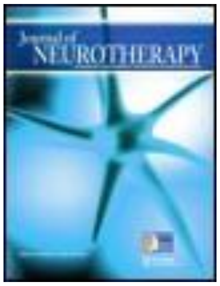

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The Temporal Dynamics of Electroencephalographic Responses to Alpha/Theta Neurofeedback Training in Healthy Subjects

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The Temporal Dynamics of Electroencephalographic Responses to Alpha/Theta Neurofeedback Training in Healthy Subjects

Tobias Egner, PhD
John H. Gruzelier, PhD

ABSTRACT. *Background*. It has been shown recently that accurate feedback of alpha and theta electroencephalographic (EEG) activity, as employed in the commonly used "alpha/theta protocol," induced linear increments in within-session theta-over-alpha ratios in comparison to non-contingent feedback in a healthy sample. These data verify that alpha/theta feedback can facilitate within-session operant control over the EEG signature targeted by the training protocol. However, it is neither known whether any between-session theta/alpha ratio changes do reliably occur, nor what kind of temporal dynamics between the alpha and theta band amplitudes characterise within-session and/or between-session theta/alpha ratio changes.

Method. In order to address these issues, analyses of an extensive data set (n = 48) of alpha/theta training in healthy volunteers were carried out. Specifically, alpha, theta, and theta/alpha ratio EEG dynamics were contrasted between groups of subjects that engaged in 10 sessions of training at PZ (n = 28), five sessions of training at PZ (n = 10), and 10 sessions at FZ (n = 10).

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Results. For alpha/theta training at PZ, significant within-session increments in theta/alpha ratios were mediated by slightly less pronounced decrements in theta than in alpha activity during the sessions. The traditional alpha/theta protocol at PZ was nevertheless associated with significant theta activity increments across the training process. For training at FZ, no significant within- or between-session changes in theta, alpha, or theta/alpha ratio values were found, but a progressively higher rate of within-session theta/alpha ratio modulation was evident across sessions. Furthermore, in contrast to the PZ groups, any changes in theta/alpha ratio at FZ were mediated by increases in theta relative to alpha amplitudes.

Conclusions. These data elucidate the dynamics underlying the within-session theta/alpha ratio increments associated with posterior alpha/theta training, and document an increase in theta activity across 10 sessions of training, offering further evidence for a neurophysiological impact of this training protocol. In addition, the contrasting EEG characteristics associated with frontal versus posterior alpha/theta training underline the heterogeneous nature of these frequency components across varying scalp sites.

KEYWORDS. Alpha/theta neurofeedback, alpha, theta, theta/alpha ratios, neurofeedback learning

INTRODUCTION

Reports of promising effects from the application of electroencephalographic (EEG) alpha/theta biofeedback training as a complementary therapeutic tool in the treatment of alcohol abuse (Peniston & Kulkosky, 1989, 1990; Saxby & Peniston, 1995) and posttraumatic stress disorder (PTSD; Peniston & Kulkosky, 1991; Peniston, Marrinan, Deming, & Kulkosky, 1993) have generated an interest in furthering the understanding of this protocol's potential benefits and underlying mechanisms. Briefly, alpha/theta neurofeedback is typically carried out by supplying auditory feedback about relative changes in alpha and theta activity levels during a state of eyes-closed rest and relaxation (e.g., Peniston & Kulkosky, 1989). The rationale of the protocol is to facilitate deep relaxation by encouraging conscious progression through alpha and theta EEG activity changes that are traditionally associated with deactivation and sleep onset, reflected in high alpha activity during initial stages of relaxation that later progressively subsides, accompanied by the emergence of slower theta (and delta) frequencies (e.g., Broughton & Hasan, 1995; De Gennaro, Ferrara, & Bertini, 2001).

While the alpha/theta feedback protocol has been conceptualised as an "EEG-based relaxation therapy" (Peniston & Kulkosky, 1999, p. 158) and proposed to facilitate "psychological reintegration" (Othmer, Othmer, & Kaiser, 1999, p. 304), published research systematically documenting such effects is scarce. Furthermore, the unambiguous evaluation if its clinical efficacy has been impeded by the fact that the training protocol has constituted one aspect of multi-component interventions, and has not been assessed in isolation.

Recently, it was documented that alpha/theta neurofeedback training at posterior midline scalp sites produced replicable significant enhancement of musical performance skills in conservatoire music students (Egner & Gruzelier, 2003). These improvements, rated single-blind by expert judges and not evident in various control groups, were prominent in attributes of artistic expression such as "musicality," and were unrelated to any changes in pre-performance state anxiety levels. Another recent report examining the electrocortical effects of alpha/theta training has supplied evidence that the protocol is associated with reliable post-training modulation of spectral EEG measures (Egner, Zech, & Gruzelier, submitted). Specifically, alpha/theta training was associated with reduced frontal high frequency (beta1 and beta2) activity during eyes-closed resting EEG recordings carried out approximately two weeks after a 10-session training regime.

In terms of the dynamics of EEG responses during the actual feedback process, Moore et al. (2000) have investigated the levels of theta-to-alpha activity ratio (t/a ratio) induced by alpha/theta feedback and found no difference to those present during alpha-only or electromyographic (EMG) feedback. On the other hand, Egner, Strawson, and Gruzelier (2002) have compared t/a ratio measures between contingent and non-contingent alpha/theta feedback regimes in a single-blind design, and reported that accurate feedback facilitated the production of significantly higher within-session t/a ratios. Specifically, averaged over five 15-minute sessions, accurate alpha/theta feedback led to a linear increase in the t/a ratio across time within sessions, suggesting learned control over the t/a EEG signature. In addition to this evidence for "within-session learning" in response to alpha/theta feedback, a measure of the progression of within-session t/a ratio increments across sessions, devised to reflect the progressive ease and depth of relaxation, has been shown to be a useful predictors of a/t training effects in healthy individuals (Egner & Gruzelier, 2003). Specifically, this "t/a learning coefficient" was expressed by the slope of regression across sessions of the correlation between t/a amplitude ratios and passage of time within each session, and this measure was highly positively correlated with improvements on a wide range of music performance criteria.

These studies suggest that alpha/theta training facilitates operant linear within-session t/a ratio increments (Egner et al., 2002), and that a measure of the progression of within-session t/a ratio increments across sessions can be useful predictors of a/t training effects in healthy individuals (Egner & Gruzelier, 2003), but many important aspects of the EEG responses to alpha/theta neurofeedback remain unexplored. For example, it is not clear from these studies whether some form of between-session learning or "carry-over" effects reliably occur in trained subjects, nor what kind of temporal dynamics between the alpha and theta band amplitudes characterise within-session and/or between-session t/a ratio changes. Furthermore, while the "t/a learning coefficient" may be a useful predictor of training effects, it has not been documented whether, across a group of training subjects, this type of progressive learning occurs to a significant degree.

In order to address these questions, we performed analyses on an extensive data set (n = 48) of a/t training in healthy volunteers stemming from previous published (Egner & Gruzelier, 2003; Egner et al., 2002) and unpublished work. We were interested in particular in the relations between alpha activity, theta activity, and t/a ratios, across time within sessions and across sessions, as well as progressive changes of within-session t/a ratios across sessions. The nature of our data sets allowed us to contrast these temporal dynamics of alpha/theta training responses between a group of subjects who engaged in ten sessions (n = 28) and subjects who engaged in five sessions of training (n = 10) at the parietal midline electrode PZ (all placements according to international ten-twenty system; Jasper, 1958). Additionally, comparisons were made with a data set from subjects who were trained for 10 sessions at the frontal midline site FZ (n = 10).

The latter study was carried out in order to clarify whether responses to alpha/theta feedback, traditionally carried out at posterior scalp locations, would exhibit similar dynamics in frontal regions. This was of particular interest as scalp-recorded theta activity does not constitute a homogeneous phenomenon solely related to deactivation or early sleep stages. Particularly in frontal midline regions, theta activity has been associated with a number of cognitive and affective processes related to activity emanating from the anterior cingulate cortex (e.g., Gevins, Smith, McEvoy, & Lu, 1997; Aftanas & Golocheikine, 2001; Burgess & Gruzelier, 2000). As previous findings suggest effects that involve high-level cognitive processes, such as on the performance of memorised music, it has been speculated that the alpha/theta protocol, although trained at posterior sites, may possibly impact on the generators of frontal midline theta activity (Egner & Gruzelier, 2003).

METHODS

Subjects. The subjects were 48 student volunteers (29 females, 19 males, mean age = 22.3, SD = 1.90) from the Royal College of Music and Imperial College London, who gave informed consent for participation in the studies. All data included in this report stem from investigations that received ethical approval by the Riverside Research Ethics Committee. The subjects took part in alpha/theta neurofeedback training regimes of either (a) ten training sessions at electrode PZ (group "PZ10"; n = 28; 19 females), (b) five training sessions at electrode PZ (group "PZ5"; n = 10; 3 females), or (c) ten training sessions at electrode FZ (group "FZ10"; n = 10; 7 females). Gender was not considered as a between-subjects factor, as there were no theoretical reasons for assuming differential effects.

Neurofeedback training. All subjects were trained with Neurocybernetics EEG biofeedback equipment (Encino, CA; software version 3.02). EEG was recorded from PZ or FZ, referenced and grounded to electrodes placed on left and right earlobes respectively. A ProComp differential amplifier (Thought Technology Ltd; Montreal, Quebec) acquired signal at 256 Hz (granting a resolution of < .01 Hz), with a gain of 10,000. Impedance was kept below 10 KΩ. The raw signal was A/D converted and low-pass filtered (0-30 Hz), and band-filters were used to extract the components to be used in the feedback task (alpha: 8-11 Hz; theta: 5-8 Hz) with a smoothing time constant of 0.5 seconds. Artifact rejection thresholds were set closely around the raw (0-30 Hz) EEG trace for each subject individually in order to suspend feedback during gross EEG fluctuations due to motor activity.

Relative increases in alpha activity were represented by volume levels of a background sound resembling a "babbling brook" with activity exceeding pre-set thresholds additionally eliciting a high gong sound. Relative increases in theta activity were represented by volume levels of an "ocean waves" background sound, with temporary supra-threshold activity additionally eliciting a low pitch gong sound. Initial alpha and theta "gong" thresholds were based on pre-feedback baseline measures taken during a two-minute period of behavioural stillness with eyes closed at the beginning of each session. Thresholds were set to trigger supra-threshold activity between 30 and 60 % of the time for both bands. During the course of each training session, the experimenter aimed to set identical reward threshold values (in terms of absolute amplitude values) for alpha and theta bands, if such setting would keep both of the bands within a range of minimally 30% to maximally 65% of time above threshold.

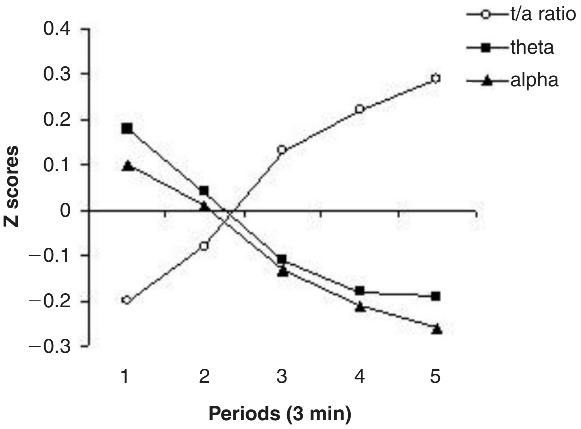
Each session of alpha/theta training consisted of 15 minutes of active feedback. Subjects rested on a comfortable reclining chair. The rationale of the alpha/theta feedback loop was explained to the subjects and they were instructed to relax deeply while allowing the feedback to guide them into maximising the amount of time spent hearing the "theta sound" feedback. Thus, the feedback contingencies were aimed at facilitating an increase in the theta/alpha ratio. After applying the electrodes, subjects were asked to relax with their eyes closed for a two-minute baseline period after which feedback, played via headphones, was initiated. The experimenter monitored the EEG for occurrence of sleep spindle activity, and if the experimenter suspected the subject had fallen asleep, the subject would be nudged slightly until they acknowledged they were awake. After 15 minutes of feedback were completed, the auditory feedback signal was slowly faded out to terminate the session.

Data analysis. From each 15-minute session, average amplitude measures in the alpha and theta bands were derived for five consecutive three-minute blocks or "periods." From these values, theta-to-alpha ratios were calculated for each period. To provide measures of within-session learning, the alpha, theta, and t/a ratio values were correlated with number of periods (one to five) averaged across sessions. As measures of between-session learning, values of alpha, theta, and t/a ratios were averaged for each session and correlated with number of sessions. The progression of within-session learning across sessions was assessed by correlating the within-session t/a ratio by period correlation coefficient (the within-session learning measure described above) with the number of sessions. In order to accommodate the possibility of less linear learning responses to the training (not captured by linear correlation coefficients), alpha and theta amplitudes, and t/a ratios were also compared between the first two and last two periods within sessions by paired-samples t-tests. Similarly, the EEG data were also compared between early and late sessions across the training program, by contrasting the first five with the last five sessions in the training groups that underwent 10 sessions of training, and by contrasting the first two and last two sessions in the group that included only five sessions with paired-samples t-tests. Test results were accepted as statistically significant at $\alpha < 0.05$.

RESULTS

Within-session dynamics. For the PZ10 group, a significant positive period by t/a ratio correlation was obtained ($r = .19, p < .05$), while number of periods correlated negatively with absolute alpha ($r = -.17, p < .05$) and theta ($r = -.15, p = .071$) amplitudes. In order to plot the absolute amplitude values and the ratio measure in the same graphs, z-score transformations were applied to all data. Figure 1 displays normalised (z-scores) amplitude and t/a ratio values across periods, and it can be seen that the increase in t/a ratio is mediated by a slightly less steep reduction in theta than in alpha activity. Accordingly, the t/a ratio correlated negatively with theta amplitudes ($r = -.28, p < .005$), and to a much greater degree negatively with alpha amplitudes ($r = -.68, p < .001$). Similarly, when comparing the first two with the last two periods, it was found that there was a significant increase in t/a ratio (t [d.f. =

FIGURE 1. Within-session alpha, theta, and theta/alpha (t/a) ratio values (normalised) for subjects trained at PZ over ten 15-minute sessions.

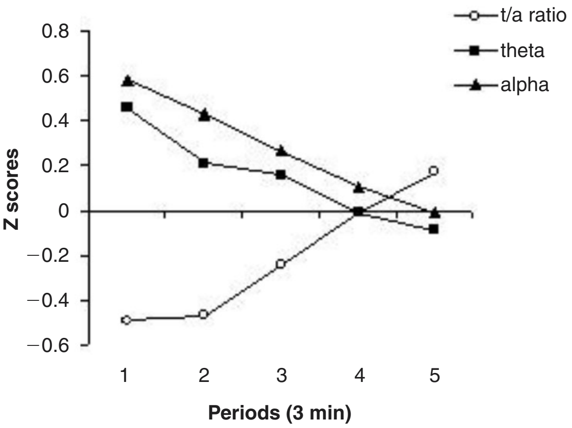


27] = −4.57, $p < .001$) and decrements in alpha (*t* [d.f. = 27] = 6.34, $p < .001$) and theta amplitudes (*t* [d.f. = 27] = 4.69, $p < .001$).

For the PZ5 group, the period by t/a ratio correlation did not reach a statistically significant level ($r = .24$, $p = .094$), and neither did the period by alpha or theta amplitude correlations. As can be seen in Figure 2 however, the temporal within-session EEG dynamics were very similar to those found in the PZ10 group, in that an incremental trend in t/a ratio was mediated by concurrent decrements in alpha and, to a slightly lesser degree, theta activity. Accordingly, t/a ratio values were negatively correlated to both alpha ($r = -.66$, $p < .001$) and theta activity ($r = -.52$, $p < .001$). Furthermore, when comparing early versus late periods, significant increments in t/a ratio (*t* [d.f. = 9] = −4.43, $p < .005$) as well as reductions in alpha amplitude (*t* [d.f. = 9] = 2.79, $p < .05$) were evident. When analysing the within-session data from the PZ10 group in a way that only takes into account the first five sessions, results very similar to those of the PZ5 group were obtained. There were no significant t/a ratio, alpha, or theta by period number correlations, but in paired-sample comparisons between early and late periods, significant t/a ratio increments (*t* [d.f. = 27] = −.317, $p < .005$) as well as alpha (*t* [d.f. = 27] = 5.20, $p < .001$) and theta (*t* [d.f. = 27] = 4.35, $p < .001$) amplitude reductions were also found.

In the FZ10 group, no evidence for a progressive increase of t/a ratios

FIGURE 2. Within-session alpha, theta, and theta/alpha (t/a) ratio values (normalised) for subjects trained at PZ over five 15-minute sessions.



across periods was found. No significant changes in EEG measures were found between early and late periods of the training sessions either. As can be observed in Figure 3, the dynamics underlying changes in within-session t/a ratios in the FZ10 group were quite different than those found in the groups trained at PZ, in that t/a ratio values correlated positively with theta ($r = .66, p < .001$) as well as alpha activity ($r = .42$, $p < .005$).

Between-session dynamics. In the PZ10 group, no correlation between t/a ratios and number of sessions was found. However, as shown in Figure 4, there was a significant positive session by theta amplitude correlation ($r = .14$, $p = .05$). Similarly, a significant increase in theta amplitude between the first and second half of the training sessions was detected (t [d.f. = 27] = -2.10, $p < .05$). The dynamics between alpha and theta amplitudes across sessions that mediated fluctuations in t/a ratio values were similar to the within-session data, as t/a ratios correlated negatively with both alpha ($r = -.63, p < .001$) and theta amplitudes ($r = -.19, p < .005$).

In the PZ5 group, neither session correlation effects, nor differences between early and late sessions were found (see Figure 5). Similar to the PZ5 within-session data and the PZ10 between-session data, t/a ratio values were also negatively correlated to both alpha ($r = -.644$, $p = .000$) and theta amplitudes ($r = -.435$, $p = .002$). When considering only the first five sessions trained in the PZ10 group, there were also no

FIGURE 3. Within-session alpha, theta, and theta/alpha (t/a) ratio values (normalised) for subjects trained at FZ over ten 15-minute sessions.

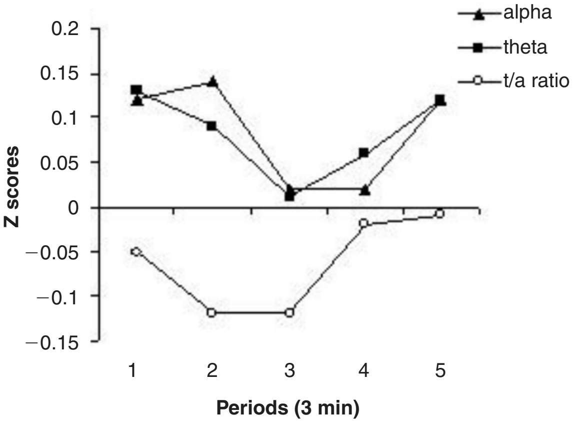


FIGURE 4. Between-session alpha, theta, and theta/alpha (t/a) ratio values (normalised) for subjects trained at PZ over ten 15-minute sessions.

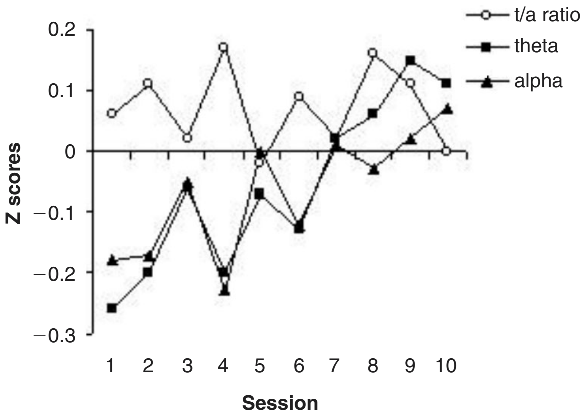
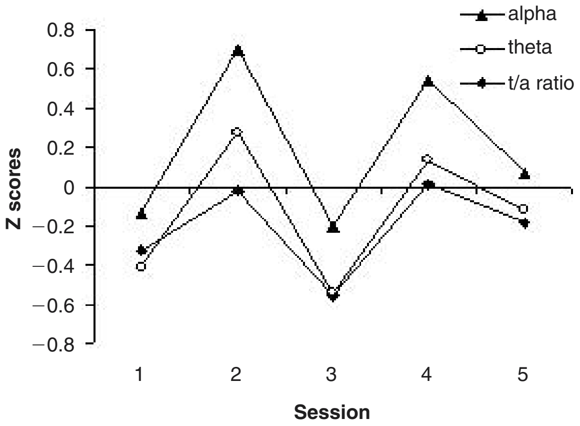
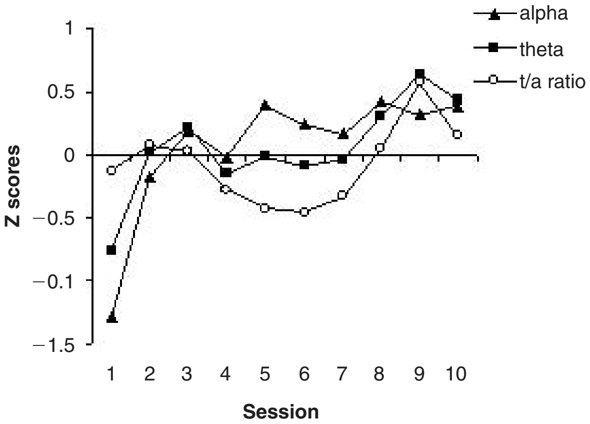


FIGURE 5. Between-session alpha, theta, and theta/alpha (t/a) ratio values (normalised) for subjects trained at PZ over five 15-minute sessions.



significant EEG measures by session correlation effects obtained. However, in comparing early versus late sessions in this group, a significant increase in theta amplitude emerges (t [d.f. = 27] = −2.43, $p < .05$), probably due to the higher power supplied by the higher number of subjects compared to the PZ5 group. In the FZ10 group, no session effects were evident (see Figure 6) in either linear correlation analyses or con-

FIGURE 6. Between-session alpha, theta, and theta/alpha (t/a) ratio values (normalised) for subjects trained at FZ over ten 15-minute sessions.



trast between early and late training stages. The relation between t/a ratio values and theta amplitudes was found to be positive (*r* = .37, *p* < .005) as it was in the within-session data, but no significant correlation was obtained between t/a ratios and alpha activity.

Progressive t/a ratio by period correlation across sessions. When correlating the t/a ratio by period correlation coefficients for each session by the number of sessions, no significant association emerged in the PZ10 or in the PZ5 group. However, in the FZ10 group, a progressively steeper slope of the t/a ratio by period correlation was evident with increasing number of sessions (*r* = .22, *p* < .05). Accordingly, in the FZ10 group, the t/a ratio by period correlations were significantly higher in the second half of the training process than in the first half (*t* [d.f. = −3.59, *p* < .01).

DISCUSSION

The results have revealed a number of important characteristics of EEG responses to alpha/theta feedback training pertinent to the understanding of the workings of this protocol. In groups of subjects who were trained over either five or 10 sessions at the PZ electrode, EEG responses in the form of the t/a ratio reflected within-session increments in this measure that corresponds to the operant contingencies of the training protocol. Interestingly, the increase in t/a ratio was associated with decreasing amplitudes in both alpha and theta, and was mediated by a less steep decrement in theta than in alpha activity. These data document that, while producing progressive within-session increases of theta-over-alpha activity in *relative* terms, alpha/theta feedback does not actually facilitate within-session increments in absolute activity in either of these feedback bands. This EEG signature corresponds to the one encountered during wakefulness-to-sleep transition (De Gennaro et al., 2001), suggesting that relative theta increments reinforced during alpha/theta feedback are reflective of deactivation.

In spite of these within-session decrements in theta activity, over the course of 10 training sessions at PZ, absolute theta activity was found to have increased significantly, suggesting that in the long run, the protocol does facilitate a real increment in the main targeted feedback band. This between-session effect was not found within five sessions of training at PZ in a group of 10 subjects, which shows that any efficacy of the training that is purported to relate to actual changes in EEG activity may not be expected to be manifest after only five training sessions. However, when considering the first five training sessions in the larger (n = 28) PZ10 group, significant theta activity increments are already observed at this training stage. The t/a ratio measure was not found to differ systematically across sessions, but the relation of t/a ratio to absolute alpha and theta amplitudes displayed a significant negative correlation in both groups that were trained at PZ.

The group of subjects who were exposed to 10 sessions of alpha/theta training at the rather unconventional frontal midline site displayed different EEG responses than the PZ groups. There was no evidence for any within-session or between-session changes in alpha, theta, or t/a ratio values. However, the group exhibited a significant progression of higher t/a ratio by period correlations across the training course, reflecting an increasing ease of producing an EEG response in line with the operant contingencies of the feedback loop. Importantly, the nature of the t/a ratio in this frontal training group was strikingly different from the posterior training groups, in that fluctuations in the t/a ratio were positively correlated with within-session alpha and theta changes, as well as with between-session theta changes. Thus, at the frontal midline site, it was relatively larger increments in theta than in alpha that underpinned any increase in t/a ratio, rather than a lesser decrease in theta than alpha activity that characterised t/a ratio changes in the PZ groups.

These data suggest that the theta and alpha activity involved in a frontal midline feedback protocol can be assumed to be of a different nature than the presumably arousal-related activity recorded in the traditional posterior protocol. By the same token, the results imply that the traditional posterior paradigm may not recruit neuronal sources associated with frontal midline theta production, where phasic theta bursts are encountered during states of highly focused concentration (e.g., Gevins et al., 1997; Aftanas & Golocheikine, 2001). The precise pinpointing of potential cognitive effects of posterior alpha/theta training on laboratory tasks, as well as an account for the effects obtained on such a complex real-life task as music performance, awaits future study. While no data have been supplied in the current study to suggest the usefulness of a frontal midline training protocol, the results at least suggest that feedback training of theta phenomena other than those associated with deep relaxation/deactivation may be a practical feasibility. However, a recent attempt of training central (CZ) theta enhancement in healthy subjects in a visual feedback paradigm has produced results suggesting that subjects did not learn to modulate this activity, and no cognitive effects were associated with this protocol (Vernon et al., 2003).

It should further be noted that conclusions from the current study are restricted to healthy subject populations only, and that it is currently not known whether the patient populations in which the alpha/theta protocol has been employed previously do exhibit comparable EEG characteristics in response to the feedback process.

CONCLUSIONS

In summary, it was found that EEG responses to traditional, posterior trained alpha/theta feedback in healthy volunteers are characterised by a within-session t/a ratio increase that is mediated, however, by within-session decrements in both alpha and theta amplitudes. Over the course of a training program of either 5 or 10 sessions however, this within-session signature is nevertheless associated with significant increments in absolute theta activity across sessions. In addition to a previous study showing post-training spectral EEG topographical increments in widespread slow waves and reductions in frontal fast wave activity (Egner et al., submitted) this documentation of between-session effects on theta activity supplies further evidence for an empirically-based neurophysiological rationale of alpha/theta training. The results pertaining to an experimental application of the alpha/theta neurofeedback protocol to frontal midline regions have indicated that the alpha and theta components involved in voluntary self-regulation at anterior sites appear to be of a different nature, and presumably different neurogenesis, than the ones involved in the posterior recordings. This finding in turn suggests that the type of theta activity that is modulated in the traditional alpha/theta protocol is not directly related to theta phenomena recorded at frontal midline sites.

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