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Critical validation studies of neurofeedback

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In the pediatric field, the most widespread application of electroencephalographic (EEG) biofeedback (neurofeedback) is for the treatment of attention deficit hyperactivity disorder (ADHD). Work began with the pioneering studies of Lubar et al [1–3] with the hypothesis that voluntary production of the sensory motor rhythm (SMR) required a child to stabilize or suppress motor activity while remaining attentive. The effect has been reduction of negative hyperactive/impulsive behaviors with simultaneous improvement of attentional capabilities.

Subsequently, the application of beta rhythm and SMR protocols to attentional disorders evolved into the more widespread applications within the field of neurofeedback, especially within the domain of clinical disorders. Only a few controlled studies have demonstrated various beneficial effects for ADHD [4–9] let alone for other applications. Rossiter and LaVaque [9] and Fuchs et al [4] reported that beta/SMR neurofeedback led to significant improvements in children's performance on laboratory attention tests and on observational ratings of behavior by parents and teachers. These improvements were at comparable levels to those observed with stimulant medication. Monastra et al [7] showed that an extensive course of beta band training in addition to standard pharmacologic treatment can lead to lasting benefits, even after medication has

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been suspended. For a full report of the methodologic issues of these and other studies, see the article by Monastra elsewhere in this issue [8]. Currently, insufficient evidence exists to support conclusively the effectiveness of EEG biofeedback for children with ADHD because of the lack of large scale randomized controlled studies.

Studies to date have provided evidence for neurofeedback's potential for enhancing attention in clinical groups and improving attentional abilities in healthy people. The work at Imperial College London has provided evidence of validation. These attempts with healthy subjects are reviewed, and although there is a special focus is on processes of relevance to ADHD, the validation is extended to alpha-theta training, which has applications to other domains. First, however, what was the theory behind the therapeutic initiative for ADHD?

Empirical and theoretical underpinnings of neurofeedback for attention deficit hyperactivity disorder

Children and adults with ADHD have been trained to enhance two main frequency bands: the SMR (12–15 Hz) and low beta, or beta 1 (15–20 Hz). Typically these are combined with inhibiting slow wave theta activity (4–7 Hz). Theta has well-established associations with drowsiness, inattention, and hypnogogic experiences, as detailed later. Such strategies chime with two sources of evidence [10]. First, there are important relations between the behavioral characteristics of ADHD (eg, inattention and overactivity) and reduced SMR and beta frequencies on the one hand and enhanced slow wave theta activity on the other. Second, an excess of theta and relative lack of SMR and beta have been disclosed in the EEG recordings of children with ADHD. The second of these issues is dealt with first, followed by the behavioral and cognitive significance of the EEG rhythms and serves to introduce the cognitive studies in healthy subjects.

Electroencephalogram and attention deficit hyperactivity disorder

There is ample evidence of an excess of theta and a lack of beta frequencies in children with ADHD. To consider some of the evidence, Mann et al [11] recorded an increase in absolute amplitude in the theta band during a resting condition, predominantly in the frontal regions, in comparison with controls. In tasks that required sustained attention, there was a greater increase in theta activity in frontal and central regions and a decrease in beta activity in posterior and temporal regions. This excess in the slow wave activity of children with ADHD, particularly in the frontal midline regions, has proved to be robust and replicable [12–15].

Support for beta reductions and theta elevations has been forthcoming from studies of Clarke et al [14,16], who showed less posterior beta and alpha in ADHD children controls. Further clarification was provided once subtypes of

ADHD, such as inattentive (ADHDin), hyperactive (ADHDhyp) and combined (ADHDcom) types, were taken into account. In a group of 60 children aged 8 to 12 years in an eyes-closed resting paradigm, Clarke et al found that the ADHDcom group exhibited greater levels of absolute delta and theta and lower levels of absolute beta compared with the ADHDin group, which was closer to the controls [14]. In a larger replication sample [16], measures from the frontal region showed qualitative differences between two ADHD groups, with greater absolute and relative theta and theta/alpha ratios in the frontal region compared with the central region for the ADHDcom group relative to the ADHDin group, which was closer to the controls.

Monastra et al [15] examined the EEG of 482 individuals aged 6 to 30 years, recording from a single channel at the vertex (Cz) while the participants completed reading, listening, and drawing tasks. All the persons classified as having ADHD exhibited higher ratios of theta-beta power; the ratios were even greater for the younger participants. The theta-beta power ratios served as a basis for differentiating between participants with ADHD and nonclinical control participants. The predictive power of the quantitative EEG was high, with more than 85% consistency between classifications derived from the quantitative EEG index and measures of behavior and academic performance. More recently this was replicated with a group of 129 individuals aged 6 to 20 years [17]. Monastra et al [18] also conducted a direct comparison of the classification agreement of the EEG compared with behavioral and continuous performance task (CPT) measures by examining 285 individuals aged 6 to 20 years. They found high classification agreement of 83% between the EEG and the behavioral measure from the attention deficit disorders evaluation scale. There was also an agreement of 70% between the EEG and the test of variables of attention. These findings led Monastra and colleagues [15,17] to suggest that values derived from the EEG analysis can serve as the basis for accurate classification of participants as ADHD, with a level of accuracy comparable to the existing behavioral and CPT tests used to identify ADHD. See the contributions of Monastra and Chabot [12,13,15,17,19] for further discussion of these issues.

Behavioral correlates of the electroencephalogram

The original idea of using EEG frequency band activity as a feedback criterion in biofeedback stemmed partly from the close association between the speed of EEG frequencies and the arousal state. Slow brainwaves in the delta range (approximately 0–4 Hz) are primarily found during deep sleep. Slightly faster theta waves (approximately 4–8 Hz) are often associated with drowsiness and early sleep stages, whereas the adjacent alpha frequency (approximately 8–12 Hz) is characteristic of a relaxed, waking state. Faster frequencies in the beta (approximately 12–30 Hz) and gamma ranges (>30 Hz) are associated with more aroused, active cortical processing during mental operations in the alert brain. It is important to stress that this association between EEG rhythms and arousal/activational state is a convenient simplification, because in the context of carrying out different tasks any one particular brain rhythm may reflect many diverse functional states of neural communication and may be generated through different processes by various anatomic structures. Many aspects of EEG generation and functional significance are under active research and are not yet entirely understood.

Sensory motor rhythm

Turning to the behavioral significance of SMR and beta 1 EEG bands, pioneering research was set in motion by Sterman's experiments on cats in the 1960s [17], in which during learned suppression of a previously conditioned response (pressing a bar for food), a particular brain rhythm emerged over the cats' sensorimotor cortex [20–23]. This rhythm was characterized by a frequency range of 12 to 20 Hz, with a spectral peak in the area of 12 to 14 Hz, and has since been referred to as the SMR [20]. Researchers studied this rhythm directly, attempting to teach the cats to produce SMR through instrumental learning by making a food reward contingent on the occurrence of SMR bursts [22,23]. Cats learned this feat of EEG self-regulation with apparent ease, and the behavior associated with SMR production was one of behavioral stillness, with SMR bursts regularly preceded by a drop in muscle tone.

Sterman's laboratory also was commissioned to establish dose-response functions of a highly epileptogenic rocket fuel. Serendipitously, they found that when using the cats that previously had taken part in SMR conditioning, they displayed elevated epileptic seizure thresholds compared with untrained cats. This research was extrapolated successfully to humans. It has been documented repeatedly that epileptic motor seizure incidence could be lowered significantly by SMR feedback training [24–28]. In acknowledgment of the apparent quieting effect of SMR training on the excitability of the sensorimotor system, Lubar et al [1] first applied a protocol of SMR-enhancement to the treatment of ADHD.

Beta activity

The SMR protocol often has been complemented or substituted by a training protocol that combines suppression of theta activity with increments in higher beta components, such as the beta 1 band (15–18 Hz). These types of "beta" protocols have been conceptualized as targeting improvements in attentiveness [3]. Beta activity has been associated with states of high alertness, concentration, and focused attention. To give some contemporary evidence, consistent with the suggestion that beta activity may represent a psychophysiologic correlate of attentional processing [29], increased beta band activity was found during a visual-spatial selective attention task when subjects attended to stimuli [30]. The requirement to divide attention between two tasks resulted in a concomitant decrease in beta activity [31]. It follows that the low levels of beta produced by children with ADHD are believed to have a detrimental effect on their ability to focus and concentrate. This also suggests that training beta activity may benefit children who suffer predominantly from problems of inattention or low arousal.

Validation of the influence of neurofeedback training on attention in healthy participants

The studies with children with ADHD, although important, had not established a direct association between the ability to learn to enhance the desired frequency band in the EEG and the improvement in behavior and cognition. Egner and Gruzelier [32] set out to explore whether similar cognitive improvements could be achieved through training with the neurofeedback protocols and whether improvements in attention could be predicted on the basis of regression models of indices of learning ability to increase relative and absolute SMR and beta 1 amplitudes within each session. This would provide necessary validation of the effects on attention of these training protocols and support the assumption that enhancing SMR over sensorimotor cortex reduces the impulsive behavior characteristic of ADHD, whereas enhancing beta 1 activity improves sustained attention.

Before the studies to be reviewed, there was only one investigation of beta training in application to the enhancement of cognitive performance in healthy subjects. Rasey et al [33] trained four students for 20 sessions of beta enhancement paired with theta-alpha inhibition. As a dependent measure, the authors used a 19-channel EEG recording taken under various psychological conditions before and subsequent to training and as behavioral dependent measures subjects performed the Wechsler Adult Intelligence Scales - Revised and the Intermediate Visual and Auditory Attention Test. Only the latter measure disclosed some improvements in learners versus nonlearners, categories that were based on learning indices. But in the absence of any inferential statistics, little information can be drawn from this small study.

The first study examined a group of music students who were trained on an attention-targeting neurofeedback protocol that involved ten 15-minute sessions of training beta 1 at C3 and SMR at C4 [32]. The assessment of attention performance was performed using a computerized CPT that displayed two classes of stimuli: ‘‘targets,’’ which require the participant to respond as quickly and accurately as possible by pushing a response switch, and ‘‘non-targets,’’ which require the participant to refrain from responding, as with the test of variables of attention used in ADHD research. Two types of errors can be incurred on such a task: (1) errors of omission by failing to respond to a target stimulus and (2) errors of commission by erroneously responding to a nontarget stimulus. Respectively, these errors are believed to reflect inattentiveness and impulsiveness. A further attention measure has been derived from signal detection theory [34] and termed ‘‘perceptual sensitivity’’ or ‘‘d prime’’ (d′). This takes into account both error types by expressing a ratio of hit rate to false alarm rate.

From the emergent data, researchers established that ten training sessions of beta 1 and SMR neurofeedback led to a significant reduction in errors. More specifically, students showed a significant reduction in commission errors as compared with measures taken before training. When exploring the link between the process of learned EEG self-regulation and the reduction in impulsive mistakes, researchers found that the relative success at enhancing the SMR was highly positively correlated with reduced commission errors. This means that participants who fared well on the SMR feedback task were the ones who most decreased their impulsive mistakes after training. These findings support the notion that learned SMR enhancement is associated with improved response inhibition, and they constitute the first evidence for cognitive performance enhancement through neurofeedback in healthy volunteers. The results are shown in Fig. 1.

The attention-enhancing potential of beta 1 neurofeedback also was corroborated by electrocortical performance measures related to selective

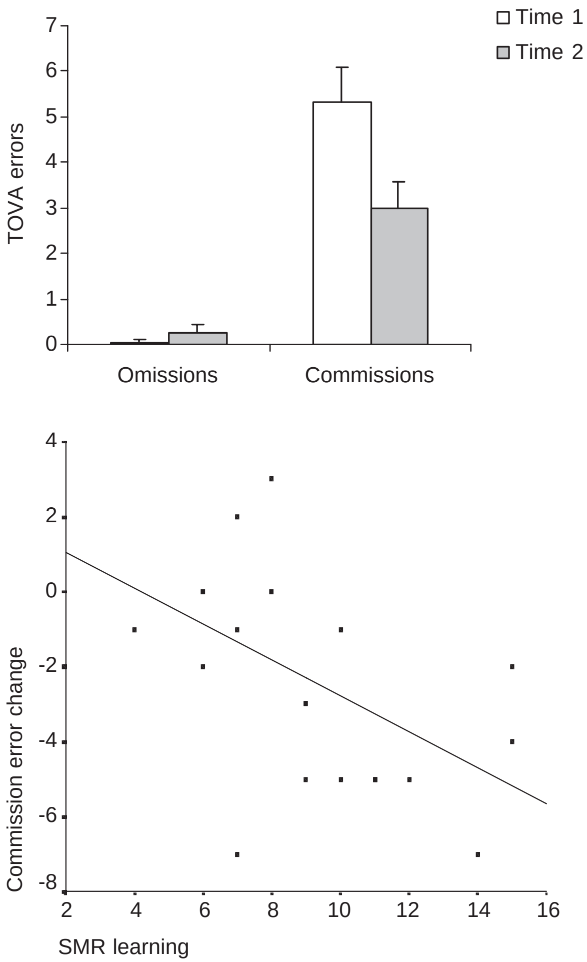

Fig. 1. Pre- to posttraining change scores for errors of omission and commission (*top panel*) and regression line of best fit for the correlation between SMR learning index and commission error reduction (*bottom panel*).

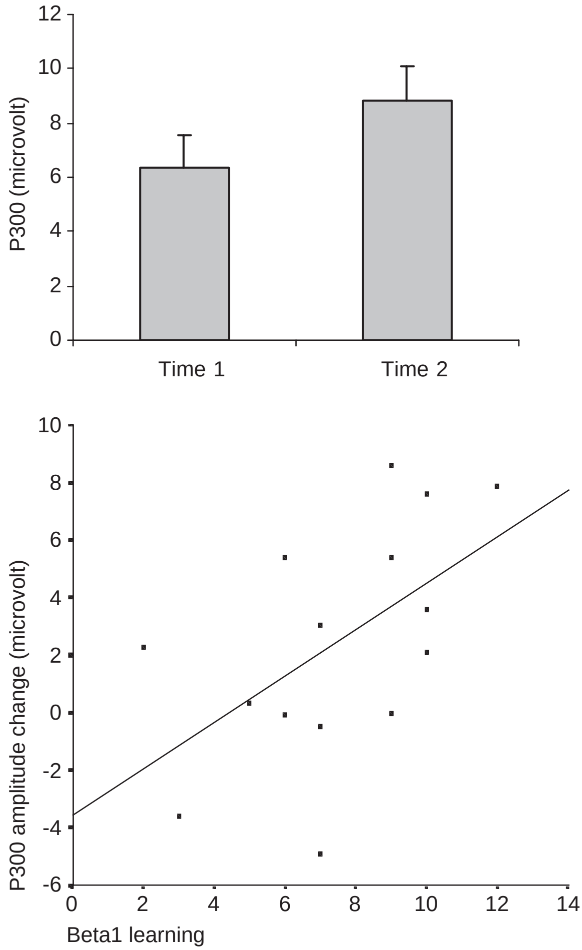

Fig. 2. Pre- to posttraining change scores for P300 ERP mean amplitudes (*top panel*) and regression line of best fit for the correlation between beta 1 learning index and P300 increments (*bottom panel*).

attention processes (Fig. 2) [32]. Beta 1 training was associated with increments in the P300b event-related brain potential on a task that required active monitoring and detection of auditory target stimuli. Specifically, responses to target stimuli increased significantly at frontal, central, and parietal locations. The P300b has been conceptualized as representing activity in neuronal sources responsible for updating relevant stimulus environment information in working memory [35]. Of critical theoretical importance was the finding that beta and SMR learning correlated positively with the P300b increases.

In a second study [36], the main results were replicated using separate groups of students for SMR and beta 1 training and compared with a control group. Effects were measured with continuous performance and divided attention tasks.

Stronger effects were demonstrated with the more complex divided attention task. SMR training benefited omission errors and reduced reaction time variability, whereas the d′ measure improved on both tasks. Beta 1 training was followed by reduced reaction times on the less complex test of variables of attention, and in both studies there were larger P300b amplitudes, especially at central and parietal placements and in keeping with the posterior scalp distribution of the P300b as before.

In a third study [37], medical students were randomized to one of three groups: (1) SMR training while inhibiting theta and beta (18–22Hz), (2) eyes-open theta training while inhibiting delta and alpha, and (3) a nontraining control group. There were eight sessions with a Cz electrode placement. The effect of training was compared on a CPT with a two- or three-digit sequence target, which varied the memory load, and on a semantic working memory task with words presented randomly or in semantic clusters. There was clear evidence of operant control over the SMR, but participants were unable to achieve this with eyes-open theta training. In the two-digit CPT there were highly significant reductions in errors of omission and commission with SMR training, which were not observed in the other groups (Fig. 3). There was no advantage to SMR training

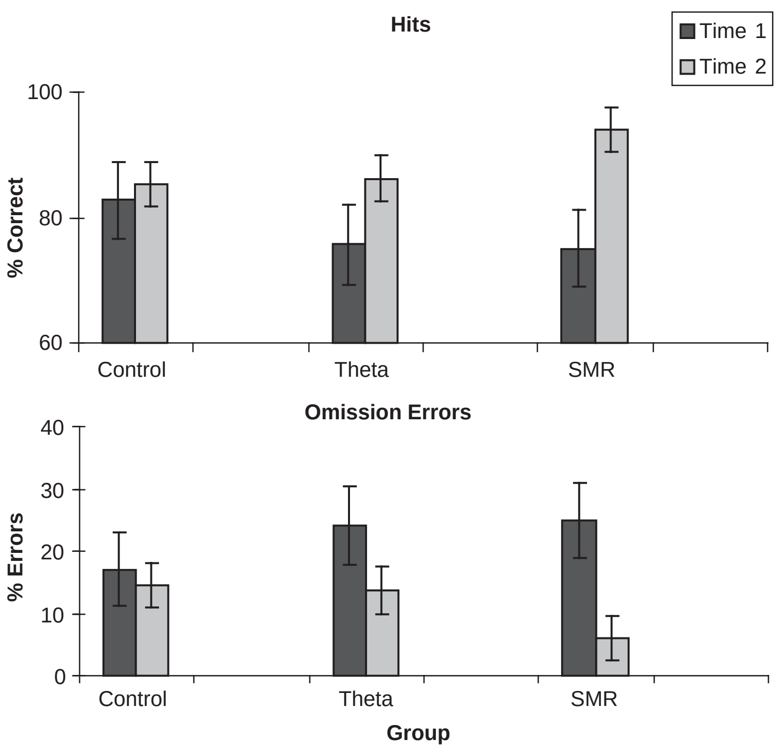

Fig. 3. Percentage hits (*top panel*) and omission errors (*bottom panel*) for two-sequence attention CPT at time 1 and time 2 for the control, theta, and SMR groups.

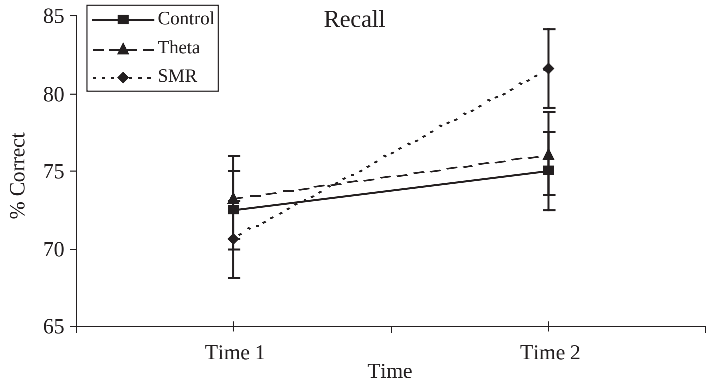

Fig. 4. Percentage correct recall (with standard error bars) for semantic working memory task, collapsed across nonclustered and clustered versions, at time 1 and time 2 for the control, theta, and SMR groups.

with the three-digit task, however. More robust effects were found with the semantic working memory task in favor of SMR training. As shown in Fig. 4, improvements on the order of 10% were found with clustered and unclustered recall with only eight sessions of training.

Together the results of these three experiments have significance for the treatment of ADHD. There was some evidence in all three experiments that impulsive errors on CPT tasks may be reduced after SMR training. Omission errors also benefited, along with an increase in perceptual sensitivity (d′) in the music students. Improvements in attention in students could be predicted on the basis of regression models of indices of learning ability to increase relative and absolute SMR and beta 1 amplitudes within each session. The increments in SMR and beta 1 activity also could predict the increases in P300b amplitude. This finding had not been demonstrated previously, and it provided important validation of the effects on attention of these training protocols widely used with children with ADHD. The results support the assumption that enhancing SMR over sensorimotor cortex will reduce the impulsive behavior characteristic of ADHD.

Alpha-theta training and performance enhancement

This process is a widely used clinical and optimal performance protocol that involves increasing the ratio between theta and the usually more dominant alpha activity. Its origins lie with what is believed to be the first ever application of neurofeedback training by Kamiya [38]. He found that participants made aware of alpha frequency bursts (8–12 Hz) in their EEG recorded from the occipital scalp regions eventually could identify alpha in the absence of feedback. They also seemed to be able to increase voluntarily the incidence of the alpha rhythm, and they reported the experience of the so-called "alpha state" as being relaxing and peaceful. Subsequently, several studies reported alpha density enhancement accompanied by a reduction in anxiety or physiologic arousal by means of alpha feedback training [39–42]. In replicating this work, however, the subjective and physiologic states were not always reproduced, participants did not always succeed in actually enhancing alpha activity above pre-feedback levels [43], and sometimes the behavioral and phenomenologic effects could be attributed to social variables, such as positive expectancies [44] and perceived success with training [45].

More recently, an alpha-theta neurofeedback protocol emerged as an adjuvant to the treatment of alcoholism [46–48] and posttraumatic stress disorder [49]. (For more discussion, see the articles by Trudeau and Hammond elsewhere in this issue.) The protocol aims to facilitate a rise in levels of theta (4–8 Hz) over alpha (8–12 Hz) activity in a state of eyes-closed relaxation. Normally on closure of the eyes and onset of relaxation, the EEG displays high amplitude rhythmic alpha activity. With further deactivation, alpha activity slowly subsides and slower theta activity gradually becomes predominant [50,51], typically in conjunction with an increase in delta, although ongoing research shows that theta may increase independently of delta. The point in time when theta activity supersedes alpha activity, the so-called theta-alpha "crossover," is commonly associated with loss of consciousness and the onset of early sleep stages. By teaching participants to raise theta over alpha activity while not falling asleep, the alpha-theta protocol aims to produce a state of deep relaxation and deactivation consciously, apparently resembling a meditative state that would normally be unconscious.

A series of studies was undertaken to establish evidence of operant control over the alpha-theta ratio and to establish its ecologic validity for performance enhancement in music students. The cognitive and affective mediation of the beneficial effects achieved also was explored. Because the purpose of the music performance measurements in the neurofeedback studies was to assess performance variables of high ecologic validity and pedagogic relevance, it seemed appropriate to use an evaluation scheme by which students are assessed customarily. For this reason, the marking scheme of the Associated Boards of the Royal Schools of Music [52] was adapted to take into account segmented aspects of performance quality, including instrumental competence, musicality, communicative ability, and overall performance quality. Table 1 contains a listing of the assessment categories.

Although examination assessments within a conservatory are normally based on live performances by teachers internal and external to the institution, in the context of a scientific investigation this type of evaluation procedure would seem to introduce potential sources of bias. Foremost, the assessors would be aware of the order of pre- and posttraining performances, which might induce expectations of improved performances. To exert maximum control over such biases, the performances were videotaped, randomized, and then evaluated only by experienced assessors external to the institution and blind as to the order of performances and experimental group membership of the students. To assess

Table 1
Correlations between musical performance change and alpha-theta learning

	Alpha-theta 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 0.021
Ability to cope with situational 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 for all subjects participating in neurofeedback training in experiment 1. Major evaluation categories are in bold type, with their associated subscales following.

whether any changes in music performance ratings were related to pre-performance anxiety, the Spielberger's State Anxiety Inventory [53] was administered to each participant just before performance.

In the first study, students were randomly assigned to a mixed course of beta 1/SMR and alpha-theta training, to a no-training control group, or to the neurofeedback protocols as for the first group, with additional interventions that consisted of mental skills training and aerobics [54,55]. These comparison groups were conceived to allow for the assessment of neurofeedback's impact on performance as a stand-alone intervention versus a subcomponent of a more elaborate training program while controlling for the presumed natural progression in performance quality that resulted from the standard conservatory training through the no-training control group. It was found that improvements in performance were evident in the neurofeedback-only group but not in the neurofeedback group that engaged in additional interventions or in the no-training control group (Fig. 5). The neurofeedback group improved most markedly on ratings of overall quality of performance and their "musicality."

Importantly, an alpha-theta training learning index, which reflects increasing ease and depth of relaxation across the training process, correlated highly positively with music performance improvements. As can be seen in Table 1, alpha-theta learning was significantly associated (ie, $P < 0.05$) with trends of improvement in 9 out of 13 rating criteria, including the main four. Neither the SMR nor the beta 1 protocols were related to improvements in music performance. Differential improvement rates between the experimental groups in this study were not related to pre-performance state anxiety, because generally decreased anxiety levels between the first and second performances did not differ

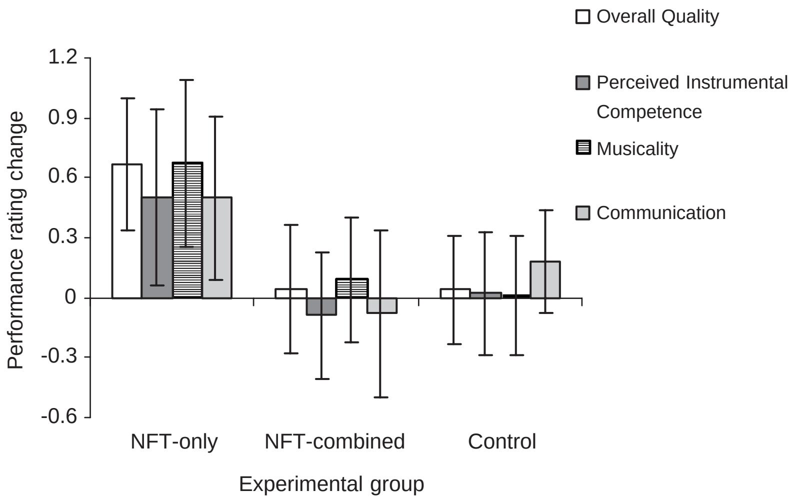

Fig. 5. Pre- to posttraining change scores on the main musical evaluation categories by experimental group.

between groups [54,56]. Because the relation between neurofeedback learning and improvement in music performance held for both groups that received neurofeedback but only the neurofeedback alone group showed improvement in music performance, we can only infer that mental skills training and aerobics in some way suppressed the beneficial influences of neurofeedback. Perhaps a longer intervention program would have benefited the other interventions.

These findings supply evidence for a potential benefit of neurofeedback on a highly ecologically valid music performance measure. The fact that music performance quality changes were not related to SMR and beta 1 learning suggests that improvements were not mediated by attention-related variables. The fact that alpha-theta learning correlated highly with changes in virtually all music evaluation categories would seem to point to a single, pervasive factor mediating these correlations. Given the nature of the alpha-theta protocol and these relationships, a prime candidate for effect mediation would seem to be pre-performance anxiety, but as indicated previously, the data did not support this assumption.

To clarify the seemingly strong association between alpha-theta neurofeedback and performance enhancement, a constructive replication study was devised [54–56]. Participants were randomly allocated to one of the following groups: an alpha-theta, SMR, or beta 1 neurofeedback training group, a physical exercise program, or a mental skills training program. Music performances were assessed before and subsequent to training. A further comparison group also was integrated into the study that consisted of students involved in a course of Alexander technique training. This technique is considered an established tool for improving performance in music conservatories worldwide and engaged participants in a comparable amount of one-to-one interaction as the neurofeedback intervention.

Analysis of music performance ratings from three expert judges who were blind to the experimental conditions revealed that the alpha-theta group displayed significant improvements. Neither the beta 1 nor the SMR group exhibited any posttraining performance changes. Similarly, students from the Alexander technique, physical exercise, and mental skills training groups showed no posttraining changes. In the alpha-theta group, evaluation scores for "musicality," "stylistic accuracy," "interpretative imagination," and "overall quality" all improved significantly (Fig. 6). These increments represent average alpha-theta group improvements between 13.5% and 17%, with a mean improvement rate of 12% across all evaluation scales. Individual participants displayed improvements of more than 50% on some evaluation criteria. As in the first study, all groups reported significantly less pre-performance anxiety before the posttraining performance, with no differences between groups.

In the previous study, alpha-theta learning correlated with musical improvements across all evaluation categories. The protocol's performance-enhancing effects proved to be replicable, particularly with respect to parameters on the "musicality" and other artistic evaluation categories (Table 1). These data could be interpreted as indicating that alpha-theta training led especially to improvements on attributes of artistic expression as opposed to technical skills, which in turn improved overall performance. In turn, these results suggest that alpha-theta training seems reliably to enhance artistic aspects of musical performance skills—independently of training on additional neurofeedback protocols—and these effects are superior to the other interventions in this respect.

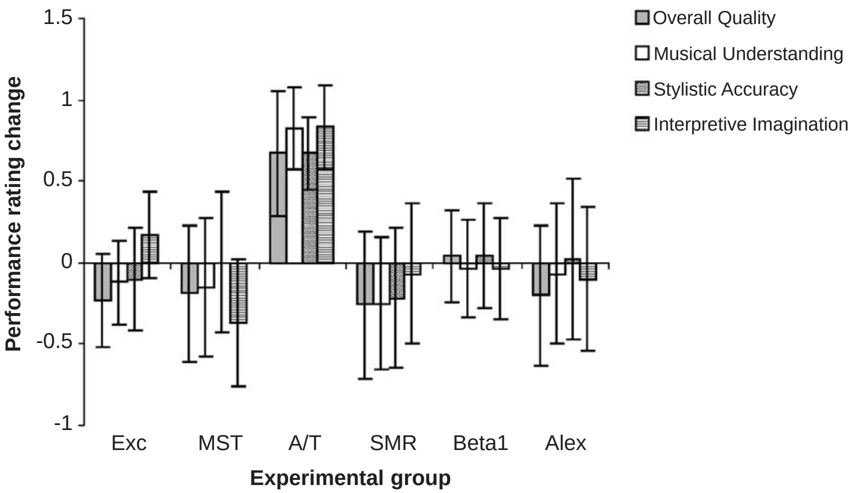

Fig. 6. Neurofeedback and music performance. Mean change scores (± SEM) for the physical exercise (Exc), mental skills training (MST), alpha/theta (A/T), SMR (SMR), beta 1 (Beta1), and Alexander Technique (Alex) groups on a 10-point rating scale of musical evaluation criteria. The a/t group displays musical improvements in overall quality (+14.4%), musical understanding (+16.4%), stylistic accuracy (+13.5%), and interpretative imagination (+17%).

Implications of validation for sensory motor rhythm and beta 1 training

Most previous studies that have attempted to portray any association between EEG parameters and behavioral dependent measures have done so merely by documenting some kind of posttraining EEG changes that were presumably related to the actual training process and further presumably related to behavioral performance changes [3,7,57,58]. In none of these studies were the corresponding correlation statistics reported, however. Although attempts to formulate learning success on the basis of in-training EEG measures had been made to classify trainee participants as learners or nonlearners [2,32,59], these stopped short of directly correlating learning indices with changes in outcome measures, whether behavioral or electrophysiologic. Arguably, the earliest case study reports by Lubar and Shouse [1,2] came closest to specifically documenting the purported link between fulfilling feedback learning criteria and changes in dependent measures, but their results were of a descriptive nature, and the implications were further hampered by a small number of subjects.

The principle strategy to reveal a possibly causal link between a neurofeedback training regimen and dependent measure changes requires relating an index that reflects relative success at satisfying the operant feedback contingencies directly to behavioral and neurophysiologic changes. This was accomplished in our investigations. First, our studies of SMR training disclosed benefits for impulsive and inattentive aspects of attention performance. When the two aspects were combined in the d′ metric, perceptual sensitivity was enhanced after SMR training in studies and across visual and auditory sensory modalities. The critical achievement was that learning indices were capable of predicting the cognitive improvements in attention and the neurophysiologic enhancement of the P300b response. The formulation and assessment of meaningful neurofeedback performance-based predictors of the dependent measures were demonstrated.

In terms of the neurophysiologic processes underlying the improvements in attention, our studies provide support for Sterman's [17] proposal that there is decreased somatosensory and motor interference in cognitive processing as a result of SMR training, such that in ADHD it is the hyperactivity that disrupts attention, learning, and memory. The putative improved regulation of sensorimotor and somatosensory pathways reduces processing interference from irrelevant stimuli and facilitates the cognitive integration of the task-relevant stimuli, which are demonstrated in the behavioral and neurophysiologic tasks.

In keeping with traditional notions of its association with generic cortical activation and its application to cortically underaroused children and adults with ADHD, beta 1 learning correlated positively with commission error increases [33] and shorter reaction times [36]. In both reports it increased P300b amplitudes. These combined effects are compatible with an increase in the background cortical arousal in keeping with the proposal of raising cortical excitation in underaroused children with ADHD. Of theoretical and methodologic importance is the fact that some opposite effects on attention were found from SMR and beta 1 training. SMR enhancement had the positive effects and beta 1 enhancements the negative effects on impulsive response tendencies. This provides evidence of protocol specificity. The demonstration of protocol specificity counters skepticism about neurofeedback being attributable to nonspecific factors, such as therapist contact or motivation. It also questions unitary theories of neurofeedback efficacy based on thalamocortical regulation that posit interchangeability been protocols. The notion that all that is important in the learning of self-regulation of the EEG is the learning process and not the bandwidth chosen is not supported by the findings presented herein that SMR and beta 1 training had opposite effects on impulsivity. Most importantly, however, our validation places SMR and beta 1 training on a firmer footing in applications to ADHD in children and adults, whereas the improvement in semantic memory has implications for neurorehabilitation and addressing the ageing process in the elderly population.

It is remarkable that these benefits were achieved by only ten sessions of training, and clinical samples will require longer training. The next step in the validation process is duplication of these studies in clinical groups and in the case of ADHD in inattentive, hyperactive, and combined subtypes. Will the SMR protocol be effective for the hyperactive subtype and the beta 1 protocol be effective for the inattentive subtype? Will both protocols be effective for the combined subtype? Can this efficacy be measured not only by clinical outcome but also with neurocognitive measures such as those outlined herein? Do neurofeedback learning indices predict efficacy? At a theoretical level, determination of the exact nature of the cognitive impairment is required, whereas at a methodologic level, numerous issues must be clarified, such as training schedules, session length frequency and number, electrode placements, and reward and inhibit bands. Questions such as whether one trains on the basis of clinical diagnosis or EEG-based diagnosis eventually must be addressed.

Implications of validation for alpha-theta training

The results with music students [54,60] and medical students [61,62] provide the first evidence for operant control of the alpha-theta ratio. The first evidence was provided of the efficacy of the alpha-theta protocol as a sole intervention. The outcome with music students confirmed a significantly beneficial effect of alpha-theta training on a highly ecologically valid and pedagogically relevant performance measure. The improvements were equivalent to two academic grades within the conservatory assessment system. Correlations were found between learning indices and degree of performance improvement, a critical source of validation, as demonstrated with SMR and beta 1 learning with respect to attentional processes. Along with the outcome of SMR and beta 1 training, these effects cannot be accounted for by invoking practice, motivational, or generic neurofeedback factors. An explanation for the alpha-theta effects based on generic relaxation also can be discounted on the grounds that the alpha-theta training was not associated with a greater decrease in pre-performance anxiety than that seen in other groups. A mental skills training group, which engaged in extensive relaxation training, showed no detectable performance improvements. The size of the performance improvements implies great potential for the implementation of this application in music performance contexts.

In theoretical terms, the data do not seem to fit with a conceptualization of training efficacy primarily based on relaxation, the ethos of clinical applications. The need to look beyond a mere relaxation model is emphasized further by a study with medical students that showed that significantly different theta-to-alpha ratios between real and false alpha-theta feedback conditions were not reflected in differences in reports of subjective relaxation [61].

How does alpha-theta training achieve these remarkable effects? Although a theoretical link between functional correlates of theta activity and improved artistic expression in music performance can be envisaged, no effect mediation has been established. The substantive neurofeedback training effects demonstrated in these studies should serve as a motivation for empirically addressing the exact mechanisms underlying future training, however. A rigorous analysis of subjective phenomenology in our music students has disclosed important affinities between the alpha-theta state and the state of performing music well [63]. The SMR/beta training state also has shown affinities, but different ones, including mental relaxation. Phenomenologic analysis could prove useful in pinpointing psychological mediators of the training's efficacy [64].

EEG theta activity has been implicated in several mental and affective states ostensibly unrelated to relaxation processes. The clinical efficacy of alpha-theta training in patients who suffer trauma and chronic drug addiction—extending in recent evidence to young offenders with crack and cocaine misuse—implies a more powerful impact than can be achieved with relaxation and anxiety reduction alone. Theta is generated throughout the cortex in hypnogogic states and after training in meditation and hypnosis [65]; its production often can outlast the experience itself [66]. These states are typically associated with pleasure, and in the case of meditation, theta production has been associated positively with ratings of bliss [67]. Accordingly, theta seems to be associated with enhanced feelings of well-being and relaxation.

Especially relevant is the growing evidence of the role of theta in a range of memory control processes, enabling a fluent retrieval of memories into conscious awareness and working memory [68–71]. It is self-evident that memory control processes are exercised to the hilt in musical performance, when virtuoso technical accomplishment and artistry are demanded. Winson's [72] bold theory of memory, theta, dreams, and survival may have particular relevance [73]. Consistent with the evidence of the importance of theta for memory control processes, Winson posits that theta assists in making available to memory information that is necessary for survival. This theory follows observations of survival behavior in animals, which, although species specific, is united by the occurrence of theta. Theta also occurs in all species during dream sleep, with the hypothesized purpose of facilitating access to memory control processes of information regarding events that threaten survival to deal more effectively with any recurrence of threat. The process of alpha-theta training in our students involved the transient entering and re-entering of dream-like states. Let us consider that the typical music student's career trajectory has taken approximately 10 years of singular dedication to the practice and performance of music at the highest level [73], and his or her musical ability and career ambition is under the challenge of a stressful performance to be judged by teachers and other experts. Accordingly, the exercise of theta-related memory for survival processes through alpha-theta training may facilitate success. The successful student orchestrates a dazzling technical and artistic display that depends on memory control processes. This process involves a complex coordination of sensorimotor, postural, and respiratory functions, together with the expression and modulation of emotion and the expression of creative and artistic ability, as is inherent in the concept of musicality.

A further line of evidence is of interest. Posttraining effects of alpha-theta neurofeedback on the EEG amplitudes in different frequency bands across the whole scalp were examined during rest [73]. A relation was found between alpha-theta training and a reduction in high beta frequency activity (15–30 Hz) over frontal brain regions. The training's effect of reducing frontal beta band activity could be interpreted as reflecting decreased agitation and negative affect, based on associations between frontal beta activity and depression [74] and post-traumatic stress [75] and stress responses to brief painful stimulation in non-clinical groups [76]. The significant enhancement of performance skills in the long run may alleviate excessive worry about performing, the most commonly cited impediment to musicians' successful careers [77,78]. Although relevant, anxiety reduction cannot explain the results in our students. A theoretical account of alpha-theta neurofeedback efficacy must integrate its apparent role in relaxation and reducing vigilant arousal and its positive effects on artistic expression in musical performance and creativity. Further clarification of the precise nature of the alpha-theta effects is required for advancing the theoretical framework.

Regardless of the precise mechanisms underlying the training effects, the findings presented in this article have important implications with respect to the psychological and physical well-being of musicians and people in general in states of illness and health. Preliminary results have been found in elevating mood in withdrawn participants.

Future developments

Despite the validation work reported in this article, much work remains to be done to provide a scientific basis for biofeedback with the EEG spectrum. In many respects neurofeedback using slow cortical potentials championed by Birbaumer et al [79,80] is more advanced with respect to basic research, and this has demonstrable clinical applications [81–84]. The monitoring of whole-scalp EEG and fMRI changes within each SMR, beta, and alpha-theta training session also would be of interest. Can our enhancement of attention and memory demonstrated in healthy subjects be extended to clinical groups? What are longer term influences on the EEG that accompany the cognitive improvements? Eluidation of the origin of the theta activity generated during alpha-theta training and the way in which the training may affect frontal beta band and metabolic activity is a high priority [73]. The remarkable enhancement of artistic aspects of performance by alpha-theta training warrants application to the performing arts in general. Work currently underway with dancers has shown promising results [62].

Of more immediate practical concern are the questions of who is most likely to benefit from the training and how to optimize the nature and duration of the training. These issues are currently unresolved but under active investigation. Psychometric testing could possibly allow one to determine personality trait predictors of likely responsiveness to SMR-beta and alpha-theta neurofeedback and successful performance enhancement [85]. The practical details of session length, schedule length, reward contingencies, and electrode placements require controlled investigation.

Finally and crucially, the relevance of applying neurofeedback hinges decidedly on its potential to evoke long-term effects. Research to date does not permit any inferences regarding this important aspect with respect to alpha-theta training. All posttraining music performance measures were taken within a span of maximally 4 weeks after the last training session. Regarding SMR and beta training in children with ADHD, there is suggestive evidence of long-term efficacy. In the future, studies that involve regular follow-up assessments over a longer interval must be conducted to determine whether the costs of neurofeedback training in terms of time and money as a clinical and performance enhancement tool are justified by long-term returns.

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