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# Can Neurofeedback Training Enhance Performance? An Evaluation of the Evidence with Implications for Future Research

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*There have been many claims regarding the possibilities of performance enhancement training. The aim of such training is for an individual to complete a specific function or task with fewer errors and greater efficiency, resulting in a more positive outcome. The present review examined evidence from neurofeedback training studies to enhance performance in a particular area. Previous research has documented associations between specific cortical states and optimum levels of performance in a range of tasks. This information provides a plausible rationale for the use of neurofeedback to train individuals to enhance their performance. An examination of the literature revealed that neurofeedback training has been utilised to enhance performance from three main areas; sport, cognitive and artistic performance. The review examined evidence from neurofeedback training studies within each of these three areas. Some suggestive findings have been reported with regard to the use of neurofeedback training to enhance performance. However, due to a range of methodological limitations and a general failure to elicit unambiguous changes in baseline EEG activity, a clear association between neurofeedback training and enhanced performance has yet to be established. Throughout, the review highlights a number of recommendations to aid and stimulate future research.*

**KEY WORDS:** neurofeedback; performance enhancement; sport; attention; memory; music; dance.

Recent years have seen a dramatic increase in the number of claims made concerning the possibility of improving some aspect of either physical or cognitive performance via the use of feedback training (see e.g., Norris & Currieri, 1999), and the availability of venues offering such opportunities. However, an important question remains to be addressed, and that is whether such claims are supported by scientific evidence showing that it is possible to enhance some aspect of performance using this technique.

Traditionally, performance has been characterised as operating along a continuum, with dysfunctional performance positioned at one extreme and optimal performance positioned at the other (see e.g., Kirk, 2001). Changes in performance may either bring those within a distressed population, which operate at or near the dysfunctional end of the

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spectrum, up to a normative baseline, or enhance the performance of those at the normative baseline moving them closer to the optimal region. The focus of interest for this review is the training of a non-distressed population of healthy individuals whose initial performance falls within a normative baseline.

The aim of the review is to examine the evidence for using electroencephalographic (EEG) biofeedback, or neurofeedback, to enhance performance, identifying a possible rationale for such training whilst highlighting some suggestions for future research. The review will initially define neurofeedback and outline how such a technique may be used to alter electro-cortical activity. A comprehensive examination of the scientific literature was conducted (this was not restricted to any time frame and included literature searches of databases such as BIDS, PubMed and Psychlit. In addition to this, various on-line resources were utilised, such as the websites of relevant societies and any relevant conference proceedings, as well as websites of neurofeedback providers). This revealed that this technique has been used in an effort to influence performance within three main areas: these include sport, cognitive performance and artistic performance, see Table I for a summary. Hence, the review focuses on evidence of enhanced performance using this technique from each of these three areas.

## NEUROFEEDBACK

EEG biofeedback, or neurofeedback, is a sophisticated form of biofeedback based on specific aspects of cortical activity. It requires the individual to learn to modify some aspect of his/her cortical activity. This may include learning to change the amplitude, frequency and/or coherence of distinct electrophysiological components of one's own brain. The goal of neurofeedback training is to teach the individual what specific states of cortical arousal feel like and how to activate such states voluntarily. For example, during neurofeedback training the EEG is recorded and the relevant components are extracted and fed back to the individual using an online feedback loop in the form of audio, visual or combined audio-visual information. Such a format is able to represent each of the relevant electrophysiological components separately: for example, as a bar with the amplitude of a frequency represented by the size of the bar. The individual's task may then be to increase the size of the training-frequency bar and simultaneously decrease the size of the bars representing inhibitory-frequencies. On meeting this goal, a tone may sound and a symbol appear to indicate a point scored, with the aim to score as many points as possible.

It has been suggested that research aimed at enhancing performance has a number of distinct aims, these include controlling the level of arousal, attention and motivation, optimising the level of autonomic control, and the ability to shift states at will, as well as developing rehabilitative interventions for athletes suffering injury (Landers, 1985; Norris & Currieri, 1999; Wilson & Gunkelman, 2001).

The underlying rationale of using neurofeedback training to enhance performance is one based on associations. By identifying associations between particular patterns of cortical activity and specific states or aspects of behaviour that are classified as 'optimal,' one can attempt to train an individual to enhance performance by mirroring the pattern of cortical activity seen during such optimal states. An implicit assumption that permeates the neurofeedback literature and underpins current practice is that the training process will lead to changes in the EEG, which in turn produces changes in behaviour. However, it

**Table I.** Summary of Studies Using Neurofeedback Training to Enhance Sport, Cognitive and Artistic Performance

| Reference | *N* | Location | Feedback protocol | Feedback | Number of sessions | Behaviour | Learned changes in EEG | Outcome |
|---|---|---|---|---|---|---|---|---|
| Sporting performance | | | | | | | | |
| Landers et al. (1991) | 1.8<br>2.8 | T3 and T4 | Regulation of slow cortical potentials (SCP) | Visual | As many as needed to show shift | 27 shots at target | Both groups showed increase in power for 5–30 Hz for both LH and RH | LH training improved shots RH training resulted in poorer shots |
| Cognitive performance | | | | | | | | |
| Beatty et al. (1973) | 1.12<br>2. 7 | O1 and P3 | 1. Suppress theta (3–7 Hz)<br>2. Enhance theta (3–7 Hz) | Auditory eyes open | 2 × 1-h | Radar detection task | 1. Showed less theta<br>2. Showed more theta<br>2. Poorer radar performance | 1. Better radar performance<br>2. Poorer radar performance |
| Bauer (1976) | 13 | O1, O2, P3, C3, Cz, T3 | Enhance alpha (8.5–12.5 Hz) | Auditory eyes open | 4 × 1-h sessions | Free recall digit span | Showed increase in alpha | No change in recall |
| Rasey et al. (1996) | 4 | CPz–PCz | Increase beta (16–22 Hz) | Visual and auditory | Mean of 20 sessions | IVA | Limited individual correlations | Faster RTs on IVA |
| | | | Decrease high theta and low alpha (6–10 Hz) | | | WAIS-R | | No change on IVA or WAIS-R scores |
| Boynton (2001) | 30 | Pz | Increasing theta (4–8 Hz) over alpha (8–12 Hz) | Auditory | 8 | Creativity and well-being | No | No change in behaviour |

**Table I.** Continued

| Reference | $N$ | Location | Feedback protocol | Feedback | Number of sessions | Behaviour | Learned changes in EEG | Outcome |
|---|---|---|---|---|---|---|---|---|
| Egner and Gruzelier (2001) | 22 | 1. C3 | 1. Enhance beta1 (15–18 Hz) | Visual and auditory | 10 | TOVA | No | |
| | | 2. C4 | Inhibit theta (4–7 Hz) and high beta (22–30 Hz) | | | P3b ERP | | Reduction in commission errors, increase in $d'$ and P3b amplitude |
| | | | 2. Enhance SMR (12–15 Hz) Inhibit theta (4–7 Hz) and high beta (22–30 Hz) | | | | | |
| Vernon et al. (2003) | 1. 10 | Cz | 1. Enhance theta (4–8 Hz) | Visual and auditory | 8 | Attention CPT | 1. No | 1. No change in behaviour |
| | 2. 10 | | Inhibit delta (0–4 Hz) and alpha (8–12 Hz) 2 Enhance SMR (12–15 Hz) Inhibit theta (4–7 Hz) and high beta (18–22 Hz) | | | Semantic working memory | 2. Increase in SMR | 2. Increased recall in semantic working memory |
| Egner and Gruzelier (2004) | 1. 9 | Cz | 1. Enhance SMR (12–15 Hz) and inhibit theta (4–7 Hz) and high beta (22–30 Hz) | Visual and auditory | 10 | 1. TOVA, Divided attention task (DAT), Auditory oddball task | No | 1. Increased $d'$ and reduction in omission errors |
| | 2. 8 | | 2. Enhance beta1 (15–18 Hz) and inhibit theta (4–7 Hz) and high beta (22–30 Hz) | | | 2. TOVA, Divided attention task (DAT), Auditory oddball task | | 2. Reduction in RT and increased P3b amplitude |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Music performance | | | | | | | | |
| Egner and Gruzelier (2003) | 1. 22 | 1. C4, C3, Pz (combined) | 1. Enhance SMR (12–15 Hz), beta1 (15–18 Hz), theta (5–8 Hz) over alpha (8–11 Hz) (combined) | 1. Combination of visual and auditory, and auditory alone | 1.10 | 1. Music performance | 1. No | 1. Marginal improvement in music ratings associated with theta over alpha training only |
| 1. Experiment 1 | 2.1.9 | 2.1. C4 | 2.1. Enhance SMR (12–15 Hz) and inhibit theta (4–7 Hz) and high beta (22–30 Hz) | 2.1. Visual and auditory | 2.1.10 | 2.1. Music performance | 2.1. No | 2.1. No |
| 2. Experiment 2 | 2.2. 9 | 2.2. C3 | 2.2. Enhance beta1 (15–18 Hz) and inhibit theta (4–7 Hz) and high beta (22–30 Hz) | 2.2. Visual and auditory | 2.2.10 | 2.2. Music performance | 2.2. No | 2.2. No |
| | 2.3.8 | 2.3. Pz | 2.3. Enhance theta (5–8 Hz) over alpha (8–11 Hz) | 2.3. Auditory alone | 2.3. 10 | 2.3. Music performance | 2.3. No | 2.3. Improvement in music performance |
| Raymond et al. (2005) | 6 | Pz | Enhance theta (4.5–7.7 Hz) over alpha (8.5–11.5 Hz) | Auditory alone | 10 | Dance performance | No | Some improvement in dance performance |

*Note*. Showing, reference, sample size, location of neurofeedback training, parameters trained, type of feedback (i.e., auditory/visual), number of sessions, behaviour measured/examined, evidence of learning to alter the EEG and any reported changes in behaviour.

should be noted that the link between these components is not well established in either performance enhancement (see e.g., Egner, Zech, & Gruzelier, 2004) or the clinical literature (see e.g., Vernon, Frick, & Gruzelier, 2004), especially with respect to predictable changes and correlations between changes and outcome variables. For instance, research has shown that healthy participants learning to enhance low beta (11.7–14.6 Hz) at Cz exhibited a post-training decrease in low beta in the prefrontal region, and a decrease in alpha (7.8–11.7 Hz) at left-frontal regions (Egner et al., 2004). Whilst learning to raise theta (3.9–7.8 Hz) over alpha (7.8–11.7 Hz) at Pz was associated with a post-training reduction of beta1 (14.6–17.5 Hz) at prefrontal scalp sites. Furthermore, additional examination of these effects only managed to partially replicate these findings, showing that raising theta over alpha was associated with a reduction in prefrontal beta1. This shows that learning to temporarily enhance the amplitude of a specific frequency component during neurofeedback training does not necessarily translate to increased activity in that component whilst at rest. The reason for this pattern of effects is, as yet, unclear. It is possible that the difficulty in producing a clear and consistent effect on baseline EEG levels is due to the underlying complexity of the neural dynamics of the EEG. Nevertheless, further systematic investigation is imperative to examine and produce empirical validation of predictable neurophysiological outcomes as a result of neurofeedback training.

## SPORTS

Previous research has examined the EEG of expert sportsmen and found that they exhibit a distinct pattern of cortical activity from that seen in the amateur (see e.g., Bird, 1987; Collins, Powell, & Davies, 1990; Crews & Landers, 1993; Hatfield, Landers, & Ray, 1984; Radlo, Steinberg, Singer, Barba, & Melinkov, 2002; Salazar et al., 1990; Wilson, Ainsworth, & Bird, 1985). Identification of the EEG state of sporting experts prior to and during their performance provides a plausible rationale for the use of neurofeedback to create, or mimic, such patterns in the non-expert in an attempt to enhance sporting performance.

Research examining the psychophysiology of sports performers has reported hemispheric asymmetries in the EEG prior to the execution of a skill. For instance, Hatfield et al. (1984) found that during the preparatory period of a skill, left-temporal EEG alpha activity (8–12 Hz) significantly increased. A similar finding was reported by Salazar et al. (1990) who found a significant increase in spectral power at 10 and 12 Hz in the left-temporal region prior to the performance of a skill. This increase in EEG activity within the alpha frequency range has been interpreted as representing a reduction of cortical activation in the left-temporal region, reducing the covert verbalisations of the left-brain and allowing the visual-spatial processes of the right hemisphere to become more dominant (Salazar et al., 1990). These findings led researchers to examine whether a reduction in left-temporal activity prior to skill execution can be augmented via neurofeedback, and whether such training would benefit performance (Landers et al., 1991). Landers et al. (1991) examined three groups of pre-elite archers, two of which received neurofeedback training whilst the third acted as a non-contingent control group. The neurofeedback paradigm was modelled after a slow potential feedback paradigm, whereby those receiving neurofeedback training were encouraged to shift their level of cortical activity towards more negativity in either the left-temporal region or the right-temporal region. The number of neurofeedback training sessions varied, continuing until each participant reached a pre-set criterion with regard to EEG amplitude. Pre- and post training, all groups were assessed by completing a total of 27 shots at a target positioned 45 m distant, with the level of performance measured as the distance between the arrow and the centre of the target. They found that those trained to shift the level of cortical activity towards more negativity in the left-temporal region showed a significant improvement in performance, and those trained to shift the level of cortical activity towards more negativity in the right-temporal region showed significantly poorer performance.

There was no change in performance of the control group. However, examination of participants' EEG spectra from pre- to post training failed to reveal a clear pattern of change as a result of neurofeedback training. For instance, all groups, including non-feedback controls, showed an increase in power between the ranges of 5–11 and 13–30 Hz in the left hemisphere, and between 5 and 11 Hz in the right hemisphere. Nevertheless, the group given right-temporal feedback did exhibit a greater increase in power in the 13–30 Hz range in the right hemisphere compared with both the left-temporal feedback group and the control group. These findings led Landers et al. (1991) to conclude that the results provided some support for the use of neurofeedback as a method of enhancing the performance of pre-elite archers.

Whilst the findings from the Landers et al. (1991) study are encouraging they are by no means conclusive and a number of issues remain that need to be directly addressed by future researchers in order to fully elucidate the role that neurofeedback may play in enhancing the performance of athletes. First, training participants to shift their cortical level towards an increase in negativity within a particular hemisphere may be a less efficient method to enhance performance than training them to alter a particular frequency component of the EEG. For instance, previous research has shown significant increases in left-hemisphere alpha activity (8–12 Hz) during shot preparation of skilled marksmen (Hatfield et al., 1984), and between the best and worst shots of elite archers (Salazar et al., 1990). An overall increase in alpha power during the time that karate experts break wooden boards (Collins et al., 1990) and an increase in right-hemisphere alpha associated with decreased errors for highly skilled golfers has also been demonstrated (Crews & Landers, 1993). However, such changes are not consistent in location, or direction, which may be accounted for in terms of differences in sporting requirements. Nevertheless, a more systematic examination of the effect of neurofeedback training for athletes needs to include an examination of the enhancement and/or inhibition of each of the main frequency components associated with peak athletic performance. Furthermore, directly training a specific frequency component may make it easier to identify possible changes in the EEG associated with enhancing athletic performance. Finally, Landers et al. (1991) provided only visual feedback in the form of moving horizontal bars, where the position of the bar operated as a function of the slow potential shift during that trial. A recent review of clinical studies utilising neurofeedback for attention-deficit/hyperactivity disorder (ADHD) found that the majority of researchers use a combination of both visual and auditory feedback (Vernon, Frick, et al., 2004). Vernon, Frick, et al. (2004) suggest that providing both auditory and visual feedback, as opposed to a single modality, may be a more efficacious way of informing the participant of his/her psychophysiological state. Future research could directly address this issue by comparing visual feedback alone, auditory feedback alone or combined visual-auditory feedback to ascertain which method provides the most efficient training regime.

## COGNITIVE PERFORMANCE

There is a great deal of research examining the association between particular EEG frequency components and performance on specific cognitive tasks. It is beyond the scope of this article to provide a comprehensive review of what is known about such associations (for a useful review see, Klimesch, 1999) and the focus of this review is on the use of neurofeedback to enhance performance. Nevertheless, a brief synopsis of some of the main findings will serve to provide a rationale for the use of neurofeedback to enhance cognitive performance.

It is known from previous research that theta activity (4–7 Hz) has an influence on the cellular mechanisms of memory through its role in facilitating long-term potentiation (LTP) (e.g., Pavlides, Greenstein, Grudman, & Winson, 1988), and more recent studies have documented a link between recognition memory processes and theta activity recorded from the scalp (Burgess & Gruzelier, 1997). Convincing evidence of the direct relationship between theta and working memory stems from data showing that, during the encoding phase of a recognition task, only words that were later correctly recognised elicited a significant increase in theta activity (Klimesch, Doppelmayr, Schimke, & Ripper, 1997). In addition, during the latter recognition phase, greater theta activity was found for correctly recognised words but not distractors.

Research focusing on alpha (8–12 Hz) activity has shown that verbal thoughts are associated with a decrease in alpha in the left hemisphere and visual thoughts are associated with a decrease in alpha in the right hemisphere (Schwartz, Davidson, & Pugash, 1976). More recently, it has been suggested that the alpha frequency range should be separated into lower alpha (7–9.5 Hz) and upper alpha (9.5–12 Hz), based on the findings showing that the lower alpha band is predominantly associated with attentional processes, whereas upper alpha is primarily associated with semantic memory processes (Klimesch et al., 1997; Klimesch, Schimke, Ladurner, & Pfurtscheller, 1990; Klimesch, Schimke, & Schwaiger, 1994). Examination of the interplay between working memory and long-term memory has suggested that theta activity (4–8 Hz) reflects the processes of working memory, whilst upper alpha (9.5–12 Hz) reflects retrieval from long-term memory (Klimesch et al., 1997; Sarnthein, Petsche, Rappelsberger, Shaw, & von Stein, 1998; Sauseng et al., 2002).

In addition to the findings outlined previously, which highlight associations between specific frequencies of the EEG and particular cognitive processes, researchers have also attempted to document differences in patterns of cortical activity associated with good and poor cognitive performance. For instance, individuals classified as highly creative exhibit a lower mean alpha index (i.e., percentage of time in alpha [7–13 Hz]), recorded from the right occipital-parietal region, than low creative individuals (Martindale & Armstrong, 1974). Furthermore, highly creative individuals also take less time to increase their alpha activity and are more efficient at alpha suppression than less creative individuals. In addition, examination of memory performance has shown that the alpha frequency of good memory performers is higher than that of bad performers (Klimesch et al., 1990; Klimesch, Schimke, & Pfurtscheller, 1993), whilst others have reported strong positive correlations between alpha power and intelligence (Doppelmayr, Klimesch, Stadler, Polhuber, & Heine, 2002).

The associations between specific frequency components of the EEG and different aspects of cognitive processing outlined previously provide a plausible rationale for the use of neurofeedback to enhance specific cognitive processes. For instance, if performance on a specific cognitive task is associated with a particular EEG frequency, or better performance with a particular aspect of the EEG, the aim would be to train individuals to enhance that frequency component.

In reviewing the literature on the use of neurofeedback to enhance cognitive performance it became apparent that researchers had focused on four main neurofeedback training protocols, each aimed at influencing a specific aspect of the EEG. These included neurofeedback training to influence theta, alpha, the alpha/theta ratio and beta training. To maintain a clear and coherent structure, the review will focus on evidence from research focusing on each of these frequency components.

## Theta Training

Research has shown that suppression of slow theta activity (as measured by the ratio between the number of waves in the theta frequency band and the total number of waves from 3 to 30 Hz) in the left parietal-occipital region ($O_1$ and $P_3$) is associated with a concomitant increase in attentional performance when completing a simulated radar monitoring task (Beatty, Greenberg, Diebler, & O'Hanlon, 1974). Based on the notion that a decrease in arousal may be associated with an increase in theta (3–7 Hz), Beatty et al. (1974) assigned 19 participants to two groups. One group underwent neurofeedback training to suppress theta, whilst the remaining group trained to enhance theta. The training for both groups consisted of two 1-h EEG conditioning sessions. Following the training participants from each group then completed a 120 min radar detection task whilst their EEG was either recorded (EEG-unregulated) or whilst they concurrently attempted to alter their theta activity using neurofeedback (EEG-regulated). Beatty et al. (1974) found that neurofeedback made it possible for participants to selectively alter their theta ratio. For instance, the theta suppress group showed less theta activity whilst simultaneously performing both neurofeedback and the radar monitoring task compared to the monitoring task alone. In contrast, the theta augment group produced more theta in the neurofeedback and the radar monitoring task compared to the monitoring task alone. This led them to suggest that neurofeedback is effective in inducing discriminate control of EEG activity. Furthermore, they found that the theta-augment group performed significantly worse at the radar detection task, whilst the theta-suppression group performed significantly better. There was no difference in radar monitoring performance of the two groups when their EEG was monitored but not fed back to them.

At first glance it would seem that these findings show that suppression of theta can enhance attentional performance. However, closer inspection suggests that before such a conclusion can be accepted a number of additional issues need to be addressed. First, whilst changes in attentional performance were reported to accompany changes in the theta ratio, it is not made clear that absolute levels of theta changed over time. For instance, a decrease in the theta ratio could well result from an increase in either alpha (8–12 Hz), beta (13–30 Hz) or a combination of the two. This can be readily addressed in future research that reports changes in EEG spectra ratios by also reporting absolute values and showing unambiguously what is increasing and what is decreasing. Secondly, it suggests that for neurofeedback training to have an influence on performance one needs to complete both neurofeedback training and the cognitive task simultaneously. This limits the applicability of the training beyond the laboratory. Although, given that no difference was found in radar monitoring performance between the groups when their EEG was monitored but not fed back may imply that the two 1-h neurofeedback training sessions were insufficient to produce long-term changes in theta activity. Future research could directly address this issue by monitoring the effect of neurofeedback training on cognitive performance following different training intervals.

## Alpha Training

Research focusing on the alpha (8.5–12.5 Hz) frequency has examined whether enhancing alpha activity can influence short-term memory performance (Bauer, 1976). Bauer trained 13 participants to enhance their level of alpha activity over the left parietal-occipital region of the cortex in four 1-h sessions. Feedback took the form of a 400-Hz tone to indicate the presence of alpha. Following this participants were subsequently tested using a verbal free recall task and digit span memory task whilst simultaneously attempting to produce alpha. Despite showing significant increases in the percentage of alpha activity participants exhibited no change in their level of recall for either task. This led Bauer (1976) to conclude that changes in alpha had no apparent functional significance for the learning process itself.

The fact that training to increase alpha had no discernable effect on short-term memory performance may have been due to the limited number of neurofeedback training sessions. However, given that participants did exhibit an increase in alpha and that previous research has shown an association between alpha and memory performance (e.g., Klimesch et al., 1990, 1993) this interpretation is problematic. There remain a number of possibilities why training overall alpha may have had no effect on short-term memory. The first and most obvious is that whilst neurofeedback training may be able to influence gross EEG activity it simply cannot influence cognitive performance. However, before such a possibility can be accepted a more rigorous and systematic examination of the effects of neurofeedback training on cognitive performance needs to be undertaken. Another possibility stems from the traditional assumption that peak alpha frequency is the same for everyone. Such an assumption is questionable, particularly when research has shown that peak alpha frequency can vary to a considerable extent in normal age-matched participants (Klimesch et al., 1990, 1993). Future research could directly address this by defining the frequency range of alpha individually for each participant (see Klimesch et al., 1990 for a description of this method). A further possibility stems from findings suggesting that alpha may be separated into a number of distinct components, including alpha 1 (6–8 Hz), alpha 2 (8–10 Hz) and upper alpha (10–12 Hz) (see e.g., Doppelmayr et al., 2002; Klimesch, Doppelmayr, Russegger, Pachinger, & Schwaiger, 1998; Klimesch et al., 1994). Here the suggestion is that lower alpha frequencies are associated with attentional demands, whilst the upper alpha frequency is related to semantic memory. As such, the type of task used to assess cognitive performance when training to enhance a particular aspect of alpha activity may need to be more closely matched to the suggested cognitive processes associated with that particular frequency range. It should be noted that the alternative interpretations offered here are purely speculative; nevertheless, they do provide some direction for future research.

## Alpha/Theta Training

Alpha/theta neurofeedback training represents a modification of a traditional neurofeedback training paradigm, whereby the individual attempts to increase his or her level of theta activity over that of alpha. Research has utilised this approach in an attempt to enhance creativity and well-being (Boynton, 2001). For instance, Boynton (2001) had two groups of participants complete an 8-week training regime. One of the groups received neurofeedback training to enhance theta (4–8 Hz) over alpha (8–12 Hz) (alpha/theta training) and the other acted as a non-contingent control group. Both pre- and post training groups completed measures of creativity, examining aspects of cognitive fluency, flexibility and originality, as well as a measure of behavioural well-being. Boynton (2001) found no change in the EEG of those completing the neurofeedback training and no pre- versus post training differences in creativity or well-being between the two groups.

This suggests that alpha/theta training has no effect on creativity or well-being. However, Boynton (2001) suggests that the lack of any clear effects may have resulted from a confound in the training program, which included several different components, making it impossible to effectively evaluate the contribution of each component. In addition to this, Boynton (2001) highlights the length of the training schedule and the 'small' sample size as being additional limiting factors. Future research could directly address these points by conducting a comparison of different training schedules to see if a more concentrated training regime would in fact have a more beneficial effect on an individual's ability to alter their EEG, as well as its possible influence on creativity. The issue of sample size could more easily be dealt with by conducting a-priori power analyses.

## Beta Training

Research has also examined whether neurofeedback training to alter the faster beta frequencies can influence attentional processing in healthy participants (Rasey, Lubar, McIntyre, Zoffuto, & Abbott, 1996). Rasey et al. (1996) reported on four participants who completed an average of 20 training sessions to enhance beta (16–22 Hz) and inhibit high theta and low alpha (6–10 Hz) at the central-posterior region (e.g., CPz–PCz). Participants completed a combination of 'feedback only' sessions, during which they were provided with both auditory and visual feedback, and reading and listening conditions. These involved the presentation of audio feedback whilst the participants either read or listened to someone else read. Cognitive performance was examined pre- and post training using the Intermediate Visual and Auditory (IVA) attention test and the Wechsler Adult Intelligence Scale-Revised (WAIS-R). The IVA is a computerised continuous performance test that provides measures of visual and auditory attention. The WAIS-R measures global or general intelligence and is divided into two parts: the verbal scale and the performance scale. Each of these two parts is further divided into subtests, each of which taps a specific verbal or nonverbal skill.

Post training analysis of participants' EEG revealed that two of the four participants exhibited some change in their EEG in the direction of the training, which although not conclusive was suggestive of learning. Analysis of behavioural data showed that none of the participants exhibited any improvement in their IVA scores; however, the two participants that exhibited changes in their EEG completed the IVA task in less time. Furthermore, Rasey et al. (1996) classified two of the participants as 'learners' on the basis of changes in their EEG and IVA scores. However, when WAIS-R performance for the two learners was compared to that of the non-learners they found that the two learners showed poorer performance on the vocabulary subtest that was at a level that suggested impairment (Rasey et al., 1996).

Rasey et al. (1996) suggest that the data highlights ‘improvements in attentional performance among learners’ and that ‘some college students can learn to increase EEG activity’ (p. 19). Such an optimistic interpretation of the data is difficult to understand given that there was no clear evidence of a change in the EEG, no improvement either in IVA or WAIS-R performance, and that those classified as ‘learners’ actually showed poorer performance on the vocabulary subtest of the WAIS-R. A plausible explanation for the weak effects found by Rasey and colleagues may be based on the lack of power of their study, resulting from a sample size of only four participants.

More recent research has extended this work to investigate the influence of training low beta frequencies (i.e., 12–15 and 15–18 Hz) on healthy individuals (Egner & Gruzelier, 2001). Egner and Gruzelier (2001) trained 22 participants to enhance low beta both in the 12–15 and the 15–18 Hz range, whilst simultaneously inhibiting theta (4–7 Hz) and high beta (22–30 Hz). The 12–15 Hz training was conducted at the right central region (i.e., C4) and the 15–18 Hz training was conducted at the left central region (i.e., C3). All participants completed a total of 10 neurofeedback training sessions whilst pre- and post measures of attention were examined using the Tests of Variable of Attention (TOVA) (Greenberg, 1987) and an auditory oddball task that also elicited P3b event related potentials. They found that comparing pre- versus post training performance on the TOVA showed a significant reduction in commission error rate and a marginal improvement in participants’ ability to discriminate potential targets. Furthermore, participants exhibited a positive correlation between enhancing 12–15 Hz and changes in error rates and discrimination, and a negative correlation between enhancing 15–18 Hz and changes in error rates and discrimination. Data from the auditory oddball task showed no reported change in attentional behaviour, although they did find a generalised increase in P3b amplitudes, which was positively correlated with enhancing both 12–15 and 15–18 Hz. They conclude that this pattern of results represents a ‘successful enhancement of attentional performance in healthy volunteers through EEG operant conditioning techniques’ (p. 9).

The study by Egner and Gruzelier (2001) represents a reasonable attempt at examining whether neurofeedback training can positively influence cognitive performance. However, the fact that no control group was included limits the findings, and suggests that the changes in attentional processing were nothing more than the result of practice effects. To their credit, Egner and Gruzelier (2001) acknowledge this point (see p. 10) but attempt to counter the argument by suggesting that the tests used are ‘free of any practice effects’ (p. 11). Even if this were true, which is something that could be disputed as the author is unaware of any research directly addressing this issue, the problem still remains that no significant changes in the EEG were found in those undergoing neurofeedback training. This limits the conclusion that operant conditioning of participants’ EEG enhanced attentional performance. Furthermore, changes in the amplitude of an event-related component linked to attentional processing would be important if such changes coincided with relevant behavioural changes. However, no behavioural data on auditory oddball performance were reported making it difficult to identify what, if any, change in the amplitude of such a component represents. That participants exhibited some improvement in task performance is reasonably clear. What remains ambiguous is whether or not neurofeedback training had anything to do with this.

Others have attempted to extend this work and suggest that neurofeedback training to enhance low beta activity may influence semantic working memory performance (Vernon, Egner et al., 2004; Vernon et al., 2003). Vernon et al. (2003) used neurofeedback to train participants to enhance a range of different EEG frequencies. One group trained to enhance theta (4–8 Hz) whilst simultaneously inhibiting delta (0–4 Hz) and alpha (8–12 Hz). A second group underwent training to enhance low beta (12–15 Hz) whilst simultaneously inhibiting theta (4–8 Hz) and high beta (18–22 Hz), and a final group acted as a non-contingent control group. Those participants receiving the neurofeedback training completed eight 15-min training sessions, with all training conducted at Cz. All three groups completed pre- and post measures of attention and semantic working memory. Attention was measured using a computerised continuous performance task (CPT) and semantic memory was examined using a computerised conceptual span task (see, Haarmann, Davelaar, & Usher, 2003).

Contrary to expectation they found that those training to enhance theta showed a marginal within session reduction of theta. However, participants training to enhance low beta (12–15 Hz) showed significant within session increases in low beta amplitude and decreases in both theta (4–8 Hz) and high beta (18–22 Hz) amplitudes. This shows that the low beta group exhibited learning of the neurofeedback parameters. With regards to behavioural performance there was no clear pattern of effects when comparing pre- and post CPT performance, with the low beta group exhibiting some improvement in the two-sequence task and all groups, including controls, exhibiting some improvement in the three-sequence task. Nevertheless, comparing pre- and post semantic working memory performance revealed that only the group training to enhance low beta showed a significant improvement. They account for this improvement by suggesting that enhancing 12–15 Hz aids the maintenance of the working memory representation utilised in semantic working memory.

This research represents a reasonable attempt to identify whether neurofeedback can enhance cognitive performance. However, there are a number of points that suggest that these results should be interpreted with caution. For instance, whilst participants exhibited changes in 12–15 Hz in the desired direction during the neurofeedback training sessions, no changes were found across the training sessions. Despite this lack of any change in baseline EEG levels it is suggested that the pre- versus post differences found in semantic working memory are attributable to neurofeedback training. The authors are aware of this point and are rightly cautious in their interpretation, suggesting that the increase in low beta is merely *associated* with improved recall in the semantic working memory task as opposed to offering it as a causal factor. Nevertheless, further doubt is cast on the use of neurofeedback to enhance semantic memory performance from more recent research that has attempted to replicate these findings and met with little success (Vernon, Ahmed, & Gruzelier, 2004).

More recently, Egner and Gruzelier (2004) examined whether enhancing low beta (12–15 Hz) and beta1 (15–18 Hz) may have differential effects on attentional processing. They randomly allocated participants to one of three groups, with each group focusing on a different neurofeedback protocol. The first group underwent neurofeedback training to enhance SMR (12–15 Hz) activity and inhibit theta (4–7 Hz) and high beta (22–30 Hz), the second group underwent neurofeedback training to enhance low beta (15–18 Hz) and inhibit theta (4–7 Hz) and high beta (22–30 Hz), and the third group engaged in a non-neurofeedback training regime utilising the Alexander technique. Participants undergoing neurofeedback training completed 10 weekly sessions, each lasting approximately 15-min, with recording conducted at Cz. The non-neurofeedback group completed a similar number of weekly sessions focusing on the use of the Alexander technique. Pre- and post training all three groups were tested using the TOVA, a divided attention test and for the two neurofeedback groups only, an auditory oddball task that elicited P300 event related potentials. Examination of TOVA data showed that the SMR group exhibited a marginal improvement in their ability to discriminate targets, whilst the beta1 group exhibited a significant decrease in response times. Data from the divided attention task showed that the SMR group exhibited a significant improvement in their ability to discriminate targets as well as a reduction in omission errors and response time variability. However, all groups exhibited a reduction in response times. Finally, analysis of performance on the auditory oddball task showed no evidence of a change in behaviour; however, the beta1 group did exhibit a significant increase in P3b amplitude. These findings led them to conclude that neurofeedback training to enhance amplitude in SMR and beta1 can lead to significant and 'specific effects on cognitive-behavioural and electrocortical measures of attentional processing' (Egner & Gruzelier, 2004, p. 137), and that training to enhance SMR may improve perceptual sensitivity, whilst beta1 training may increase cortical arousal.

This represents one of the more strictly controlled and useful studies showing possible improvements in attentional processing as a function of specific neurofeedback training. Nevertheless, it is not without its limitations. For instance, no pre- versus post changes in EEG were reported for those undergoing neurofeedback training. This makes it very difficult to attribute any changes in behaviour to possible changes in the EEG. Secondly, data showing that the beta1 group exhibited a significant reduction in response times and a slight but non-significant increase in commission errors when completing the TOVA may be more parsimoniously interpreted as the result of a speed–accuracy trade-off (see Egner & Gruzelier, 2004, Table I, p. 135). Finally, despite increases in P3b amplitude for the beta1 group, they exhibited no change in their ability to complete the task. Egner and Gruzelier (2004) acknowledge this point and interpret the pattern as one indicating an increase in overall cortical arousal only (see p. 138).

These results, combined with those reviewed previously, are suggestive in the sense that individuals do seem to be able to alter some aspects of their EEG using neurofeedback training. However, at present, the evidence that neurofeedback training can result in enhanced cognitive performance is ambiguous at best.

## ARTISTIC PERFORMANCE

Early research has shown that when passively listening to music, musicians produce more alpha wave activity than non-musicians do (Wagner, 1975b). Others have shown differences in the levels of coherence of the EEG between musically educated and non-musical participants (Petsche, Lindner, Rappelsberger, & Gruber, 1988). One suggestion is that such differences in alpha activity may reflect the training or education that musicians receive (Wagner, 1975a). More recently, it has been shown that musical imagination and composing elicit greater levels of coherence in particular EEG frequencies, and that beta activity plays a major role in the processing of music (Petsche, Richter, von Stein, Etlinger, & Filz, 1993).

These findings are not exhaustive and serve merely to identify that artistic performance may be associated with specific changes in particular frequency components of the EEG, and as such they provide a rationale for the use of neurofeedback to enhance artistic performance. This in mind, recent research has reported on two successive experiments aimed at using neurofeedback to enhance music performance (Egner & Gruzelier, 2003).

In the first of these, Egner and Gruzelier (2003) report on a group of music students who completed 10 sessions of neurofeedback training, each lasting 45 min, aimed at enhancing three distinct aspects of the EEG. The first 15 min were spent attempting to enhance the SMR rhythm (12–15 Hz) at C4, the second 15 min focused on enhancing beta1 (15–18 Hz) at C3, and the final 15 min on producing high theta (5–8 Hz) to alpha (8–11 Hz) ratios at Pz. In addition to this, a subset of this group also completed a regime of physical exercise and mental skills training. Pre- and post training, all participants were examined on a 15 min rendition of a piece of music of their choice. Their performance was assessed internally by a panel of judges from the Royal College of Music and externally by expert judges examining video recordings of each performance. They found that participants receiving neurofeedback training exhibited a marginal improvement in musical performance. In addition, they also found that participants that completed the alpha/theta training, a regime of weekly physical exercises and mental skills training exhibited a correlation between success on the alpha/theta protocol and improved musical performance.

In the second experiment, which utilised a similar design, Egner and Gruzelier (2003) report on a separate group of participants completing ten 15-min training sessions aimed only at enhancing theta over alpha at Pz. Post training examination of participants music performance revealed significant improvements in overall quality, musical understanding, stylistic accuracy and interpretive imagination. This led them to conclude that slow wave neurofeedback training can benefit the musical performance of a non-clinical group.

Whilst the results from both experiments are suggestive there are a number of limitations that restrict the interpretation that neurofeedback as an intervention can positively influence musical performance. In Experiment 1 it is unclear whether the success in learning to alter levels of alpha and theta is confounded by the order of training. For instance, all participants undergoing neurofeedback training initially completed 10 training sessions of SMR training, followed by beta1 training. This was then followed by a further 10 sessions of alpha/theta training. Thus, participants' ability to alter their alpha/theta levels may be nothing more than the result of these additional neurofeedback training sessions. In addition to this, it also remains unclear whether changes in the alpha/theta ratios were the result of alpha decreasing, theta increasing, or a combination of the two. Furthermore, the correlation reported between changes in alpha/theta and improved musical performance is confounded by including those who also completed the physical exercise regime and mental skills training. The implication here is that, at best, any improvement in musical performance is the result of a combination of alpha/theta training, physical exercise and mental skills training. Finally, in the second experiment changes in musical performance are again documented for those completing alpha/theta neurofeedback training. However, no changes in amplitude of theta, alpha or the theta-to-alpha ratio are reported. As such, a clear case cannot be made for suggesting that neurofeedback training alone can positively influence music performance.

In an attempt to gain further understanding of the potential use of neurofeedback to enhance artistic performance, researchers have compared alpha/theta neurofeedback training to traditional biofeedback training on dance performance (Raymond, Sajid, Parkinson, & Gruzelier, 2005). They allocated participants to one of three groups; Group 1 completed 10 sessions of neurofeedback training aimed at enhancing theta (4.5–7.7 Hz) over alpha (8.5–11.5 Hz) at Pz. Group 2 completed 10 sessions of biofeedback training aimed at controlling heart rate variability (HRV) and the final group acted as a non-contingent control group. Pre- and post training participants' dance performance from all three groups was rated by two qualified judges. These ratings showed that dance performance for all three groups improved. However, when differences in dance performance were divided by the number of practice sessions they found that only those completing some form of feedback training (i.e., neurofeedback or biofeedback) showed improved dance performance. This led them to suggest that both alpha/theta training and HRV biofeedback training can improve dance performance.

Whilst representing an interesting possibility this study is again limited by the fact that there were no reported changes in the EEG for those undertaking neurofeedback training, and no changes in HRV for those completing the biofeedback training. Furthermore, the improved dance performance shown by both feedback groups may be nothing more than a confound of participant–experimenter interaction. The failure to ensure that the control group maintained an equal level of experimenter contact gives rise to the possibility that both feedback interventions show an improvement in performance merely as a result of taking part in a training scheme, irrespective of what that scheme provided.

## CONCLUDING REMARKS

Given the reported association between specific patterns of cortical activity and particular levels of performance it seems plausible to utilise neurofeedback as a tool to train individuals to re-create patterns of cortical activity in an attempt to enhance performance. However, it seems the plethora of claims regarding the use of neurofeedback training to enhance performance is matched only by the paucity of research showing a clear effect. For instance, attempts to increase low frequency EEG oscillations in archers has been associated with improved accuracy, despite no clear pattern of changes in the EEG (Landers et al., 1991). Suppression of theta activity has been associated with increased attentional performance, but again there was no reported change in baseline levels of the EEG (Beatty et al., 1974). Meanwhile, attempts to increase alpha had no discernible effect on memory performance (Bauer, 1976), and alpha/theta training had no effect on creativity (Boynton, 2001). Research examining the effects of low beta neurofeedback training on cognitive performance has met with some intriguing results (Egner & Gruzelier, 2001, 2004; Rasey et al., 1996; Vernon, Ahmed, et al., 2004; Vernon, Egner, et al., 2004; Vernon et al., 2003). Nevertheless, a range of methodological flaws and a failure to document clear changes in the EEG following neurofeedback training limit such findings. A similar picture emerges for research utilising neurofeedback to enhance artistic performance (Egner & Gruzelier, 2003; Raymond et al., 2005). As such, whilst the findings outlined previously are suggestive, a clear connection between neurofeedback training and enhanced performance has yet to be established.

It should be stressed that it is not the aim of this review to suggest that neurofeedback training cannot enhance performance, merely that the evidence to date is equivocal. With this in mind, an additional aim of the present review was to identify possible shortcomings throughout and highlight a number of recommendations that future researchers may wish to adopt. These recommendations included: measuring pre- and post EEG baselines to monitor changes resulting from neurofeedback training. Where possible, utilising a moving baseline measurement of the EEG to control for possible changes in arousal. To always include a non-contingent control group, ideally one that receives everything the experimental group does, including equal contact time and ideally pre- and post QEEG measures. To obtain clear pre- and post training measures of behaviour, and to correlate changes in EEG to changes in behaviour.

As mentioned previously, some of the findings from the neurofeedback training studies are intriguing and suggestive. As such, it remains the domain of future researchers to elucidate precisely what effect neurofeedback training may have on performance.

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