ($t(df = 7) = -3.1$, $p < 0.01$), interpretative imagination ($t(df = 7) = -3.21$, $p < 0.01$), and overall quality ($t(df) = 7) = -1.76$, $p = 06$; one-tailed p values) were all improved (see Fig. 1). These increments represent average a/t group improvements between 13.5% and 17%, with a mean improvement rate of 12% across all evaluation scales. No significant differences in initial performance scores were evident between groups. As in experiment 1, a main effect of time on self-reported pre-performance anxiety was found, as all groups tended

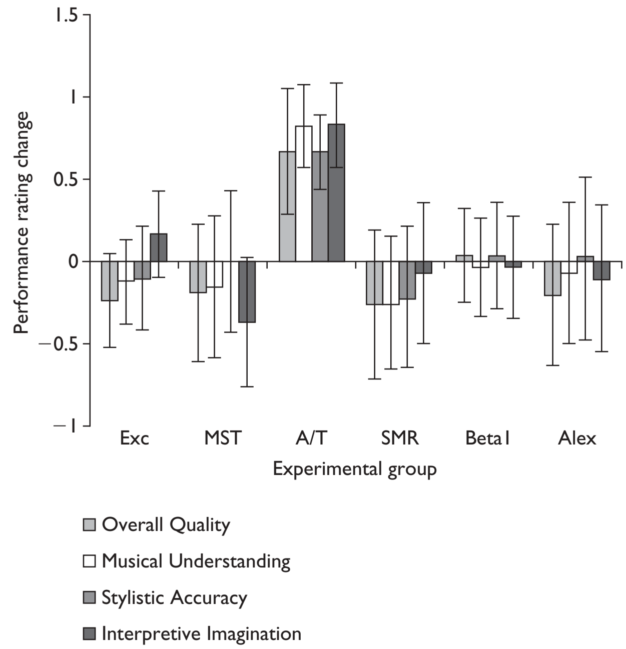

Fig. 1. Neurofeedback and music performance. Mean change scores (± s.e.m.) for the physical exercise (Exc), mental skills training (MST), alpha/theta (A/T), SMR (SMR), beta1 (Beta1), and Alexander technique (Alex) groups on a 10-point rating scale of musical evaluation criteria. The a/t group displays musical improvements in overall quality (+ 14.4%), musical understanding (+16.4%), stylistic accuracy (+13.5 %), and interpretative imagination (+17%).

to report less anxiety prior to the post-training performance ($F(1,44) = 5.14$, $p < 0.05$), with the beta1 group displaying a significant within-group reduction ($t(df) = 7) = 3.04$, $p < 0.05$).

DISCUSSION

These data represent the first evidence for neurofeedback training's beneficial impact on non-laboratory measures in a non-clinical population and, to the authors' knowledge, the first successful instance of applying a neuroscientific tool to the performing arts. The results demonstrated that slow wave neurofeedback training benefited musical performance under stressful conditions in healthy volunteers. In experiment 1, students who had participated in a training program of beta1, SMR, and alpha/theta neurofeedback showed marginal musical performance improvements not evident in a no-training control group, nor in a group that had engaged in additional mental skills and physical exercise training regimes. Across all students that engaged in neurofeedback training, levels of musical improvement co-varied significantly with learning to increase theta over alpha amplitudes in an eyes-closed resting state, while learning on the attention-related beta1 and SMR protocols were unrelated to performance changes. In experiment 2, these findings were corroborated in an independent-groups design. In line with expectations generated from study 1, participants in the a/t training group improved significantly on a number of performance criteria, while no changes were evident in the beta1, SMR, physical exercise, mental skills, and Alexander technique groups.

The two studies taken together lend credence to the suggestion that a/t neurofeedback enhances music performance to a degree of potential professional significance. It is noteworthy that it was particularly attributes of artistic expression (belonging to the evaluation category of musicality/musical understanding), as opposed to technical aspects, which were elevated by a/t training. At face value, our findings would suggest that repeated facilitation of a state of deep relaxation benefits artistic expression. While one prime mediator candidate for such effects would be reduced pre-performance anxiety, state anxiety self-report measures collected prior to performances showed no group $\times$ performance interaction effects. However, that the effects of a/t training may not necessarily be reflected in self-reported phenomenology has also been shown in a recent study where appraisal of subjective arousal states did not differ between an accurate feedback and a mock feedback condition, even though significantly different EEG alpha/theta signatures were observed [21]. In support of the notion that a/t training effects may nevertheless be mediated by modified arousal levels, we have found that a/t training's impact on spectral EEG topography is characterised by a reduction in fast beta band activity in frontal scalp regions [22]. Excessive frontal beta activity has been linked to anxiety [23] and post-traumatic stress disorder (PTSD) [24], and can be observed in healthy subjects under stress during induced tonic pain [25].

It should be noted that theta activity as such has been implicated in a number of cognitive and affective states ostensibly unrelated to general deactivation or to sleep stages. Frontocentral theta activity has been associated with states of focused attention such as working memory tasks [26] and meditative concentration [27]. With respect to affective aspects, frontal theta activity has been associated with feelings of well-being [27], relief from anxiety [28] and reduced sympathetic autonomic activation [29].

In light of these associations, a number of possible alternative mediators for the impact of a/t training on music performance arise for future investigation. Irrespective of the precise mechanisms underlying the training effects however, our results have important implications with respect to the performer's psychological and physical well-being. The significant enhancement of performance skills may in the long run alleviate excessive worry about performing which is the most commonly cited impediment to musicians' successful careers [30] and contributes greatly to the performers' general career stress [31].

CONCLUSION

Data from two successive experiments were reported that document significant enhancement of music performance quality by means of an EEG neurofeedback protocol which repeatedly facilitates a wakeful eyes-closed state characterised by the progressive rise of theta over alpha band amplitudes. These findings underline the potential relevance of neurofeedback assisted EEG band modulation to a wide scope of optimal performance applications within and beyond the clinical realm.

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