The effect of training distinct neurofeedback protocols on aspects of cognitive performance

David Vernon*, Tobias Egner, Nick Cooper, Theresa Compton, Claire Neilands, Amna Sheri, John Gruzelier

Department of Cognitive Neuroscience and Behaviour, Imperial College London, Charing Cross Hospital, St. Dunstans Road, London W6 8RF, UK

Abstract

The use of neurofeedback as an operant conditioning paradigm has disclosed that participants are able to gain some control over particular aspects of their electroencephalogram (EEG). Based on the association between theta activity (4–7 Hz) and working memory performance, and sensorimotor rhythm (SMR) activity (12–15 Hz) and attentional processing, we investigated the possibility that training healthy individuals to enhance either of these frequencies would specifically influence a particular aspect of cognitive performance, relative to a non-neurofeedback control-group. The results revealed that after eight sessions of neurofeedback the SMR-group were able to selectively enhance their SMR activity, as indexed by increased SMR/theta and SMR/beta ratios. In contrast, those trained to selectively enhance theta activity failed to exhibit any changes in their EEG. Furthermore, the SMR-group exhibited a significant and clear improvement in cued recall performance, using a semantic working memory task, and to a lesser extent showed improved accuracy of focused attentional processing using a 2-sequence continuous performance task. This suggests that normal healthy individuals can learn to increase a specific component of their EEG activity, and that such enhanced activity may facilitate semantic processing in a working memory task and to a lesser extent focused attention. We discuss possible mechanisms that could mediate such effects and indicate a number of directions for future research.
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1. Introduction

Neurofeedback refers to an operant conditioning paradigm where participants learn to influence the electrical activity of their brain. Learned self-regulation of specific AC frequency components and of slow cortical potentials (SCPs) of the electroencephalograph (EEG) has been shown to be of considerable clinical value. For instance, neurofeedback as an intervention has been shown to be particularly useful in reference to pathologies characterised by dysfunctional regulation of cortical arousal, such as epilepsy (Sterman and Friar, 1972; Sterman et al., 1974) and attention deficit hyperactivity disorder (ADHD) (Linden et al.,

*Corresponding author. Tel.: +44-208-3830854; fax: +44-208-8461670.

E-mail address: d.vernon@ic.ac.uk (D. Vernon).

1996; Lubar et al., 1995a; Rossiter and LaVaque, 1995; Shouse and Lubar, 1979). Further clinical applications include the use of slow wave alpha/theta feedback training as a complementary therapeutic tool in the treatment of substance abuse (Peniston and Kulkosky, 1989), the use of learned SCP control as a means of brain–computer communication in paralysed patients (Birbaumer et al., 1999), while feasibility studies have also been reported in schizophrenia (Gruzelier et al., 1999). Clinical improvements following neurofeedback training (NFT) have been reported to coincide with a 'normalisation' of the EEG frequency spectrum (Sterman and Shouse, 1980). This has led to the proposal that such training may facilitate long-term modulation of excitation levels in cortical and thalamocortical networks (Sterman, 1996).

Recent research has extended this work, focusing on healthy individuals, to show that following a series of NFT sessions, not only are such individuals able to exert some control over their EEG but also that such changes are associated with improved attentional processing in terms of behavioural and electrocortical measures (Egner and Gruzelier, 2001). Substantial benefits have also been documented in music performance measures in conservatoire students (Gruzelier et al., 2002).

The above research has led to the conceptualisation of neurofeedback as a mechanism that may be used to stimulate and/or regulate cerebral activity, which in turn may influence cognitive processing. However, it remains unclear to what extent training individuals to enhance a particular frequency and inhibit another will specifically influence cognitive performance. Based on the reported associations between theta activity (4–7 Hz) and working memory (Kahana et al., 1999; Klimesch, 1999; Klimesch et al., 2001) and sensorimotor rhythm (SMR) activity (12–15 Hz) and attention (Egner and Gruzelier, 2001; Rossiter and LaVaque, 1995), we examined the possibility that training healthy individuals to enhance one of these frequencies, via neurofeedback, would positively influence a particular aspect of their cognitive performance. Furthermore, comparing the performance of individuals, trained to enhance distinct frequencies, should help us to delineate the differ-

ential effects such training may have on various aspects of cognitive performance. Before presenting our results we outline a summary of the research, highlighting associations between distinct EEG frequency components and aspects of cognitive processing, which provided the motivation for the present study.

1.1. Theta (4–7 Hz) and working memory

Working memory refers to the ability to hold information transiently in mind in the service of comprehension, thinking and planning (Baddeley, 1986, 1997; Baddeley and Hitch, 1974). It is known from previous research that theta activity has an influence on the cellular mechanisms of memory through its role in facilitating long-term potentiation (e.g. Pavlides et al., 1988), and more recent studies have documented a link between recognition memory processes and theta activity recorded from the scalp (Burgess and 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 exhibited a significant increase in theta activity (Klimesch et al., 1997). In addition, during the later recognition phase, greater theta activity was found for correctly recognised words but not distractors. Based on research showing that working memory utilises the posterior association cortex, involved in the storage of sensory information, and the pre-frontal cortex which updates the information (e.g. Gevins et al., 1997; Goldman-Rakic, 1988; Klimesch et al., 1994), one proposal is that theta activity links these two regions together during a working memory task (Sarnthein et al., 1998; see also von Stein et al., 1999; von Stein and Sarnthein, 2000). This idea is consistent with research highlighting a functional relationship between theta and working memory, whereby an increase in working memory load was associated with a concurrent increase in theta power (Grunwald et al., 2001). These findings have led to the proposal that theta, inter alia, may be involved in the encoding and retrieval of information in working memory (Klimesch, 1996, 1999).

1.2. SMR (12–15 Hz) and attention

Over the past three decades research has indicated that operant training of SMR activity has a beneficial effect on the attentional processing ability of individuals with learning difficulties. Following early case reports by Lubar and Shouse (1979), Shouse and Lubar (1979)), research has disclosed that NFT of the SMR significantly improved scores on measures of sustained attention for individuals diagnosed with attention deficit disorder and ADHD (Fuchs et al., in press, Lubar and Lubar, 1984; Rossiter and LaVaque, 1995; Tansey, 1991; Tinius and Tinius, 2000). More recent research extended this work to investigate the influence of SMR training on healthy individuals (Egner and Gruzelier, 2001). Egner and Gruzelier (2001) found that enhancement of SMR activity was associated with a reduction in commission errors and improved perceptual sensitivity on the 'Test Of Variables Of Attention' (TOVA), as well as increases in the attention-related P3b event-related potential. This led them to conclude that SMR NFT can enhance attentional processing in healthy participants.

It should be noted that beyond the neurofeedback literature, cortical activity in the range of 10–14 Hz has been associated with semantic processing (Haarmann et al., submitted for publication). For instance, Haarmann et al. (submitted for publication) report greater coherence in this frequency between the anterior and posterior regions during the rehearsal of words in a semantic working memory task. This increased activity is thought to represent the maintenance or rehearsal of the working memory representation.

The direct relationship between SMR activity and its influence on cognitive performance is not yet fully understood. However, neurophysiological research on animals has shown that, during inactive but focused and alert behaviour, the attenuation of somatosensory inputs promotes burst firing in the ventrobasal thalamic nuclei, initiating SMR (Howe and Sterman, 1972). More recently, human research has also shown greater activity in the 11–15 Hz range, localised to the sensory projection area of the cortex, when visually attending to stimuli compared to the completion of a motor task (Mann et al., 1996). This led to the suggestion that motor activity, which would be associated with suppression of SMR activity, may interfere with both perceptual and integrative components of information processing (Sterman, 1996). Consequently, learned voluntary control of SMR activity may facilitate information processing by decreasing such motor interference, whilst at the same time maintaining perceptual and memory functions at the ready.

1.3. Present study

The research outlined above demonstrates associations between greater activity in a particular EEG frequency and performance on a particular cognitive task. An empirical question to emerge from such associations is whether individuals trained to enhance a particular EEG frequency, via neurofeedback, would exhibit a concurrent improvement in the cognitive task associated with that frequency component.

In order to investigate this possibility we initially examined the semantic working memory and attention performance of three groups of healthy individuals at time 1, and again after two of the groups had completed a series of NFT sessions (i.e. at time 2) which required them to enhance a particular frequency component. The first NFT group was instructed to enhance theta (4–7 Hz) activity and simultaneously inhibit delta (0–4 Hz) and alpha (8–12 Hz) activity. We are unaware of any research that has examined the effect of this type of training on cognitive performance, however, based on the association between theta and working memory outlined above, we predict that enhancing theta activity should positively influence working memory performance. It is unclear at this stage whether theta training will also have a concomitant effect on attention performance. The second NFT group were required to enhance their SMR activity (12–15 Hz), simultaneously inhibiting theta (4–7 Hz) and beta (18–22 Hz). Consistent with previous research we would expect SMR training to positively influence attention (Egner and Gruzelier, 2001; Lubar and Shouse, 1976; Lubar et al., 1995a; Rossiter and LaVaque, 1995), however, it remains unclear to what extent

such training is task specific and may or may not influence performance on a semantic working memory task (cf. Haarmann et al., submitted for publication). The final group acted as controls, completing both cognitive tasks at time 1 and time 2 but did not participate in any NFT. It could be argued that by requiring the control-group to undergo training and providing them with false feedback, may account more accurately for aspects of contact, expectation and motivation. However, we are particularly interested in comparing the performance of two distinct neurofeedback groups, which may enable us to delineate the effects of theta and SMR training on aspects of cognitive performance. As such, comparing cognitive performance between neurofeedback groups would be expected to equate for levels of contact, expectation and motivation, whilst comparing performance between a neurofeedback group and a non-neurofeedback control-group would also account for non-specific learning effects. Furthermore, the use of sham feedback as an adequate control has been criticised as both 'impossible and inappropriate' (Kotchoubey et al., 2001, pp 406) because such training is quickly and easily recognised as false.

2. Method

2.1. Participants

Thirty undergraduate medical students (18 male and 12 females, aged 20–28 years: $M = 22.1$, S.D. $= 1.77$) were recruited from Imperial College London. Participants were pseudo-randomly allocated to one of three groups, controlling for factors such as age, gender and cognitive performance at time 1. All neurofeedback participants remained naïve as to their specific group membership until being fully debriefed at the end of the training program. The study was approved by the Riverside Research Ethics Committee (RREC 2828). One of the participants in the *theta-group* dropped out after 3 weeks of NFT.

2.2. Materials

2.2.1. Attention performance

Focused visual attention was examined using a computerised continuous performance task (CPT).

Participants were presented with two blocks of digit sequences. Each block consisted of 700 digits ranging from 1 to 9 and contained 53 target sequences. There were two 3-digit target sequences (e.g. 3–5–7 and 5–7–9) in the first block and three 3-digit target sequences (e.g. 2–4–6, 3–5–7 and 5–7–9) in the second block. The position of the target sequence within each block was randomised by the computer prior to presentation. The aim was for the participant to identify, using a key-press, the relevant target sequence (e.g. 3–5–7) in each block as quickly and as accurately as possible, whilst refraining from responding to non-targets. Dependant measures include omission errors (e.g. missed targets), commission errors (e.g. response to non-targets), response latency and variability.

2.2.2. Conceptual span task

The conceptual span task is a computerised memory recall task, presented in both a non-clustered (CS-NC) and clustered (CS-C) format, used to measure semantic working memory and developed by Haarmann et al. (in press). Both the non-clustered and the clustered version contain 18 trials, three each from six different semantic categories (e.g. fruit; animal; country; body-part; electric-item; transport). In the non-clustered version each trial contained 9 individually presented words, selected from three different semantic categories (e.g. fruit; animal; country), with word order randomised by the computer prior to presentation. In the clustered version, each trial contained 12 words from three different semantic categories. However, here the words were presented one at a time clustered together in their relevant categories, with each 4-word cluster appearing equally as often in each position within the trial. All words were presented individually on screen for 1000 ms, and at the end of each trial a semantic cue was presented which required participants to recall out loud all previously seen words contained within the specified category. Responses were noted by the experimenter with trial commencement initiated upon a participant signal. The dependant measure for both versions was accuracy of recall.

2.3. Neurofeedback training

NFT was conducted over a period of 4 weeks, with each participant receiving two training sessions per-week. NFT was administered using the Neurocybernetics (Encino, CA) EEG Biofeedback system and the ProComp (Thought Technology Ltd, Montreal, Quebec) differential amplifier. Signal was acquired at 160 Hz, A/D converted and band filtered to extract delta (0–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), SMR (12–15 Hz) and beta (18–22 Hz) components. To allow for a direct comparison between NFT groups EEG was recorded from CZ for all training, with reference placed on the left and ground electrode on the right earlobes respectively. Artefact rejection thresholds were set for each participant individually, suspending feedback when eye-movements or other muscle activity caused gross EEG fluctuations. Group training protocols consisted of the following: the *theta-group* underwent training to enhance theta and simultaneously inhibit delta and alpha activity, whilst the *SMR-group* were trained to enhance SMR activity and inhibit theta and beta activity. EEG was recorded and the relevant frequency components were extracted and fed back using an audio–visual online feedback loop in the form of a video game. The game format represented each frequency component as a bar, with the amplitude of the frequency represented by the size of the bar. The participants' task was to increase the size of the training frequency bar and simultaneously decrease the size of the bars representing the inhibitory frequencies. On meeting this goal a tone would sound and a symbol appear to indicate a point scored, with the aim to score as many points as possible.

2.4. Procedure

All participants completed the two cognitive tasks in the same order ((1) attention-CPT; (2) semantic working memory), at *time1* and at *time2*. Following completion of the tasks at *time1* participants were allocated to their respective groups. Those undertaking NFT then completed eight sessions over a 4-week period, requiring them to enhance either *theta* (i.e. *theta-group*) or *SMR* (i.e.

SMR-group) activity. Each NFT session contained five 3-min periods, with each 3-min period consisting of 170 s feedback and a 10 s 'blink break'. The workings of this feedback loop were explained to the participants and they were instructed to let the feedback guide them into learning how to maximise their 'points' (reflecting enhancement of the given frequency component). It was not possible to ensure that the time of day for training remained constant across the sessions for each participant, hence any comparisons made between sessions could potentially introduce confounding factors resulting from changes in emotional state/arousal, amount of sleep and time between EEG acquisition and food intake (e.g. Fishbein et al., 1990). Thus, after Lubar et al. (1995a) neurofeedback learning was operationalised as an increase in the ratio of the training frequency relative to each of the two inhibitory frequencies over the five 3-min periods collapsed across the different sessions. Participants in the *control-group* did not receive any NFT and at the end of the 4-week training period (e.g. *time2*) all participants completed the two cognitive tests for the second time.

2.5. Results

2.5.1. Neurofeedback learning

Ratios of the mean amplitude for the training frequency relative to the inhibitory frequencies for each of the five periods collapsed across the eight training sessions are shown in Fig. 1. As can be seen from Fig. 1A the *theta-group* showed no increase in their mean theta/delta ratios from period 1 to period 5 (0.78 and 0.79 respectively) ($P > 0.1$), but do show a trend towards decrease in theta/alpha ratios (1.29 and 1.26 respectively) ($t(8) = 2.257$, $P = 0.054$). Examination of absolute amplitude values collapsed across sessions indicated that the decrease in theta/alpha ratios resulted from a reduction in theta from period 1 to period 5 (9.347 and 9.272 μV respectively) and an increase in alpha (7.494 and 7.655 μV respectively). In contrast, mean ratios of the *SMR-group*, seen in Fig. 1B, show an increase in the SMR/theta ratios from period 1 to period 5 (0.75 and 0.86 respectively) ($t(9) = 3.15$, $P = 0.012$). This resulted from the absolute amplitude for theta
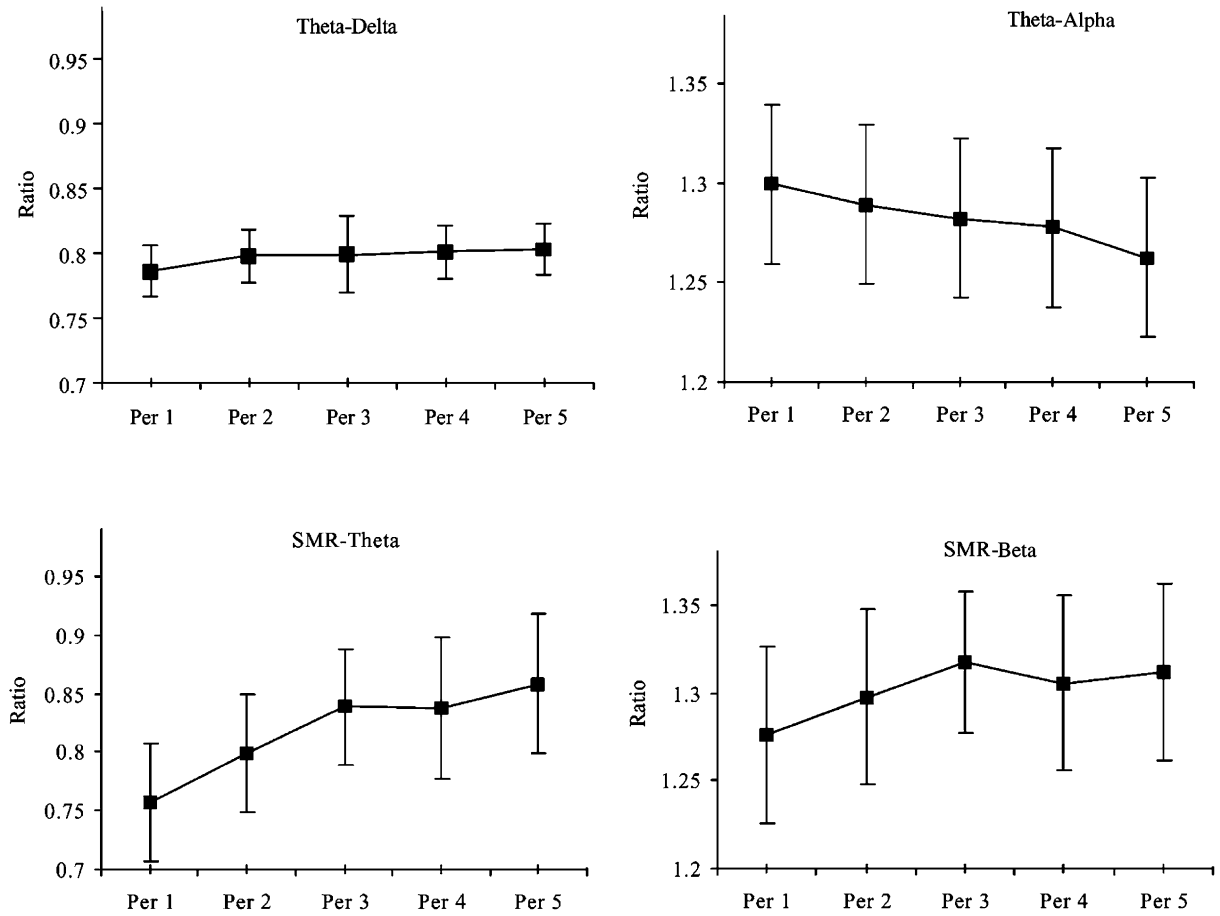
Fig. 1. Upper panel (1A) shows mean ratio of theta/delta and theta/alpha amplitude and lower panel (1B) shows mean ratio of SMR/theta and SMR/beta amplitude, across the five periods collapsed across the eight training sessions.

decreasing from period 1 to period 5 (10.987 and 10.606 μV respectively) whilst amplitudes of SMR increased (8.993 and 9.628 μV respectively). Furthermore, there was a trend for SMR/beta ratios to increase from period 1 to period 3 (1.27 and 1.31 respectively) ($t(9) = 2.02$, $P = 0.074$), resulting from an increase in the absolute amplitude of SMR from period 1 to period 3 (8.993 and 9.369 μV respectively) and a concurrent decrease in beta (6.601 and 6.561 μV respectively).

2.6. CPT task

Performance on the 2-sequence and 3-sequence CPT tasks were examined separately using a 2

(Time: *time1* vs. *time2*)×3 (Group: *Control*, *Theta* and *SMR*) mixed analysis of variance (ANOVA).

2.6.1. 2-Sequence task

Analysis of hits revealed a main effect of Time, showing an increase in the number of hits from *time1* to *time2* (79.5 and 89.8% respectively) ($F(1, 35) = 11.32$, $P < 0.002$, Mse = 184). However, planned comparisons disclosed that only the *SMR-group* exhibited a significant increase in their hit rate from *time1* to *time2* (75 and 93.8% respectively) ($F = 9.61$, $P < 0.004$). A similar pattern was found for omission errors, with groups showing a decrease in omission responses over time (20.45 and 10.1% respectively) ($F(1, 35) = 11.32$, $P <$
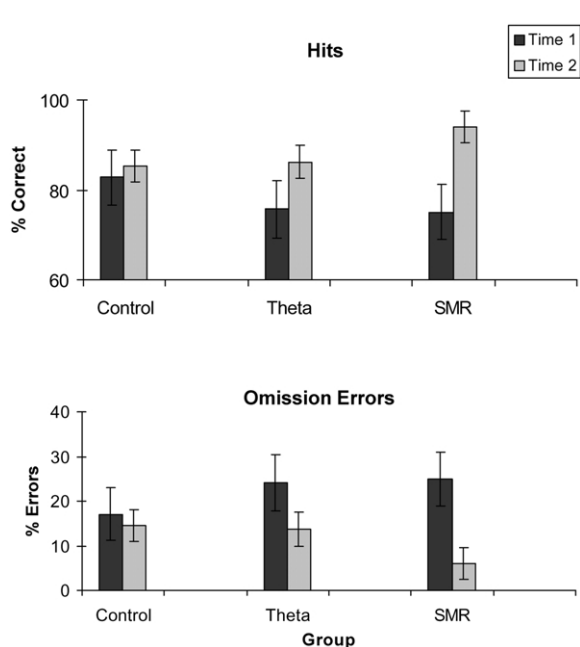
Fig. 2. Percentage Hits and Omission errors (with standard error bars) for 2-sequence attention CPT at time 1 and time 2 for the control, theta- and SMR-groups.

0.002. Mse $= 184$), and planned comparisons showing that only the *SMR-group* exhibited a significant reduction in omission errors from *time1* to *time2* (24.9 and 6.1% respectively) ($F = 9.64$, $P < 0.004$), this pattern is evident in Fig. 2. It should be noted that the lack of a Group×Time interaction suggests that the pattern of results found for the *SMR-group* should be interpreted with caution.

2.6.2. 3-Sequence task

There was a main effect of Time for both hits, increasing from *time1* to *time2* (71.1 and 82.7% respectively) ($F(1, 35) = 38.15$, $P < 0.0001$, Mse $= 68$), and omission errors, decreasing from *time1* to *time2* (28.8 and 17.3% respectively) ($F(1, 35) = 38.2$, $P < 0.0001$, Mse $= 66$). No other effects were significant ($F < 1.5$).

2.7. Working memory task

Mean percentage recall was examined using a 2 (Task: *non-clustered* vs. *clustered*)×2 (Time:

time1 vs. *time2*)×3 (Group: *control*, *theta* and *SMR*) mixed ANOVA. This showed a main effect of Task, with participants exhibiting greater recall in the *clustered* relative to the *non-clustered* version (79.3 and 70.2% respectively) ($F(1, 35) = 62.59$, $P < 0.0001$, Mse $= 52.5$). There was also a main effect of Time ($F(1, 35) = 21.2$, $P < 0.0001$, Mse $= 36.6$) and a Time×Group interaction ($F(3, 35) = 5.2$, $P < 0.004$, Mse $= 36.6$). As can be seen from Fig. 3, planned comparisons of the Time×Group interaction revealed that only the *SMR-group* exhibited an increase in recall from *time1* to *time2* (70.6 and 81.6% respectively) ($F(1, 9) = 26.4$, $P < 0.001$, Mse $= 45$).

3. Discussion

The SMR-group showed clear evidence of neurofeedback learning as indexed by increased ratios of SMR/theta and SMR/beta over time. In contrast the theta-group failed to exhibit any indication of neurofeedback learning. Furthermore, the SMR-group exhibited improved accuracy when completing the 2-sequence attention CPT at time 2, however, all participants showed improved accuracy for the 3-sequence task. Finally, all participants exhibited greater recall when completing the clustered version of the working memory task, however, only the SMR-group showed an increase in the accuracy of their working memory performance over time.

That healthy participants are able to learn to selectively enhance their SMR activity is consistent with previous research (Egner and Gruzelier, 2001). These data suggest that eight sessions of operant training of EEG activity are sufficient to produce significant changes in a specific EEG frequency of healthy individuals assessed objectively. The fact that the theta-group failed to exhibit any indication of 'learning' may be accounted for by the particular methodology used. For instance, we required participants to focus on a computer screen that provided both visual and auditory feedback. In contrast, theta training utilising both healthy (Egner et al., in press) and clinical populations (Peniston and Kulkosky, 1989, 1999) is traditionally viewed as forming part of a relaxation
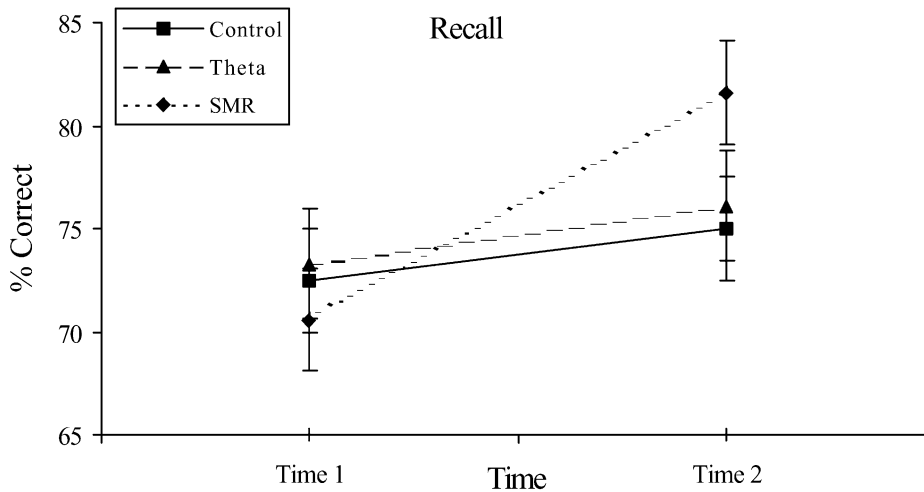
Fig. 3. Percentage correct recall (with standard error bars) for semantic working memory task, collapsed across non-clustered and clustered versions, at time 1 and time 2 for the control, theta- and SMR-groups.

inducing technique, originally associated with meditation (Kassamatau and Hirai, 1969). Such training invariably requires participants to relax with their eyes closed, receiving only auditory feedback. Utilising such methods research has shown that healthy individuals are capable of increasing their theta/alpha ratios after only five sessions of NFT (Egner et al., in press). No 'eyes-closed' theta-group was included here, and as such a direct comparison is beyond the scope of this article. Thus, the failure of the theta-group examined here to demonstrate any learning of the operant contingencies may be a direct result of their having to focus with eyes open, receiving both auditory and visual feedback. Consequently, future researchers in this area could elucidate such alternatives by conducting a direct comparison between an 'eyes-open' theta-group and an 'eyes-closed' group to ascertain what if any differences such training may have.

Those trained to enhance their SMR activity exhibited greater accuracy in the 2-sequence attention CPT. This replicates previous research showing that training to enhance SMR activity can influence attention of both healthy individuals (Egner and Gruzelier, 2001) and clinical populations (Fuchs et al., in press, Lubar and Shouse, 1976; Rossiter and LaVaque, 1995). Such a finding

is consistent with the proposal that training individuals to enhance their SMR activity may result in decreased motor interference which in turn may facilitate attentional processing (Sterman, 1996). However, such an account should be interpreted with caution as all participants exhibited improved accuracy for the 3-sequence CPT, suggesting that to some extent the pattern of effects could be the result of practice effects. Alternatively, it is possible that the lack of a clear effect stems from the particular CPT used. Traditionally, when examining the influence of SMR activity on attention, the TOVA has been used to measure 'sustained attention' performance (Egner and Gruzelier, 2001; Lubar et al., 1995a,b; Rossiter and LaVaque, 1995). This is a simple go/no-go task where the participant is required to ascertain whether a small non-letter symbol appears on screen or not. In contrast, the attention CPT used here required participants to identify a number of specific target sequences, which may require more than just sustained attention. Thus, it is possible that the different tasks tap distinct aspects of functional attention. For instance, it has been suggested that there are three dominant networks utilised in attentional processing; alerting, orienting and executive control (Posner and Peterson, 1990). The alerting

network achieves and maintains an alert state, the orienting network selects information from sensory input and the executive control network works to resolve conflict among responses. It may be that the sustained attention required to complete the TOVA predominantly involves the alerting and orienting networks, i.e., alerting and orienting the individual to the absence/presence of a target. In contrast, the focused attention required to complete the CPT utilised here may require a higher working memory load and as such rely to a greater extent on the executive network, used in resolving the conflict between target and non-target sequences. It should be noted that such a possibility is speculative as the authors are unaware of any research focusing on the differential influence of SMR training on the distinct networks of attention. As such it remains the domain of future research to elucidate this point.

Regarding working memory performance, all participants showed greater recall when the words appeared clustered together. Such a finding is consistent with research showing that working memory includes a semantic component, which aids the on-line processing of semantic relations (Haarmann et al., in press). Haarmann et al. (in press) propose that the maintenance of semantically related words in working memory is aided in part by the pre-existing semantic relations stored in long-term memory. More specifically, the relations between the words helps to support their continued activation. As such, presenting words clustered together according to their semantic category would be expected to help maintain them, resulting in greater recall.

Based on the association between greater theta activity and better working memory performance outlined in Section 1, we predicted that training individuals to enhance theta may influence working memory performance. However, given that the theta-group failed to show any such enhancement, the lack of an effect on working memory performance is not wholly unexpected. Nevertheless, it remains the domain of future research to ascertain whether the same pattern would be evident following an 'eyes-closed' theta training regime. In contrast, the SMR-group exhibited a clear improvement in working memory performance. It

could be argued that such a pattern is the result of improved attentional processing. Such a proposal would be consistent with the suggestion that the central executive component of working memory functions more like an attentional system than a memory store (Baddeley, 1986, 1997; Baddeley and Hitch, 1974). However, if the enhancement in working memory performance were the result of improved attention one would also expect to see clear improvements in the attention CPT used. For reasons outlined above, this was not the case. An alternative account stems from recent research showing that working memory includes a semantic component capable of processing the meaning of words online, and identified as operating within a frequency range of 10–14 Hz (Haarmann et al., submitted for publication). We know from previous research that working memory is based on a neuronal circuit involving the interaction between attentional control systems located in the prefrontal cortex and the storage of sensory information in the posterior association cortex (Sarnthein et al., 1998; von Stein et al., 1999; von Stein and Sarnthein, 2000). Haarmann et al. (submitted for publication) have reported an increase in coherence in the 10–14 Hz band between frontal and posterior regions during a semantic working memory task. They suggest that such an increase reflects the active maintenance of an integrated memory representation in working memory, after the build up of the initial representation has been completed. Hence, training participants to enhance their SMR activity (i.e. 12–15 Hz) may to some extent aid in the maintenance of the memory representation utilised in semantic working memory. Such enhanced representations would by their very nature be expected to result in more accurate recall.

In conclusion, we have shown that eight sessions of NFT is sufficient for healthy participants to exhibit selective enhancement of their SMR activity. Furthermore, enhanced SMR activity is associated with a limited improvement in the accuracy of attentional processing and a clear improvement in the recall of a semantic working memory task. Such effects suggest that NFT can positively influence cognitive processing in healthy individuals.

Acknowledgments

References

Baddeley, A.D., 1986. Working Memory. OUP, Oxford.

Baddeley, A.D., 1997. Human Memory: Theory and practice. Erlbaum, Hove East Sussex.

Baddeley, A.D., Hitch, G., 1974. Working Memory. In: Bower, G.A. (Ed.), Recent Advances in Learning and Motivation, vol. 8. Academic Press, New York,.

Birbaumer, N., Ghanayim, N., Hinterberger, T., et al., 1999. A spelling device for the paralysed. Nature 398, 297–298.

Burgess, A.P., Gruzelier, J.H., 1997. Short duration synchronization of human theta rhythm during recognition memory. Neuroreport 8, 1039–1042.

Egner, T., Gruzelier, J.H., 2001. Learned self-regulation of EEG frequency components affects attention and event-related brain potentials in humans. Neuroreport 12, 4155–4159.

Egner, T., Strawson, E., Gruzelier, J.H. EEG signature and phenomenology of alpha/theta neurofeedback training versus mock feedback. Applied Psychophysiology and Biofeedback, in press.

Fishbein, D.H., Thatcher, R.W., Cantor, D.S., 1990. Ingestion of carbohydrates varying in complexity produce differential brain responses. Clin. Electroencephalogr. 21, 5–11.

Fuchs, T., Birbaumer, N., Lutzenberger, W., Gruzelier, J.H., Kaiser, J., (in press). Neurofeedback treatment for attention-deficit/hyperactivity disorder in children: a comparison with methylphenidate. Appl. Psychophysiol. Biofeedback.

Gevins, A., Smith, M.E., McEvoy, L., Yu, D., 1997. High-resolution EEG mapping of cortical activation related to working memory: effects of task difficulty, type of processing, and practice. Cereb. Cortex 7, 374–385.

Goldman-Rakic, P.S., 1988. Topography of cognition: parallel distributed networks in primate association cortex. Annu. Rev. Neurosci. 11, 137–156.

Grunwald, M., Weiss, T., Krause, W., et al., 2001. Theta power in the EEG of humans during ongoing processing in a haptic object recognition task. Brain Res. Cogn. Brain Res. 11, 33–37.

Gruzelier, J., Egner, T., Williamon, A., Valentine, E., 2002. Comparing learned EEG self-regulation and the Alexander technique as a means of enhancing musical performance. Paper presented at the Proceedings of the seventh international conference on music perception and cognition, Sydney, Adelaide.

Gruzelier, J., Hardman, E., Wild, J., Zaman, R., 1999. Learned control of slow potential interhemispheric asymmetry in schizophrenia. Int. J. Psychophysiol. 34, 341–348.

Haarmann, H.J., Cameron, K.A., Ruchkin, D.S. Active maintenance of sentence meaning in working memory, submitted for publication.

Haarmann, H.J., Davelaar, E.J., Usher, M. Individual differences in semantic short-term memory capacity and reading comprehension. J. Memory Lang., in press.

Howe, R.C., Sterman, M.B., 1972. Cortical-subcortical EEG correlates of suppressed motor behavior during sleep and waking in the cat. Electroencephalogr. Clin. Neurophysiol. 32, 681–695.

Kahana, M.J., Sekuler, R., Caplan, J.B., Kirschen, M., Madsen, J.R., 1999. Human theta oscillations exhibit task dependence during virtual maze navigation. Nature 399, 781–784.

Kassamatau, A., Hirai, T., 1969. An electroencephalic study of Zen meditation. Psychologia 12, 205–225.

Klimesch, W., 1996. Memory processes, brain oscillations and EEG synchronization. Int. J. Psychophysiol. 24, 61–100.

Klimesch, W., 1999. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Res. Rev. 29, 169–195.

Klimesch, W., Doppelmayr, M., Schimke, H., Ripper, B., 1997. Theta synchronisation and alpha desynchronisation in a memory task. Psychophysiology 34, 169–176.

Klimesch, W., Doppelmayr, M., Stadler, W., Pollhuber, D., Sauseng, P., Rohm, D., 2001. Episodic retrieval is reflected by a process specific increase in human electroencephalographic theta activity. Neurosci. Lett. 302, 49–52.

Klimesch, W., Schimke, H., Schwaiger, J., 1994. Episodic and semantic memory: an analysis in the EEG theta and alpha band. Electroencephalogr. Clin. Neurophysiol. 91, 428–441.

Kotchoubey, B., Strehl, U., Uhlmann, C., et al., 2001. Modification of slow cortical potentials in patients with refractory epilepsy: a controlled outcome study. Epilepsia 42, 406–416.

Linden, M., Habib, T., Radojevic, V., 1996. A controlled study of the effects of EEG biofeedback on cognition and behaviour of children with ADD and LD. Biofeedback Self Regul. 21, 35–49.

Lubar, J.F., Shouse, M.N., 1976. EEG and behavioral changes in a hyperkinetic child concurrent with training of the sensorimotor rhythm (SMR): a preliminary report. Biofeedback Self Regul. 1, 293–306.

Lubar, J.F., Swartwood, M.O., Swartwood, J.N., O'Donnell, P.H., 1995a. Evaluation of the effectiveness of EEG neurofeedback training for ADHD in a clinical setting as measured by changes in T.O.V.A. scores, behavioural ratings, and WISC-R performance. Biofeedback Self Regul. 20, 83–99.

Lubar, J.F., Swartwood, M.O., Swartwood, J.N., Timmerman, D.L., 1995b. Quantitative EEG and auditory event related potentials in the evaluation of attention deficit/hyperactivity disorder: effects of methylphenidate and implications for neurofeedback training. J. Psychoeducational Assess. 143–160.

Lubar, J.O., Lubar, J.F., 1984. Electroencephalographic biofeedback of SMR and beta for treatment of attention deficit disorders in a clinical setting. Biofeedback Self Regul. 9, 1–23.

Mann, C.A., Sterman, M.B., Kaiser, D.A., 1996. Suppression of EEG rhythmic frequencies during somato-motor and visuo-motor behavior. Int. J. Psychophysiol. 23, 1–7.

Pavlides, C., Greenstein, Y.J., Grudman, M., Winson, J., 1988. Long-term potentiation in the dentate gyrus is induced preferentially on the positive phase of theta rhythm. Brain Res. 439, 383–387.

Peniston, E.G., Kulkosky, P.J., 1989. Alpha–theta brainwave training and beta-endorphin levels in alcoholics. Alcohol Clin. Exp. Res. 13, 271–279.

Peniston, E.G., Kulkosky, P.J., 1999. Neurofeedback in the treatment of addictive disorders. In: Evans, A.J.R. (Ed.), Introduction to Quantitative EEG and Neurofeedback. Academic Press, San Diego, pp. 157–179.

Posner, M.I., Peterson, S.E., 1990. The attention systems of the human brain. Annu. Rev. Neurosci. 19, 25–42.

Rossiter, T.R., LaVaque, T.J., 1995. A comparison of EEG biofeedback and psychostimulants in treating attention deficit hyperactivity disorders. J. Neurother. 48–59.

Sarnthein, J., Petsche, H., Rappelsberger, P., Shaw, G.L., von Stein, A., 1998. Synchronization between prefrontal and posterior association cortex during human working memory. Proc. Natl. Acad. Sci. USA 95, 7092–7096.

Shouse, M.N., Lubar, J.F., 1979. Operant conditioning of EEG rhythms and Ritalin in the treatment of Hyperkinesis. Biofeedback Self Regul. 299–312.

Sterman, M.B., 1996. Physiological origins and functional correlates of EEG rhythmic activities: implications for self-regulation. Biofeedback Self Regul. 21, 3–33.

Sterman, M.B., Friar, L., 1972. Suppression of seizures in an epileptic following sensorimotor EEG feedback training. Electroencephalogr. Clin. Neurophysiol. 33, 89–95.

Sterman, M.B., Macdonald, L.R., Stone, R.K., 1974. Biofeedback training of the sensorimotor electroencephalogram rhythm in man: effects on epilepsy. Epilepsia 15, 395–416.

Sterman, M.B., Shouse, M.N., 1980. Quantitative analysis of training, sleep EEG and clinical response to EEG operant conditioning in epileptics. Electroencephalogr. Clin. Neurophysiol. 49, 558–576.

Tansey, M.A., 1991. Wechsler (WISC-R) changes following treatment of learning disabilities via EEG biofeedback training in a private practice setting. Austr. J. Psychol. 43, 147–153.

Tinius, T.P., Tinius, K.A., 2000. Changes after EEG biofeedback and cognitive retraining in adults with mild traumatic brain injury and attention deficit hyperactivity disorder. J. Neurother. 4, 27–41.

von Stein, A., Rappelsberger, P., Sarnthein, J., Petsche, H., 1999. Synchronization between temporal and parietal cortex during multimodal object processing in man. Cereb. Cortex 9, 137–150.

von Stein, A., Sarnthein, J., 2000. Different frequencies for different scales of cortical integration from local gamma to long range alpha/theta synchronisation. Int. J. Psychophysiol. 38, 301–313.