Review

EEG-neurofeedback for optimising performance. I: A review of cognitive and affective outcome in healthy participants

John H. Gruzelier*

Goldsmiths, University of London, UK

ABSTRACT

A re-emergence of research on EEG-neurofeedback followed controlled evidence of clinical benefits and validation of cognitive/affective gains in healthy participants including correlations in support of feedback learning mediating outcome. Controlled studies with healthy and elderly participants, which have increased exponentially, are reviewed including protocols from the clinic: sensory-motor rhythm, beta1 and alpha/theta ratios, down-training theta maxima, and from neuroscience: upper-alpha, theta, gamma, alpha desynchronisation. Outcome gains include sustained attention, orienting and executive attention, the P300b, memory, spatial rotation, RT, complex psychomotor skills, implicit procedural memory, recognition memory, perceptual binding, intelligence, mood and well-being. Twenty-three of the controlled studies report neurofeedback learning indices along with beneficial outcomes, of which eight report correlations in support of a meditation link, results which will be supplemented by further creativity and the performing arts evidence in Part II. Validity evidence from optimal performance studies represents an advance for the neurofeedback field demonstrating that cross fertilisation between clinical and optimal performance domains will be fruitful. Theoretical and methodological issues are outlined further in Part III.

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* Correspondence to: Department of Psychology, Goldsmiths, University of London, Lewisham Way, London SE14 6NW, UK. Tel.: +44 20 8 2992203.
   E-mail addresses: jgruzelier@gold.ac.uk, j.gruzelier@gold.ac.uk

1. Introduction

1.1. Historical background

Since the 1960s (Kamiya, 1968, 1969) the ability has been demonstrated for learned control of brain electrical activity through instantaneous feedback in the form of spectral power, event-related potentials or slow cortical potentials, putatively through operant conditioning or volitional control. This has now been extended to fMRI (e.g., Yoo et al., 2004; Weiskopf et al., 2004; deCharms, 2008; Rota et al., 2009; Hamilton et al., 2010; Zotev et al., 2011; Berman et al., 2012; Ruiz et al., 2013), transcranial doppler sonography (Duschek et al., 2011) and near infrared spectrometry (NIRS; Mihara et al., 2012; Kober et al., 2013). However, in contrast to autonomic and somatic peripheral biofeedback which became an established domain of Health Psychology (Feuerstein et al., 1988; Brannon and Feist, 2009), EEG-biofeedback was sidelined by science in the 1980s largely due to flawed studies and clinical overstatement, combined with the equivocal outcome of theoretically simplistic applications of alpha training for relaxation, when at the time psychophysiological understanding of alpha was at an early stage and was under the sway of unitary arousal models (Lindsley, 1952; Duffy, 1957). From the 1980s university research on EEG-biofeedback, later branded neurofeedback, was confined to a few centres, notably under the direction of Sterman (e.g., Sterman and Friar, 1972; Sterman et al., 1970, 1974; Sterman, 1996, 2000) and Lubar (e.g., Lubar and Shouse, 1976; Lubar and Lubar, 1984; Lubar et al., 1995a,b) in the USA and Birbaumer in Germany (Elbert et al., 1984; Rockstroh, 1989). Meanwhile a largely dedicated practitioner following arose outside of universities, especially in North America, encouraged by instrumentation companies. While helping keep the field alive and inventing diverse treatment protocols, this following mostly proceeded without scientific validation, sometimes accompanied by pseudo theorising and advertising speak.

Over the last decade or so university research, largely in Europe, has revisited neurofeedback, a revival of interest which the Society of Applied Neuroscience (SAN) has encouraged, and, as this review shows scientific evaluation and an evidence-base for applications is growing exponentially. This has come at a time when enhancing potential by 'brain training' is fashionable in contemporary culture (Owen et al., 2010; Rabipour and Raz, 2012), making the cause of scientific validation ever more essential and urgent, for aside from false promises, premature popularisation has led science to discard a field more than once.

1.2. Purview

While 'neurofeedback' has now been applied to a range of brain imaging modalities, here the focus will be on the accumulating evidence of validation particularly this millennium in favour of neurofeedback applications with the EEG in healthy participants, commonly called the 'optimal' or 'peak performance' field. Validation has taken the form of controlled studies showing differential group outcomes advantaging a neurofeedback protocol, and more importantly has included correlation between the feedback learning and the outcome allowing the mediation of neurofeedback learning to be inferred. The review will be initially structured around neurofeedback protocols in conjunction with psychological processes, followed by applications in sport and with the elderly. A companion review, Part II, will cover applications in the performing arts and creativity (Gruzelier, 2013a) while Part III will be devoted to methodological and theoretical issues in order to help advance this re-emergent field (Gruzelier, in preparation). The review will not concern clinical applications which have been the main concern of the field to date. To give some examples there are reviews on Attention Deficit Hyperactivity Disorder (ADHD; Arns et al., 2009; Lofthouse et al., 2012), epilepsy (Tan et al., 2009), autism spectrum disorder (Coben et al., 2010); controlled studies on addiction (Scott et al., 2005), tinnitus (Hartmann et al., 2013) and insomnia (Cortoos et al., 2010); case studies on stroke (Bearden et al., 2003), anxiety and depression (Hammond, 2005) and cognitive disorganisation with anhedonia in conjunction with drug misuse (Unterrainer et al., 2013). Similarly there are reviews on the burgeoning approach branded Brain Computer Interface (BCI), one typically focussing on the neuro-rehabilitation of patients with tetraplegia from brain or spinal cord injuries enabling patients through EEG feedback to communicate and/or physically interact with their environment, and up until now largely consisting of engineering innovations and a small clinical evidence base (Birbaumer et al., 2008; Mak and Wolpaw, 2009; Silvoni et al., 2011).

1.3. Protocols

As will be seen a diversity of neurofeedback training protocols has been applied for optimising performance. The most popular one has involved training-up the amplitude of the Sensory Motor Rhythm (SMR) 12–15 Hz band while inhibiting outer-lying bands in the EEG spectrum. This had followed evidence that within the 12–15 Hz frequency range recordings from sensory-motor and pre-motor cortices showed a distinctive oscillation which was

maximal during periods of quiet wakefulness, with reduced muscle tone, and was absent during goal directed activity and desynchronising with motor intention (Sterman and Wyrwicka, 1967; Wyrwicka and Sterman, 1968; Sterman and Friar, 1972; Sterman et al., 1974). Notably application of the SMR neurofeedback protocol has reduced motor seizure rates in epileptic patients while normalising their sleep patterns and EEG (Sterman, 2000; Sterman and Friar, 1972; Sterman et al., 1970, 1974). By extrapolating to ADHD the potential of reducing the excitability of the sensorimotor system with concomitant suppression of theta, and following SMR training with training up adjacent low beta activity (16–22 Hz; beta1) an index of EEG desynchronisation, improvements in attention and hyperactivity were first demonstrated in case studies and early controlled trials (e.g., Lubar and Shouse, 1976; Lubar et al., 1995a; Rossiter and LaVaque, 1995; Linden et al., 1996) and now have a substantive evidence base (Monastra et al., 2005; Arns et al., 2009; Lofthouse et al., 2012).

Another pioneering protocol involved raising the theta-alpha ratio with auditory feedback and eyes closed, termed alpha/theta (A/T) training. Following on from the earliest attempts to up-train alpha for relaxation and reduce anxiety (Budzynski and Stoyva, 1972; Hardt and Kamiya, 1978), the focus on theta first grew out of diverse cultural evidence that the deeply relaxing, hypnogic reverie or twilight theta state was conducive to creative insights (see Gruzelier, 2009). From clinical studies the goal evolved of elevating theta over alpha to achieve crossover. Early on this had demonstrable benefits for addiction and PTSD which included enhanced well-being when introduced as a central part of a therapeutic package (e.g., Peniston and Kulkosky, 1989, 1991; Saxby and Peniston, 1995).

Subsequently the SMR and A/T protocols have been contrasted for their optimal performance effects in healthy participants, while new neurofeedback protocols have been developed from contemporary neuroscience including training upper-alpha, peak alpha frequency, gamma, and various theta protocols, the subject of this review. Historically self-regulation of slow cortical potentials (SCPs) had received extensive validation (Elbert et al., 1984; Rockstroh, 1989), but has not attracted interest in the optimal performance field despite promise in trials with ADHD where it has been compared favourably with EEG-spectrum training (Gevensleben et al., 2009).

1.4. Issues considered

In what must be a necessarily concise selection of study features to be considered the following issues have been documented.

What evidence is there that feedback learning occurred? Have learning indices been reported or is learning inferred from demonstration that a group receiving neurofeedback out-performed a comparison group? What would evidence of learning consist of: learning curves within sessions, across sessions, the correlation of learning indices with outcome assessments? If the most basic theoretical premise about neurofeedback holds, namely that the brain's rhythms are changed by training, is learning reflected in subsequent training sessions including baselines?

There are issues of specificity. (i) Is there band specificity or independence such that only the trained bands are influenced or is there leakage or even reciprocity within the EEG spectrum? (ii) Is there specificity and independence regarding cognitive/affective outcome such that performance enhancement is specific to some processes leaving other processes unchanged? (iii) Is there topographical specificity such that the EEG outcome is specific to the training site, or is it distributed locally beyond the training site, or is it only distal from the training site?

Are there sufficient sessions to give learning a chance given that a learning process is being built? Can learning even be obtained from one-session and if so what is the validation? What is the interval between sessions given there are considerations for learning of spaced versus distributed practice. Are some people unable to learn to self-regulate their brain rhythms – sometimes termed non-responders? The outsider may be surprised at how few subjects are typically included in most intervention studies. Consider though that with say fourteen subject sessions to include a ten session course of training plus two pre and post-training outcome assessments, then for a study involving three groups of ten this would add up to 420 experimenter sessions to acquire data, and not allowing for dropout replacements which are inevitable when enterprising, mostly student subjects are required to fit fourteen sessions into their busy lives; let alone the logistics of engaging as trainees professionals such as eye surgeons (Ros et al., 2009).

All these issues will be reconsidered in detail in Part III focussing on methodology and theory (Gruzelier, in preparation). In Part I the over-riding objective will be to weigh up the now rapidly accumulating evidence base in the search of validation of neurofeedback, a concern of the author's from an early review (Gruzelier et al., 2006). As will be seen the majority of studies report evidence of neurofeedback learning and in this respect the optimal performance field is far ahead of other neurofeedback domains in reporting evidence of learning.

2. EEG spectral neurofeedback

2.1. SMR and diverse protocols

2.1.1. Sustained attention, selective attention and memory: SMR and beta1 training

SMR and beta1 neurofeedback protocols widely used with ADHD were found to have a positive impact on the sustained attention of healthy subjects in two studies (Egner and Gruzelier, 2001, 2004a) which were an adjunct to music performance enhancement (Egner and Gruzelier, 2003; see for review Gruzelier, 2012, 2013a). In the first music study as a secondary aim SMR (12–15 Hz, C4) and beta1 (15–18 Hz, C3) protocols with theta (4–7 Hz) and high beta (22–30 Hz; beta2) inhibits were compared in twenty-two music students. Protocols were administered each for 15-min, twice a week for five weeks. A timed continuous performance, go/no-go, attention task (Greenberg and Kindschi, 1999), used as a gold standard in the ADHD field (Monastra et al., 2005; Arns et al., 2009), assessed attentiveness through omission errors and impulsiveness through commission errors while a perceptual sensitivity or d-prime index took into account both error types. Additionally the auditory event-related potential P300b was recorded with a 28-electrode montage, along with the resting EEG (Egner et al., 2004).

The behavioural task disclosed a significant reduction in commission errors contributing to an increase in d-prime, which were positively associated in regression analysis with learned increases within session in SMR and beta1 amplitudes, especially SMR amplitudes, learning indices that were positively correlated ($r = 0.65$, $p < 0.01$). When the effect of beta1 on SMR was examined with partial correlation, the positive relation between SMR and commission error reduction was increased ($r = -0.79$, $p < 0.001$), and see Fig. 1, while when controlling for the effect of SMR on beta1 the opposite relation with the beta1 increment was disclosed ($r = 0.71$, $p < 0.001$) in keeping with increased arousal. Therefore evidence was provided of protocol specific effects on the behavioural measures of attention, in other words SMR and beta1 training had different consequences and were not interchangeable and importantly supported a mediational link between the SMR training and increased attentiveness.

The psychophysiological assessment disclosed that event-related P300b amplitudes following training were larger across
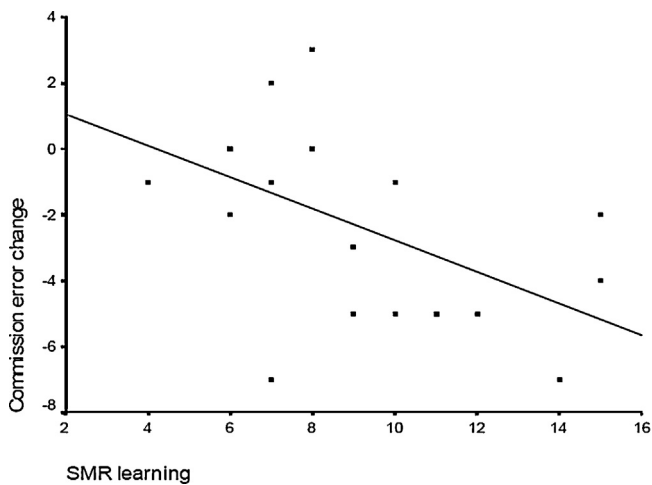
Fig. 1. SMR ratio learning indices positively associated with the reduction in commission errors in sustained attention ($r = -0.79$, $p < 0.001$) (Egner and Gruzelier, 2001).

frontal (F3, FZ, F4), central (C3, CZ, C4) and parietal (P3, PZ, P4) scalp, with the SMR effect stronger with frontal and C3 derivations and the beta1 effect stronger with central derivations. Otherwise the relations between the protocols and the P300b did not differ for both protocols disclosed positive correlations with learning indices (SMR, $r = 0.49$, $p < 0.06$; beta1, $r = 0.55$, $p < 0.05$, and see Fig. 2) in support of common influences on perceptual and cognitive integration processes reflected in the P300b, possibly through top-down resource allocation. In contrast the opposite relations of the protocols with behavioural attention measures conceivably may reflect converse influences on the subsequent motor response as required by the timed go/no-go sustained attention task (Egner and Gruzelier, 2001).

A second study (Egner and Gruzelier, 2004a) involved an independent group design with another group of twenty-five

conservatoire students randomised to ten weekly sessions of SMR and beta1 (Cz) training or to a control group trained in the Alexander technique popular in performing arts conservatoires and involving postural and stress reduction. The sustained attention task and auditory P300b paradigm were repeated and supplemented by a more complex auditory divided attention task. Both behavioural attention tasks showed an increase in d-prime following SMR training, here attributable to improvements in commission errors as well as omission errors in the more complex task. Response time variability in the divided attention task was also improved in the SMR group, while a single advantage in the beta1 group was a reduction in response time. These results provided further evidence of protocol specificity, as was the case here with the P300b amplitudes which were enlarged following beta1 training only especially at central and parietal placements. A topographical resting eyes closed EEG outcome assessment with both studies was also undertaken which mainly disclosed a frontal long-term locus (Egner et al., 2004) and is discussed in Part III.

The data from the two studies were interpreted as indicating a general attention-enhancing effect of SMR training beyond impulse control, and an arousal-enhancing effect of beta1 training. Theoretically the SMR result was consistent with improved response inhibition following inhibition of sensory-motor cortex (Sterman, 1996), while beta1 enhanced the signal-to-noise ratio in stimulus processing. The latter when combined with an impulsive response tendency was in keeping with heightened activity in a noradrenergic vigilance network, one associated with fast but commission error-prone response tendencies in models of attention (Posner and Raichle, 1996). The differential group effects and the correlations with feedback learning discounted nonspecific influences such as generic learning effects, practice, motivation and expectancy and so validated the impact of neurofeedback learning.

In a third study (Vernon et al., 2003) with a primary interest in training up theta in order to improve working memory (see Section 2.4.2) medical students were randomised to one of three groups: SMR training while inhibiting theta (4–7 Hz) and beta (18–22 Hz), eyes open theta training while inhibiting delta (0–4 Hz) and alpha
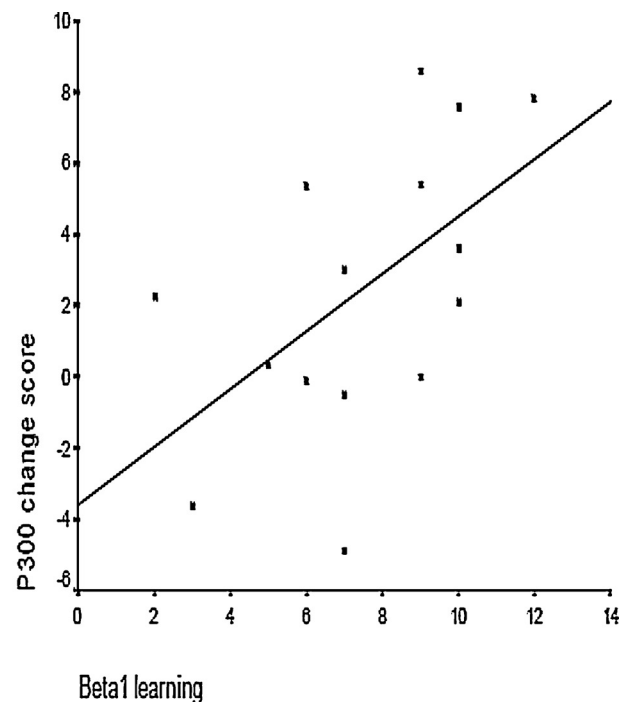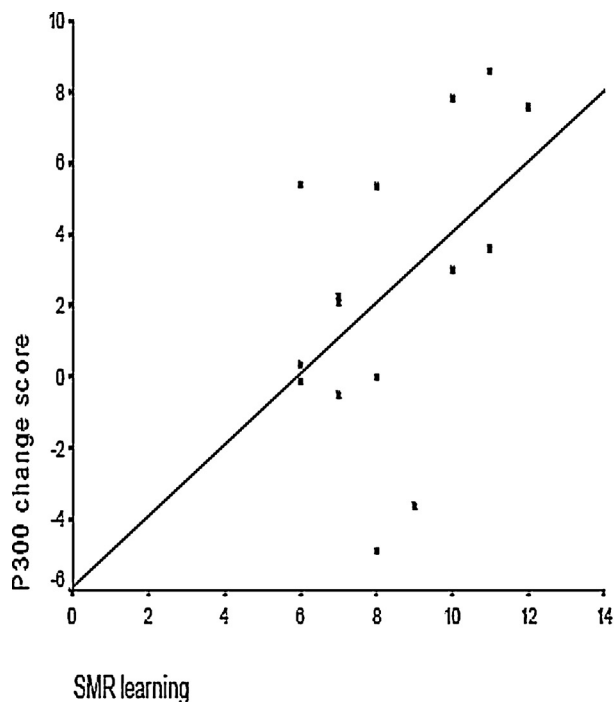

Fig. 2. The increase in amplitude of P300b correlated with learning indices of SMR ratio ($r = 0.49$, $p < 0.06$) and beta1 ratio ($r = 0.55$, $p < 0.05$) protocols (Egner and Gruzelier, 2001).

(8–12 Hz), both with a Cz placement, and a non-training control group. The effect of eight twice-weekly sessions were examined on a sustained attention task with memory load varied by a two- or three-digit sequence target, and on a cued-recall semantic working memory task with words presented in semantic clusters or randomly (Haarman et al., 2003). While there was clear evidence of operant control over the SMR from a within-session increase in SMR and reductions in theta and beta, this was not achieved with eyes-open theta training and indeed alpha increased relative to theta (Section 2.4.2). Following SMR training the two-digit CPT disclosed highly significant reductions in errors of omission and commission which were not observed in the other groups, whereas outcome on the three-digit task with it greater demands on memory load was not improved by either protocol. Invoking a three-network model of attention (Posner and Peterson, 1990) it was inferred that SMR training may act on alerting and orienting networks favouring simple target detection as in the 2-digit task and not the executive attention network invoked in the 3-digit task with the greater memory load; though with hindsight eight sessions may have been insufficient for the more difficult task.

Notwithstanding, the more robust effects in favour of SMR training were found with the semantic working memory task where there were gains of the order of 10% with both clustered and unclustered recall. Working memory has been shown to involve the interaction of attention and memory storage circuitry including respectively a frontal executive control system and posterior association cortex (Sarnthein et al., 1998; von Stein et al., 2000; von Stein and Sarntheim, 2000), while Haarmann and Cameron (2005) have reported an increase in coherence in the 10–14 Hz band between frontal and posterior regions during semantic working memory. This connectivity may be facilitated by SMR (and upper-alpha) training.

The sustained attention task (Greenberg and Kindschi, 1999) has also been examined in 11 year olds as an adjunct to a creative music performance study (Gruzelier et al., 2013; Gruzelier, 2012, and see Part II, Gruzelier, 2013a). Thirty-three children were randomised to 10 weekly sessions of an SMR/theta/beta2 protocol, or to A/T training, or to a no-intervention control group. Cumulative learning was found within and across sessions for theta/alpha and SMR/beta2 ratios, while the SMR/theta ratio remained unchanged. Referring here only to the outcome with sustained attention, there was a highly significant improvement in d-prime for the neurofeedback groups, largely attributable to a reduction in commission errors. The gain was much greater following A/T training with only a weak improvement following SMR training, however, in contrast to the increase in the SMR/beta2 ratio the SMR/theta ratio was unchanged indicating less than optimal learning. That these benefits, which aside from sustained attention included improved music performance and well-being (Gruzelier et al., 2013), occurred with only 10 sessions of training has important pedagogic implications for the value of neurofeedback in school children, quite aside from the fact that according to the attention test manual 19/33 children were classifiably ADHD on the basis of their attention performance and may not have been expected to respond with only 10 sessions when in the clinic thirty would be a minimum.

In children of a similar age, and comparing girls with boys, Barnea et al. (2005) examined a Hebrew word/nonword recognition decision task allowing an independent contribution to reading from each hemisphere. 20 Israeli 10–12 year olds received SMR/theta training for 20 half hour sessions at either C3 or C4, with groups counterbalanced for gender. Setting aside results that in the absence of a control group may have reflected possible practice or nonspecific confounds, the protocols improved language processing in the hemispheres differentially – C3 training improved word recognition and C4 nonword recognition, in line with left hemispheric specialisation for words and the right for nonwords. At the
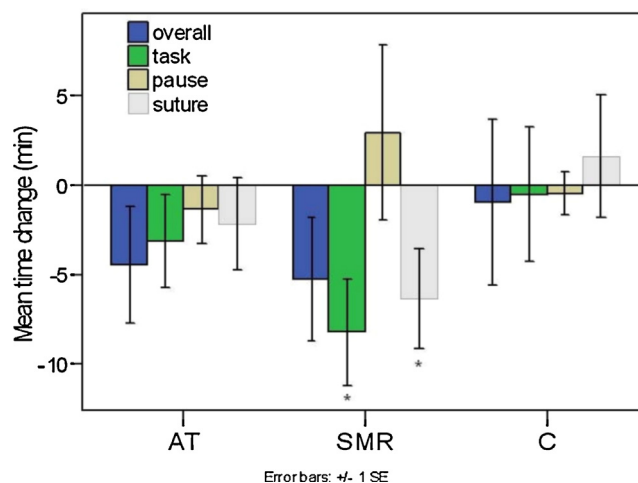

Fig. 3. Temporal changes in technical skills in a simulated cataract operation following alpha/theta (A/T) or SMR ratio protocols and in non-intervention controls (C) (Ros et al., 2009).

same time whereas accuracy of reading was improved by training at C3 in girls, it was improved by C4 training in boys from which the authors inferred the involvement of contralateral callosal circuitry. Bilateral circuitry was also implicated, for whereas latency of response to nonwords was improved with C4 training, C3 training improved both word and nonword recognition. In the authors' words: "The results suggest that the lateralised NF protocol activates asymmetric hemispheric control circuits which modify distant hemispheric networks and are organised differently in boys and girls." P. 314.

2.1.2. Visuo-motor skills: SMR and alpha/theta

SMR/theta and A/T neurofeedback protocols have also been applied to enhance the visuo-motor skills of junior doctors training to become ophthalmic surgeons (Ros et al., 2009). Twenty doctors were randomised to either SMR ratio or theta/alpha ratio protocols, of whom 8/20 before hand participated in a wait-list control group. Outcome was measured by a simulated cataract surgery skills lab procedure assessed by timed measures, self-report anxiety ratings and technique ratings from filmed performance by two consultant surgeons (SMR group inter-rater reliability, $r = 0.85$). While improvements following A/T training were not significant and there was no change in controls, following SMR training the time on task was improved by 26% and this was greatest for the more complex suture task (Fig. 3). The gain following SMR training with the objective timed measures found a counterpart in the subjective consultant ratings of improvement especially for the suture task, and furthermore the timed improvement correlated with the surgeon ratings. The SMR group also showed a reduction in anxiety.

Further light was shed through positive relations between within- and between-session learning from both protocols and microsurgical performance. Interestingly within-session SMR learning correlated with the pause time between tasks ($r = 0.72$, $p < 0.019$) when allowing with partial correlation for the association between longer pause time and more efficient performance overall ($r = 0.70$, $p < 0.035$). As the pause between tasks was longer with SMR training, though not significantly so, this implied that SMR training in producing a better performance achieved this through a more modulated performance, faster performance overall with longer, perhaps preparatory pauses between tasks. Though A/T training did not significantly improve performance overall, the better the within-session A/T learning the greater was the improvement in surgical technique ($r = 0.64$, $p < 0.047$) and the more efficient was the technical performance ($r = -0.52$, $p < 0.06$).

Performance-change Pre/Post NFT in the number of correct answers in the visuspatial rotation task
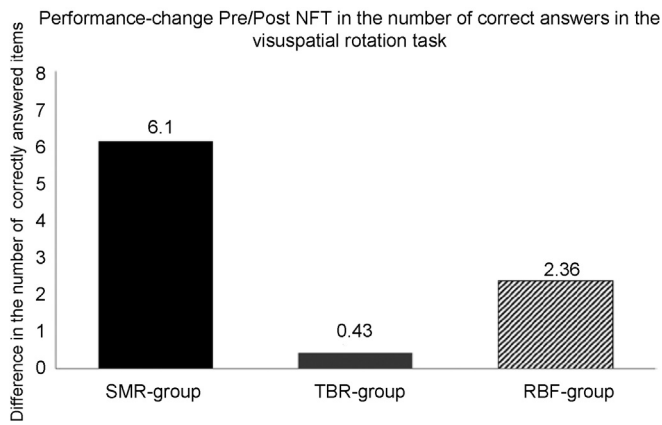

Fig. 4. Improvements in visuospatial rotation in SMR, theta/beta ratio (TBR) and random bin feedback (TBR) control groups (Doppelmayr and Weber, 2011).

When the A/T group was median split into those with the higher and lower improvement in technique, it was the higher improvement group who showed the superior theta/alpha ratio, an index of hypnogogia (Gruzelier, 2009). Of possible relevance to these individual differences was the challenge of achieving the A/T goal of borderline sleep within sessions given that the half hour sessions were sandwiched into the busy schedules of the junior doctors. An increase in the theta/alpha ratio was also associated with a reduction in performance anxiety. A complimentary result was found when the same median split was applied to the SMR group; those in the lower improvement group showed a 10% falloff in the SMR/theta ratio, shown to be attributable to an increase in theta in later sessions, the opposite to the training goal of inhibiting theta. Poorer improvement in surgical technique was also found to be accompanied by a greater lapse of time between training sessions, an important methodological issue (Gruzelier, in preparation). In conclusion both SMR and A/T could be seen to benefit psychomotor skills when effective learning was taken into account.

2.1.3. Visuospatial rotation and RT: SMR ratio and theta/beta1 reduction

Doppelmayr and Weber (2011) delivered thirty training sessions (C3/4) to an SMR (12–15 Hz) group ($N = 13$) or to a group ($N = 14$) receiving a theta (4.5–7.5 Hz)/beta1 (15–21 Hz) ratio reduction protocol which has had a successful outcome in ADHD research (Leins et al., 2007; Gevensleben et al., 2009). There were theta, beta2 and eye-blink inhibits. In addition a control group ($N = 14$) was instructed to either increase or decrease the amplitude of different 1-Hz bands within the range of 6–35 Hz, variable over sessions. Only the SMR group evinced learning, showing a highly significant progressive linear amplitude increase accompanied by a significant increase in reward threshold; though learning only differed from baseline after 26–30 days of training. Pre-and post-training assessments included spatial rotation, simple and choice reaction time, letter cancellation and a creativity test. Of these measures SMR training facilitated spatial rotation (Fig. 4) and simple and choice reaction time, tasks which required visuospatial processing, access to semantic memory, and the integration of relevant stimuli. SMR training benefits were attributed to improved regulatory control of somatosensory and sensorimotor pathways, which in turn led to more efficient attention resulting in a better integration of task-relevant stimuli, in line with Egner and Gruzelier (2001).

2.1.4. Sleep, memory and SMR

A series of studies has shown that SMR training without inhibits transfers to the sleeping state. The potential for SMR training to enhance sleep arose from the earliest demonstrations in cats

(Sterman et al., 1969) following evidence that a dominance of oscillations overlapping the SMR 12–15 Hz band occurred in stage II NREM sleep, leading to the descriptor of sleep spindles (rolandic mu or wicket rhythms; Niedermeyer, 2005). Cognitive associations with sleep spindles in recent reports have included over-night memory consolidation of motor procedural memory and declarative memory, learning aptitude, implicit learning and intelligence (e.g., Fogel et al., 2007; Schabus et al., 2004). Hauri (1981) and Hauri et al. (1982) went on apply SMR training in the treatment of insomnia in controlled studies.

Berner et al. (2006) in a pilot study with healthy subjects explored the effect of Cz neurofeedback in the range 11.6–16 Hz on sleep spindle activity (C3, C4) and the sleep EEG (Fz, C3, Cz, C4, Pz, O1, O2) while declarative memory was assessed after neurofeedback and again after a night in the sleep laboratory. Eleven participants previously shown to be capable of raising their alpha power through feedback were assigned either to neurofeedback or to the same protocol but with sham feedback. The protocols were given in a single session in four 10-min training blocks each separated by 2 min breaks. While the experimental group was successful in raising power in the training band, the single neurofeedback session did not have an impact on either spindle activity in sleep or declarative memory. However, though compromised by small group sizes a tendency was reported for power in the training band to be increased at Fz and Cz relative to the pre-training baseline in the first half of the night in stage 2–4 NREM sleep, a period during which the spindle activity correlated positively with memory. When all eleven subjects were categorised according to their overall memory those with the higher memory score showed more spindle activity during the early period of sleep in support of an aptitude to learn new verbal items (Gruber et al., 2008). The resting eyes-open EEG was examined for carryover effects immediately after neurofeedback, and while there was no increase in sigma the authors reported 'a noticeable' but statistically nonsignificant increase in slower 4–10 Hz bands, which would be in keeping with relaxation.

Hoedlmoser et al. (2008) went on to assign twenty-seven participants to 10 sessions of either SMR (12–15 Hz) C3 training without inhibits or to a control group receiving randomised frequency training of 3 Hz bins between 3 and 20 Hz, excluding the SMR band. Pre-and post-training assessment consisted of a declarative word-pair memory task before and after a 90 min afternoon nap in the sleep laboratory, as well as EEG sleep characteristics from a 15 electrode recording. In addition to learned changes during feedback sessions, the impact of neurofeedback was also estimated from successive pretraining baselines with the assumption of cumulative learning carrying over day by day. There was evidence of successful learning through an increase in SMR amplitude from early to late sessions, and while a cumulative increase across SMR baselines was not observed there was a transfer to the tonic EEG in the post training nap with an increased spindle number and shorter sleep latency indicative of improved sleep quality. Furthermore following SMR training immediate retrieval in the declarative memory task was facilitated both before and after the nap, whereas neither group showed improvements in memory consolidation as a result of the nap per se. This was interpreted as neurofeedback improving memory through an indirect nonspecific influence facilitating attention or relaxation during learning/retrieval of the task.

SMR training was later extended by the same group (Schabus et al., 2013) to twenty-four patients with primary insomnia who in a counterbalanced design each received 10 sessions of SMR C3 training together with 5 sessions of sham training involving random 3 Hz bins between 7 and 20 Hz excluding SMR, which were scheduled over 3–6 weeks. SMR was monitored bilaterally along with beta (16–25 Hz). At C3 there was a linear increase during SMR training in both SMR and broad-band beta amplitude, with a similar
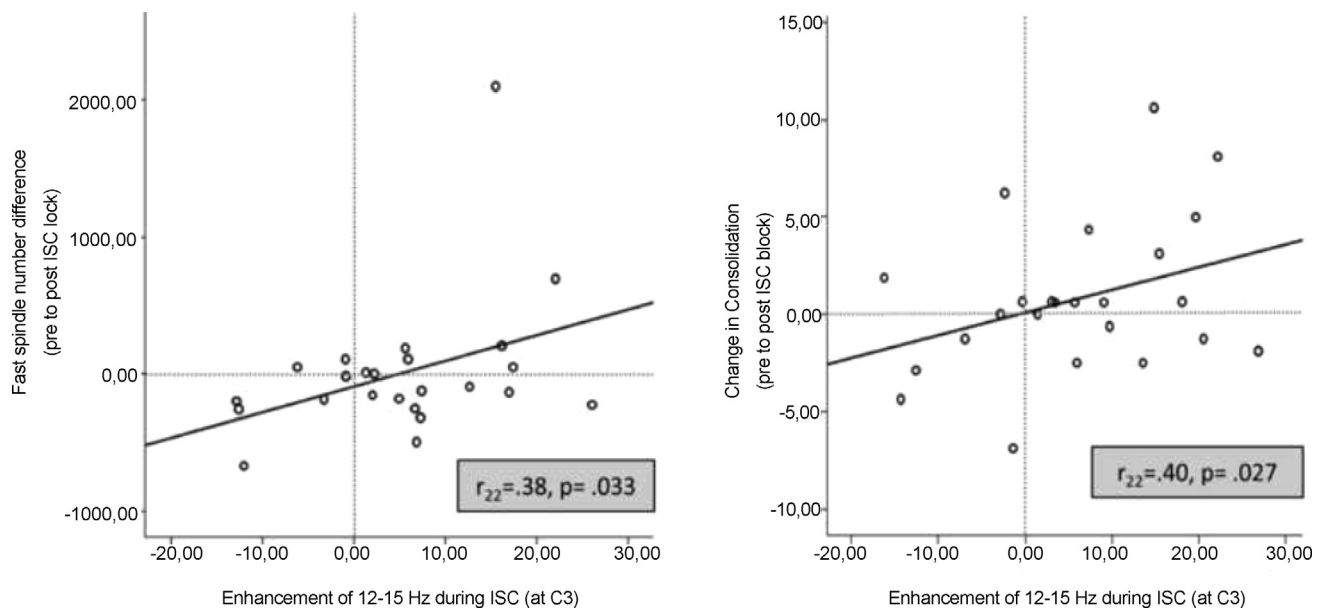
Fig. 5. Positive correlations between SMR learning and increase in frequency of fast spindles (left) ($r = p < 0.38$, $p < 0.04$) and memory consolidation (right) ($r = 0.40$, $p < 0.027$) (Schabus et al., 2013).

but nonsignificant effect contralaterally, without an impact on the post-session EEG. The degree of enhancement in SMR was found positively related to the training course; the longer patients took to attend for training the better was the SMR amplitude gain. Outcome benefits included fewer awakenings and a longer time spent in slow wave sleep. However, the majority of findings were correlational relating to individual differences in the SMR training gain which correlated positively both with the increase in spindle frequency (13–15 Hz, C3) in NREM sleep and with over-night memory consolidation, see Fig. 5, which in turn correlated positively with the increased frequency of spindles. Importantly the counterbalanced design allowed within-subject comparisons of the impact of SMR versus sham training in groups differentiated by condition order. For both there was evidence that sham training had deleterious effects on the number of awakenings and of the time spent in slow wave sleep.

2.2. Alpha activity

Since the original EEG-biofeedback studies viewing alpha synchronisation as an index of relaxation, while desynchronisation remains associated with excitation, contemporary neuroscience has regarded alpha synchronisation as an active top-down inhibitory process for the exclusion of conflicting or irrelevant input (von Stein et al., 2000; Cooper et al., 2003; Basar, 2006; Klimesch et al., 2007) rather than as a brain idling index. The neural mechanisms underlying alpha production are incompletely understood with the classical view of thalamo-cortical circuits giving way to distributed alpha networks (Basar et al., 1997; Lopes da Silva et al., 1997; Klimesch, 1999). Different psychological associations have been posited between upper and lower alpha (Klimesch et al., 1993, 1996, 2007; Petsche et al., 1997). Furthermore peak alpha frequency has been positively associated with intelligence and negatively with ageing (Jaušovec et al., 2001; Clark et al., 2004; Duffy et al., 1984; Jausovec and Jausovec, 2000). Indeed the considerable individual differences in the alpha peak have led to an individual adjusted frequency procedure with alpha and sometimes adjacent frequencies (IAF; Klimesch et al., 1993). These are amongst the factors that have informed new protocols for neurofeedback, and see Bazanova and Vernon (2013, in this issue) for further aspects of alpha methodology.

2.2.1. Visuospatial rotation: high alpha

Informed by a transmagnetic stimulation (TMS) study in which mental rotation of a cube was enhanced by the TMS frequency which had been determined by the individual's alpha peak frequency (Klimesch et al., 1993), and secondly by the evidence that good cognitive performance was associated with high resting alpha power/low task-related alpha power and with the opposite relations in theta power (Klimesch, 1999), Hanslmayr et al. (2006) explored raising high-alpha power versus reducing theta power (F3, Fz, F4 and P3, Pz, P4) both individually adjusted, in a counterbalanced design with outcome assessed through spatial rotation. In a single-session experiment subjects ($N = 18$) were trained in separate 20-min blocks of trials separated by the cognitive task. Results were analysed for the nine subjects with successful alpha learning and the ten with theta learning; only four in the alpha group were in the theta group. Raising upper alpha improved spatial rotation accuracy by about 10% post alpha training, and importantly there was a positive correlation between them ($r = 0.41$–0.55, $p < 0.05$), while learned control of theta reduction was not related to the behavioural or EEG outcome. EEG monitoring during the post-training assessment disclosed that the increase in upper-alpha power was sustained up until task onset but bore no relation to phasic alpha power induced by the task, in line with an influence of upper-alpha neurofeedback training on tonic rather than phasic EEG power. An increase in alpha at the right parieto-occipital placements, a primary locus for spatial rotation, correlated with the gain in upper-alpha power, offering the possibility that had this region been used for feedback larger improvements in mental rotation might have been obtained.

Zoefel et al. (2011) went on to compare in five daily sessions visuospatial rotation in subjects ($N = 14$) trained to raise their upper-alpha amplitude versus a non-training control group ($N = 10$) with the alpha band individually adjusted each day. Successful training with feedback from bilateral parieto-occipital electrodes (P3, Pz, P4, O1, O2) was observed in 11/14 subjects, such that there was a linear increase in amplitude within/across sessions, and the baseline was higher in the fifth session than in the first session, demonstrating cumulative effects of learning in the tonic EEG that carried over from day to day. In support of training-bandwidth specificity the increase in the upper alpha band was independent of adjacent alpha and beta bands. Rotation was elevated only with
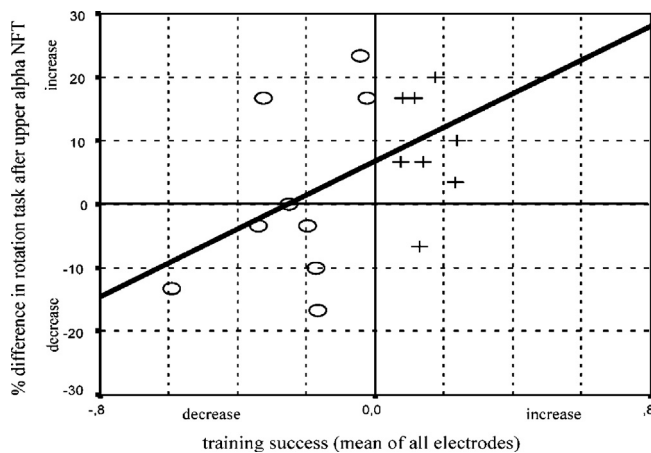
Fig. 6. Percentage change in spatial rotation task following one session of upper-alpha training ($r = 0.41–0.55$, $p < 0.05$) (Hanslmayr et al., 2006).

neurofeedback and training also led to a higher upper-alpha amplitude than in controls.

2.2.2. Upper-alpha synchronisation and memory

Upper-alpha training has also been explored for effects on working memory with an adaptation of the conceptual span test of Haarmann et al. (2003). Escolano et al. (2011) trained participants on five consecutive days with five 15-min blocks and feedback averaged from parietal and occipital placements. IAF was computed daily from the 7.5 to 12.5 Hz band while changes in saturation of a fixation square were counted (active task) and comparisons were made between the 6/9 who were capable of increasing their upper alpha band (IAF +2) and six no-training controls. Working memory was improved following training. Though within-session changes were not significant there was clear evidence of feedback learning across all twenty-five session blocks, and there was evidence of learning carrying over from day to day when comparing the first and fifth sessions during both the pre-session active task and a passive task without counting. In comparing whether there was training band specificity by examining lower alpha (IAF −1 to −3) and low beta (IAF +3 to +5), while independence was found for the active task, in the passive task there was a spread to include lower alpha.

Working memory has also been examined with digits backwards and forwards as an outcome measure (Nan et al., 2012) comparing sixteen participants who received upper-alpha Cz training based on IAF with sixteen non-training controls. They were given short condensed trials where in each session there were ten 20-s trials separated by 5 s when cognitive strategies were written down. There were three or four sessions within a day and a total of twenty sessions within fifteen days. In addition to the memory task pre and post-assessments consisted of eyes open and closed resting EEG (0.5–16 Hz). The relative amplitude increase in all bands between theta and sigma was positively correlated with session number while there was a negative correlation with delta. Memory improved with training and the improvement correlated positively with the increase in relative alpha power in the trained band only, in support of training-band specificity. There was no change in the post-training resting EEG. Mental strategies were mostly positive such as thoughts of love, family and friends.

2.2.3. Alpha desynchronisation and procedural learning

The impact on procedural learning of training down the mu rhythm (8–12 Hz) from the right motor cortex (C4) in a single 30-min session was examined in ten dextral subjects by Ros et al. (2013). The experiment was designed as an adjunct to a TMS

neurofeedback experiment (Ros et al., 2010) with a TMS protocol shown to increase corticospinal motor evoked potentials and reduce short-interval intracortical inhibition (see Gruzelier, in preparation). Serial left hand reaction-times were obtained with a task developed to assess implicit procedural memory through repeating sequences intended to be unrecognised by the participants (Nissen and Bullemer, 1987). The task was performed twice in a counterbalanced design separated by a day, and on one occasion was preceded by neurofeedback. Reduced RTs followed training, suggesting that alpha desynchronisation acted to prime the motor cortex facilitating procedural learning.

2.3. Feature binding and fluid intelligence: gamma and beta training

Keizer et al. (2010a,b) set out to revisit earlier evidence (Bird et al., 1978) of the ability to modulate gamma activity with neurofeedback, an ability found to be sustained over 2–3 years. With outcome measures of feature binding (Hommel, 1998) and fluid intelligence (Raven, 1938), Keizer et al. (2010a) compared a group ($N = 7$) trained over eight sessions to increase gamma (36–44 Hz) without increasing beta (12–20 Hz) with a group ($N = 7$) trained to do the opposite – increase beta without increasing gamma. Occipital midline electrode (Oz) training was obtained with testing spread across 10–11 days. Elevation of gamma with a maximum between 30 and 60 Hz was successful for the experimental group reaching a plateau on the 6th session, with a positive correlation between increases in power and in intelligence scores ($r = 0.82$, $p < 0.05$), a relation which extended from 16 to 60 Hz, much wider than the gamma training-up band and including the beta inhibit band, see Fig. 7. However, inhibition was found below the inhibited band where there was a reduction in slower frequencies below 10 Hz and importantly this reduction disclosed a suggestive negative correlation with slow wave 2–4 Hz power ($r = −0.70$, $p < 0.08$). While the comparison group was unsuccessful at increasing beta (12–20 Hz) and reducing gamma, there was an increase in slower wave activity maximal at 10–12 Hz which was in the opposite direction to the experimental group. Compatible with this there was a group difference in the RT episodic binding measure; this was reduced in the experimental group (mean 14.6 vs. 10.4) while doubling in length in the comparison group (mean 13.5 vs. 26.3).

Keizer et al. (2010b) went on to take into account frontal (Fz) as well as visual (Oz) functions given that the gamma influenced executive control processes are frontally situated. Coherence between the cortices was examined following the implication that fast wave activity in the gamma range acts focally, whereas slower activity acts over longer distances (von Stein et al., 2000; Varela et al., 2001). One important procedural modification involved restricting training to the primary band of interest, rather than requiring simultaneous control of gamma and beta as in the earlier experiment. Furthermore the two procedures differed in that the gamma feedback was from the occipital electrode only while beta feedback was the average of the two sites, occipital and frontal. Fifteen subjects received between 7 and 8 sessions of training, with pre and post-assessments as before and a recognition memory task adapted from Cycowicz et al. (2001) which distinguished between familiarity and recollection. This task had provided evidence, albeit equivocal, for a possible double dissociation between the two EEG bands and between knowing and recollection processes in long-term memory (c.t. Burgess and Ali, 2002; Gruber et al., 2008).

While the full bandwidth spectrum in this experiment was not disclosed, a lack of learning specificity vis a vis band and topography was disclosed by comparing the first and last sessions at the two sites. Oz gamma training evinced learning at the Oz training site across sessions but only within the last session, and Oz training influenced the frontal Fz non-training site where there
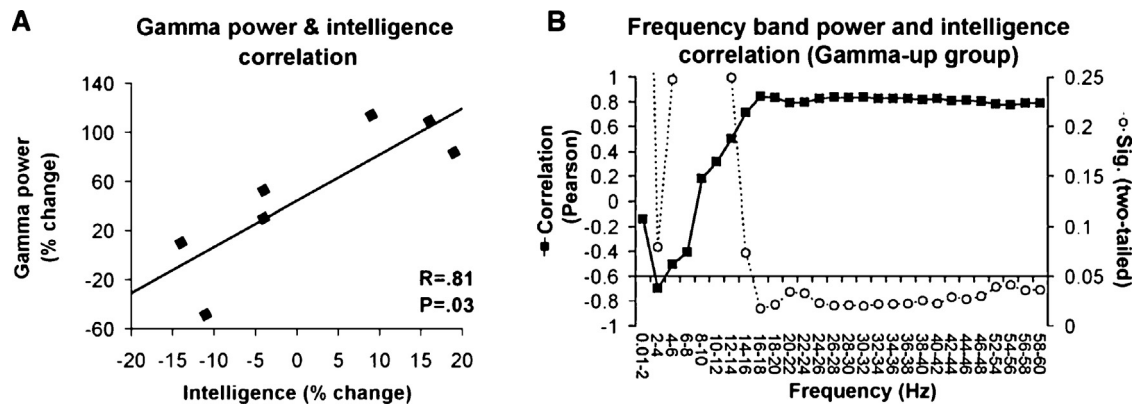
Fig. 7. Percentage change in gamma power correlated with percentage change in fluid intelligence (r = 0.81, p < 0.03) (Keizer et al., 2010a).

was across-session learning in gamma and within-session learning in beta1, disclosing a spread of influence beyond the gamma training band. In contrast beta1 training, where feedback was the average of both frontal and occipital derivations, resulted in within-session learning frontally, but despite this there was no evidence of learning across sessions at either Oz or Fz. Possible interactions between sites were examined with coherence analysis. Within-session gamma coherence increased in session one for both groups, but this was not seen in the last session. On the other hand across sessions gamma Oz-Fz coherence increased in both groups, while beta coherence was increased only by beta training. Turning to the cognitive outcome the binding results of the previous experiment were replicated insofar as shape-location and location-response integration showed reduced costs following gamma feedback training, moderating the effects of task-irrelevant feature bindings, while the recognition memory task results disclosed the hypothesised double dissociation with gamma training improving recollection and beta training familiarity.

2.4. Theta (eyes-open)

While classically theta was associated with drowsiness, there has been more recent evidence of theta's role in learning and memorial processes and effort in attention. Theta facilitates long-term potentiation, is involved in recognition memory in encoding and recognition (Burgess and Gruzelier, 1997; Klimesch et al., 1997), is related to working memory load (Grunwald et al., 2001) and has been invoked in the encoding and retrieval of information in working memory (Klimesch, 1999) and in linking a parietal-prefrontal circuit both for storage and up-dating (Sarnthein et al., 1998; von Stein et al., 2000; von Stein and Sarntheim, 2000). Theta activity has also been implicated in memory consolidation through sleep (Buzsaki, 2002; Mitchell et al., 2008; Walker and Stickgold, 2004). Frontal theta, while associated with increasing memory load, also synchronises with task demands, focussed attention, sustained concentration and meditation (Inouye et al., 1994; Grunwald et al., 2001; Jensen and Tesche, 2002; Onton et al., 2005; Kubota et al., 2001; Missonnier and Deiber, 2006; Lagopoulos et al., 2009).

2.4.1. Frontal theta

In a methodological experiment Enriquez-Geppert et al. (2013a,b) set out to explore the trainability of anterior theta in thirty one participants who were randomised to either training-up theta or to a pseudo feedback control group, following implications that frontal theta recorded from the midline has potential as a marker of executive functions (Mitchell et al., 2008) including cognitive control (Cavanagh et al., 2011). With no cognitive/affective outcome measures this will be outlined in Part III (Gruzelier, in preparation), however, an application of training up anterior theta with the elderly (Wang and Hsieh, 2013) is reviewed in Section 4.2.

2.4.2. Central (Cz) theta

As indicated above (Section 2.1) Vernon et al. (2003) alongside SMR training also examined eight sessions of eyes open Cz theta up-training while inhibiting both delta (0–4 Hz) and alpha (8–12 Hz), along with a non-training control group. Theta training provided no gains for a two-digit CPT or a semantic working memory task whereas SMR training was beneficial, while neither neurofeedback protocol facilitated performance on a three-digit CPT with the greater memory load. Whereas there was evidence of learning with SMR training this was not the case with training-up theta, in fact theta was effectively trained down for within sessions the desired theta/alpha ratio went significantly in the opposite direction with alpha increasing and theta decreasing, not vice versa, and without improvement in the theta/delta ratio. Most likely the broad band alpha inhibit was inappropriate given the involvement of alpha in a diversity of task related processes (Klimesch et al., 1997; Doppelmayr et al., 2002) that would encroach on neurofeedback learning.

2.4.3. Posterior theta

Classical associations of theta in relation to the arousal spectrum have involved posterior recordings with posterior theta indexing low arousal, tiredness and inattention. Beatty et al. (1974) had reported that individuals receiving theta (4–7 Hz) up-training versus down-training (O1, P3), decreased and increased respectively their radar detection performance. Since then posterior theta activity has been implicated inter alia in consolidation of memory processes through sleep (Buzsaki, 2002; Mitchell et al., 2008; Walker, 2005; Rauchs et al., 2005). Reiner et al. (2013) explored the impact of a single session of training up eyes-open theta on the learning of a 30-min finger-thumb apposition task and its repetition following one, two, three and seven nights of sleep. Participants (N = 38) were randomised to 30 min of Pz theta (4–7 Hz) or beta 1(15–22 Hz) training or to a control group who watched movies. Speed of performance improved in all groups with practice, but more so following theta training. There was an immediate advantage of (8.7%) which was sustained and saw an additional 8.5% gain between the last two sessions compared with a 4% gain in controls and no improvement in the beta group. Whereas the initial gains were attributed to synaptic consolidation, the final delayed gain was hypothesised to reflect consolidation at a systems level (Diekelmann and Born, 2010) with enhanced performance through the redistribution of new memories to multiple, distributed brain regions (Song, 2009).

That theta training was central to the improvement in speed of performance (there were no findings with accuracy) was supported by positive correlations between the ratio of theta to beta, a ratio obtained to normalise for individual differences in absolute theta, and the performance gain on all assessments following the first night's sleep, but not immediately after training. Taking the results together it was inferred that consolidation of learning during sleep was responsible for the gains following theta training, though a control for practice will be necessary to validate the involvement of sleep in the process. However, this does not detract from the main finding that theta neurofeedback contributed to the improvement in motor procedural learning.

3. Mood

3.1. Alpha/theta training

In establishing what was the first evidence of operant control over the theta/alpha ratio with eyes closed, Egner et al. (2002) had shown in healthy subjects that when comparing a contingent with a non-contingent control A/T protocol, both protocols led to identical ratings on Activation Deactivation self-report scales (Thayer, 1967), whereas only contingent training produced an increase in the theta/alpha ratio. One implication from this was that there was likely to be more to the reported clinical and performance benefits of A/T training than relaxation per se. Indeed performing arts studies with adult musicians, dancers, and actors, and child musicians, which will be reviewed in Part II (Gruzelier, 2013a, and see Gruzelier, 2012), have shown not only enhancements in Creativity and Technique, but also enhancements with a strong emotional component reflected in Communication in performance which was underpinned by ratings of Enjoyment, Confidence, and Emotional Commitment and Conviction (Egner and Gruzelier, 2003; Gruzelier et al., 2013; Gruzelier, 2012).

Raymond et al. (2005) went on to examine possible benefits for well-being in socially anxious and withdrawn students randomised to alpha/theta training or to a mock training control where feedback was non-contingent and outcome assessments were examined with the Profile of Mood States (McNair et al., 1992). Within-session learning but not between sessions was highly significant and was combined with advantages favouring contingent A/T feedback on self-ratings of Composure, Agreeableness, Elevated Mood, Confidence and Energy. The control group, who on debriefing were unaware of their control status and whose perception of learned control was on a par with the contingent group, showed no evidence of learning and reported more Composure and Tiredness. A/T training produced a 25% improvement in mood overall.

3.2. SMR ratio training

SMR enhancement has also been shown to have an impact on mood (Gruzelier, 2013b). In the first attention/ERP study with music students (Egner and Gruzelier, 2001; Section 2.1) an activation/deactivation checklist (Thayer, 1967) was examined at the beginning and end of each of the SMR and beta1 protocols which were administered for 15 min in a counterbalanced order in the same session for a total of 10 training sessions. Whereas with both protocols Tiredness was increased within sessions, Calmness was differentially affected with an improvement following SMR training only. This was theoretically consistent with the calming influence of the trained putative inhibitory influences of the SMR rhythm on the sensorimotor cortex with the consequence of reduced motor interference and reduced muscle tone (Sterman, 1996), and was endorsed by the post-training reduction in the musician's impulsivity indexed by commission errors in

a continuous performance test (Egner and Gruzelier, 2001). The increase in calmness was also consistent with an experiential analysis conducted with some of the musicians from a taped semi-structured interview (Edge and Lancaster, 2004). Five out of the ten musicians reported discernible experiences about the SMR/beta1 training which the authors encapsulated by a report of one student that it 'made the mind breathe'.

Further evidence of beneficial influences of SMR neurofeedback on mood was reported by Ros et al. (2009) in the microsurgery study with benefits for both anxiety and surgical skills. In those receiving A/T training the increase in the theta/alpha ratio, which correlated with an efficient performance, also correlated with a reduction in anxiety. Anxiety has been similarly reduced in twenty female swimmers described as adolescents with 5–6 years of professional experience (Faridnia et al., 2012) as assessed by a Sport Competition Anxiety Test (Martens, 1977) which was administered before and after neurofeedback or a control condition the details of which were not reported. Here twelve sessions of SMR (12–15 Hz) ratio training were combined with beta1 (15–18 Hz) training, both protocols with theta (4–8 Hz) and beta2 (22–37 Hz) inhibits. They were given in two 20-min blocks within a 45 min session with order of protocols not reported. Reduced anxiety scores were found solely in the neurofeedback group. Given differential influences of SMR and beta1 ratio training on mood (Gruzelier, 2013b), separation of SMR from beta1 training may have been informative.

3.3. Alpha synchronisation

Alpha training (8–12 Hz) was revisited by Van Boxtel et al. (2012) developing a user-friendly 'relaxation' device suitable for use in public with wireless electrodes mounted in an audio headset placed over the middle of the head allowing recording approximately from the central electrode chain. An alpha group (N = 18) was compared with a random beta group (N = 12) who heard a 4 Hz band between 14 and 30 Hz which differed each day, and a control group who listened only to music (N = 20). In each session the mostly college student participants listened to their choice of music which was only heard clearly when the training frequency band was enhanced. Music ranged over hard rock, easy listening and classical, assumed to have identical effects on relaxation, but with no empirical verification or matching of groups for choices. There were fifteen sessions within four weeks, and participants were trained in groups of five. The participants were instructed to 'sit back and relax' with their eyes open. Training sessions were divided into three blocks of 8 min bracketed by 5 min of one of four cognitive tasks in the fixed order of flanker task, stop-signal task, Stroop task and N-back task, and interspersed with ten subjective relaxation ratings. Roughly a week before and after training and again at an approximately four month follow-up, a topographical EEG was recorded with eyes open and closed. In addition questionnaires were completed encompassing mood, sleep and quality of life.

Importantly the recording of alpha from the headset did not differ from the laboratory recording from C3/C4 derivations. There was no statistical evidence of relaxation comparing session 1 and 15 on a rating scale, nor group differences, and in an exit interview while about half (53%) in the alpha group mentioned that the training was relaxing which was twice the number in the other groups this was not statistically significant, nor were there group advantages in questionnaire measures of mood, sleep and quality of life. Relative alpha power was averaged across lateral central, parietal and occipital placements in eyes open and closed conditions disclosing that parieto-occipital alpha was higher than central alpha. With alpha training eyes-closed alpha increased more than in the beta group, but as beta training would be activating this would be expected, while with eyes open the training course had an identical effect in

the alpha and beta groups in raising alpha, which was increased further by follow-up more so in the alpha group. Interpretation of the results is hampered by an absence overall of paired comparisons within and between groups, and inspection of the figures indicated that the music control group had considerably higher levels at baseline. Validation of the effects of the individualised music choices on relaxation may lead to a less equivocal outcome.

4. Applications

4.1. Sporting skills

Applications of neurofeedback to improve sporting performance and to compare elite with novice performance are at an early stage but will be apposite (Thompson et al., 2008). Little progress has been made since the pioneering studies of Landers et al. (1991) who reported that the feedback of an EEG analysis of slow potentials improved performance in pre-elite archers. They followed evidence that in sportsmen prior to the execution of a skill there was a unilateral slowing of left temporal activity and randomised 24 pre-elite archers to three groups: a left temporal (T3) slowing experimental group, a right temporal (T4) slowing group controlling for expectancy and motivation, and no-training controls. Training involved a 45–75 min single neurofeedback session with shooting (27 shots) examined before and after. Differential outcomes occurred in the training groups with improved accuracy in the left temporal group, a deterioration in the right temporal group, and with no change in the no-training group while examining spectral power increases on the left did not differentiate the groups, whereas beta power increased on the right in the 13–30 Hz range in the right temporal group from which evidence of cognitive processing was inferred as seen in novices for elite performance becomes automatic (Fitts and Posner, 1967).

An individualised approach has been examined in six golfers in whom EEG (FPz) in conventional spectral bands was recorded immediately before golf putting ($N = 80$), contrasting successful with unsuccessful putting attempts in order to ascertain the optimal EEG profile associated with success that met with inter-rater agreement (Arns et al., 2008). Three daily training sessions were given consisting of four conditions of eighty putts each with feedback in the second and fourth conditions. In the feedback conditions a continuous tone was presented before each putt up until the optimal EEG pattern occurred – the signal to proceed with putting. Performance was better overall with feedback, but examination of the three training sessions separately failed to show benefits in the last session; a preferential feedback effect occurred only on the second occasion in which there was evidence of cumulative learning and better performance overall. The conditions of play – outdoor or indoor – varied due to weather which may have contributed to the falloff in performance in the third, final training session. While some other reports are emerging, in the absence of controls, the validation of measures (e.g., Sherlin et al. (2013) and reporting of control procedures (e.g., Paul et al., 2012) little can be concluded.

4.2. Cognition in the elderly

A number of exploratory attempts have been made for preserving cognitive functions in the healthy elderly, with the clear conclusion that age does not exclude neurofeedback learning.

4.2.1. Alpha training

In an exploratory study of six participants aged 70–78 years Angelakis et al. (2004) contrasted: (i) increasing peak alpha frequency while inhibiting alpha amplitude (8–13 Hz) which was successful in 2/3, (ii) increasing alpha amplitude while inhibiting

peak frequency, successful in 2/2, and (iii) one mock feedback control. Thirty one to thirty five sessions were given once or twice a week involving a total of 24 min of posterior training (POz). There were impressions of differential effects on outcome measures of processing speed, executive functions and memory, all known to decline with age, with an improvement from amplitude training with processing speed and executive function, and improvement from peak frequency training with visual, verbal and working memory. They noted that similar to Egner et al. (2004), the outcome in the topographical EEG was expressed frontally and not at the posterior training site in the three with peak training, a result not seen in the other subjects. Encouragingly it may be concluded that the age range 70–78 years is not a handicap to regulating brain activity.

The implications of this pilot study were followed up by Lecomte and Juhel (2011) with 30 participants aged between 65 and 85 years who were assigned to one of three groups: an increase in upper-alpha (10–12 Hz) power while inhibiting theta (4–7 Hz; transverse montage (C3-Cz/Cz-C4)), essentially a relaxation control group performing simple yoga movements, or a no-intervention control group. Sessions involved 30 min of training on four occasions within a single week. Neurofeedback learning was on the whole successful with a significant increase over sessions in alpha power seen in 8/10, together with an increase in the alpha/theta ratio (7/10), without a significant reduction in theta (6/10). The EEG was examined pre and post training along with delayed recall and semantic fluency and a memory learning test, and following each session tension level was recorded with analogue scales of stress and anxiety. Cognitive improvements occurred in all groups while tension level fell in both training groups; none of the improvements were associated with neurofeedback learning. The four training sessions were surely too few with elderly participants.

4.2.2. Theta training

Following evidence that abnormally enhanced theta has been associated with the greater cognitive impairments in patients with either mild cognitive impairment or dementia (e.g., Babiloni et al., 2007). Becerra et al. (2012) set out to reduce theta in fourteen normal participants aged 60–85 years who had evidence of abnormally high theta in one lead. Electrode placements were individualised according to the patient's maximum theta elevation and involved the following locations for the sample: F4, C3, C4, P3, F7, F8, and T6. They were randomly assigned to either an experimental group or a noncontingent feedback control group. Thirty 30-min sessions were given over 10–12 weeks. In the experimental group theta power was successfully reduced and coincided with reductions in F3 and midline absolute theta power and left lateralised increases in alpha power. However, the control group also disclosed changes in relative theta and alpha power. Pre and post assessments consisted of the Wechsler Adult Intelligence Scale, neuropsychological scales of memory and executive functions, and topographical EEG. The neurofeedback group showed improved verbal IQ, executive functions and attention and shared memory improvements with the control group who also demonstrated a decrease in performance IQ. Links were made between normalising midline theta and improvements in attention, and between the reduction in theta at F3 and Fz and the increase in left-sided alpha regarding the improvement in verbal IQ, and the frontal changes for executive functions. Of relevance to the question of topographical specificity the reductions in theta seen in the post training EEG did not coincide with the training locations based on maximum theta power. The normalising of theta and the increase in alpha were interpreted as arising from thalamic influences (Hughes et al., 2004). That some benefits were shared with the control group, as found in the French study, indicate that aside from training, the elderly may be responsive to motivational and social factors through research engagement,

while the inclusion of a sham control task ensured that processes involved in task engagement were also shared.

Wang and Hsieh (2013) examined Fz theta (4–7 Hz) training for its potential to improve attention and recognition memory in an older (61–72 years) community sample, described as high functioning elders engaged in community work and screened for dementia and depression, who were compared with university students (21–25 years). Subjects were allocated in groups of eight, to 12 sessions over four weeks of theta training or to random 4 Hz band training in the range 10–25 Hz, both protocols were with delta and gamma inhibits. Regarding characterisation, pre-training assessments indicated that the elderly were in relatively good condition cognitively when compared with the students, with superior Attention Network Task (Fan et al., 2002) accuracy scores, though RTs were slower (a speed/accuracy trade off?), recognition memory was poorer, while a topographical recording of the resting eyes-open EEG showed less theta and delta power in the older group in the fronto-central midline region (c.t. Becerra et al., 2012), which carried over to the post-training assessment.

Importantly the elderly were capable of increasing midline frontal theta and learning indices disclosed evidence of neurofeedback learning equally in both students and the older sample, and in the EEG no difference between them at Fz; these effects were absent in the control groups. Furthermore following neurofeedback measures showed improvements specific to the elderly were found in orienting (RT ANT) and in recognition memory, while ANT conflict was improved in both groups relative to the sham controls; there was no impact on alerting, see Fig. 8. Correlational data between the neurofeedback learning indices and the cognitive outcome would have confirmed a meditational link with the theta training.

4.2.3. Gamma training

Further support for the ability of older subjects to engage with neurofeedback training was obtained by Staufenbiel et al. (2013) with twenty participants aged 58–80 years allocated to either eight sessions of Fz gamma (36–44 Hz) or broad band low beta (12–20 Hz) training and with no more than two days between sessions. The main aim was to extend to the elderly the improvement in fluid intelligence following gamma neurofeedback in younger participants (Keizer et al., 2010a), in view of gamma deficiency reports in the elderly and in dementia (Werkle-Bergner et al., 2009; Stam et al., 2002), along with the differential benefits from beta and gamma training respectively on familiarity and recollection in recognition memory. Before and after the training course eyes-open EEG was examined across frontal, central and parietal chains and frontal and central chains within sessions, together with a well-being questionnaire concerning appetite, need for sleep, concentration, memory and mood.

There was evidence of within-session learning in both groups. Gamma training increased both gamma and beta amplitude while beta training demonstrated band specificity with a comprehensive increase in broad band beta. In contrast there was no evidence of gamma learning across sessions and with only a tendency for beta amplitude to increase following beta training (and to decrease with gamma training). In neither group was there an impact on the post-training resting EEG, nor did gamma show specificity regarding other outcome measures, whereas following beta training one notes a weak tendency for an average 27% increase in fluid intelligence, but one in keeping with Keizer et al's (2010a) correlation between fluid intelligence and a broad 16–60 Hz band. Familiarity in recognition memory increased in both groups supported by self-reported improvements in memory; a likely reflection of engagement with the experimental procedure rather than a reflection of learned control must be considered. The self-assessment questionnaire also disclosed in both groups reduced appetite, and a tendency for a greater need for sleep following beta training, which given the impact of SMR on sleep spindles may have arisen from inclusion of the SMR band within the beta training band. Changes in gamma were not correlated with outcome, though an increase in beta power at F4 was correlated with a reduction in appetite and an increase in beta power at F4 and C4 correlated weakly with a smaller recollection memory score.

5. Validation

Having reviewed the efficacy of EEG-neurofeedback for optimising function in healthy individuals, before concluding Part I there are two sources of evidence in support of validation to be summarised. The first is where a neurofeedback experimental group is characterised by a uniquely successful cognitive and/or affective outcome when compared with a comparison group and/or a control group; should in the absence of a control group two neurofeedback protocols show the same benefits these are not included as the result may be a reflection of nonspecific influences on training. The second source is where there is evidence of neurofeedback learning coupled with affirmative inter-relations between learning and post-training assessments. This represents the stronger verification with as yet a smaller evidence base. Group differences favouring neurofeedback are ordered according to spectral training band, mindful that protocols may differ in methodological features such as electrode placements, inhibits and so on. Gains are assigned to the particular EEG band that discloses them rather than to the protocol training bands themselves should the latter not have been fruitful.

5.1. Cognitive and affective outcome

5.1.1. SMR ratio

From this the most extensively studied EEG-neurofeedback protocol, with clinical origins, a substantive range of cognitive and affective differential group advantages has been reported in controlled studies of healthy participants including:

(i) Sustained attention in children and adults along with enhancement of ERP indices of attention (Egner and Gruzelier, 2001, 2004a,b; Vernon et al., 2003; Gruzelier et al., 2013).
(ii) Memory in adults and children (Vernon et al., 2003; Barnea et al., 2005; Hoedlmoser et al., 2008).
(iii) Spatial rotation (Doppelmayr and Weber, 2011).
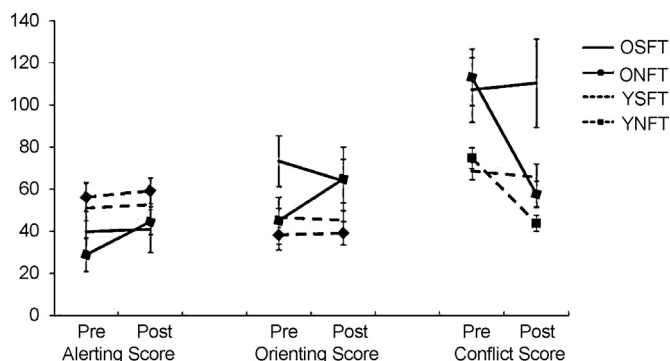(iv) Reaction time and complex psychomotor skills (Doppelmayr and Weber, 2011; Ros et al., 2009).

Fig. 8. Pre and post –training alerting, orienting and conflict scores in elderly (O) and students (Y) receiving frontal theta up-training or sham training (Wang and Hsieh, 2013).

(v) Calmness and reduced performance anxiety (Ros et al., 2009; Faridnia et al., 2012; Gruzelier, 2013b).
(vi) Increased frequency of sleep spindles associated with improved memory (Berner et al., 2006; Hoedlmoser et al., 2008; Schabus et al., 2013).

The various outcomes with healthy participants provide support for SMR training in the treatment of ADHD for information processing, affect regulation and sleep (Monastra et al., 2005; Arns and Keneman, 2013). There are also promising applications in the performing arts, especially for novice performance requiring lower-level skills when compared with elite performance, which will be outlined in Part II (Gruzelier, 2013a).

5.1.2. Beta and gamma

Surprisingly, given that the classical EEG response to cognitive and affective engagement is the production of beta activity through desynchronisation of the EEG (Ray and Cole, 1985), and that up-training of the 'beta'/theta ratio is a standard ADHD protocol, there have been few investigations of beta training to date with healthy participants, or it has been of secondary interest, or included as a control protocol.

Beta together with gamma training has resulted in a number of benefits:

(i) Egner and Gruzelier (2001) found that beta1 shared with SMR learning positive relations with an increase in the P300b amplitude, a gain which in the case of beta1, but not SMR training, was replicable (Egner and Gruzelier, 2004a,b) and compatible with enhanced arousal following beta1 training.
(ii) A comparison of gamma (36–44 Hz) and broad low beta band (12–20 Hz) protocols disclosed improved recollection in long-term memory and perceptual binding following gamma training and improved familiarity in recognition memory following beta training (Keizer et al., 2010b), with the proviso that training-up gamma also increased beta (12–20 Hz) amplitude.
(iii) In the elderly there was a tendency for a gain in fluid intelligence following broad-band beta training (Staufenbiel et al., 2013), in support of Keizer et al. (2010a) (Fig. 7).

In view of the gains following beta training caution is warranted when beta training is used for secondary purposes such as a control for nonspecific influences on training. Similarly the use of random narrow band beta as a control procedure (Van Boxtel et al., 2012) must be applied with caution when considered, firstly with the extensive evidence of one-trial neurofeedback learning (Landers et al., 1991; Hanslmayr et al., 2006; Berner et al., 2006; Ros et al., 2010, 2012, 2013; Reiner et al., 2013), and secondly with the leakage of training band influences within the beta spectrum (Keizer et al., 2010a,b). Furthermore given relations between arousal and beta, over-arousal may result and reduce performance in line with the Yerkes Dobson inverted-U relation between arousal and performance (Duffy, 1957; Anderson, 1990).

5.1.3. Theta

Theta protocols have provided promising outcomes:

(i) Training-down theta with placements individualised on the basis of EEG theta maxima coincided with improvements in verbal IQ, executive functions and attention in the elderly (Becerra et al., 2012).
(ii) Training-up frontal theta in university students and a healthy elderly sample improved executive attention in both groups and improved recognition memory and orienting in the elderly (Wang and Hsieh, 2013).
(iii) One session of training-up theta at Pz improved motor procedural learning with additional gains following sleep (Reiner et al., 2013).
(iv) Training-up the theta/alpha ratio with eyes closed with children led to a reduction in impulsive errors in a continuous performance test (Gruzelier et al., 2013).
(v) Training-up the theta/alpha ratio with eyes closed led to improvements in mood and well-being in students (Raymond et al., 2005).

In terms of affective processes wide ranging benefits encompassing ratings of Composure, Agreeableness, Elevated Mood, Confidence and Energy on the profile of Mood States (McNair, etc.), provide support for earlier clinical studies where the A/T protocol was incorporated with other treatment procedures (Peniston and Kulkosky, 1989, 1990, 1991; Saxby and Peniston, 1995). The influence of A/T training on mood would appear to go beyond anxiety reduction and raise affect and energy levels, boosting self confidence and commitment in performance, as well as psychological integration (Raymond et al., 2005; Gruzelier, 2009, 2013a). Interestingly superior A/T learning has also led to cognitive gains including improved surgical performance aside from a reduction in performance anxiety, and substantive improvements in sustained attention in children (Gruzelier et al., 2013). But by far the more extensive evidence is the impact on creativity in the performing arts which is outlined in Part II (Gruzelier, 2013a).

5.1.4. Alpha power

Successful outcomes have included:

(i) Gains in spatial rotation through the training-up of the combined frontal/parietal chains (Hanslmayr et al., 2006) and through posterior alpha training (Zoefel et al., 2011).
(ii) Working memory facilitation by increasing posterior upper-alpha power (Escolano et al., 2011), and with a centrally located derivation (Nan et al., 2012).
(iii) In contrast training down broadband alpha in the form of the mu rhythm from motor cortex producing EEG desynchronisation facilitated implicit procedural memory indexed by reduced RTs compatible with increased arousal (Ros et al., 2013).

Training upper-alpha power holds promise for further applications. The question has been posed (Hanslmayr et al., 2006) as to whether upper-alpha enhancement may be responsible for gains following SMR training due to upper-alpha falling within the SMR band, given the individual differences in the peak alpha frequency, which tend not to be taken into consideration with the IAF procedure when other bands have been trained. However, firstly in the upper-alpha training studies involving parietal/occipital training Nan et al. (2012) reported a broad-band increase extending from theta to sigma whereas it was only the upper-alpha band that correlated with improved memory, while Zoefel et al. (2011) reported independence of upper-alpha from the sensory-motor rhythm band. Secondly the induced cognitive effects of SMR training (Section 2.1) would be much broader than the contemporary views of upper-alpha correlates (Klimesch, 1999). Nevertheless studies contrasting upper-alpha and SMR training and also with lower-alpha will be informative.

5.2. Relations between neurofeedback learning and outcome

In this penultimate section of Part I the focus will be on the evidence of neurofeedback learning indices that correlated with improvements in outcome assessments. This demonstration is of singular significance because the correlation between a

learning index and improvement in an outcome assessment provides support for the crucial mediation link between performance enhancement and feedback learning.

There are seven studies reporting affirmative correlations between learning and outcome measures out of the twenty-three controlled studies that have reported group advantages in favour of neurofeedback coupled with evidence of neurofeedback learning. In addition to the seven reports there are others which pertain to creativity and the performing arts which are reviewed in Part II. Learning assessment will be taken at face value and no distinction will be made between within-session learning and cumulative learning across sessions, issues that will be considered in detail in Part III. Here the seven studies are categorised by neurofeedback protocol and they provide nine instances in all of feedback learning-outcome relations (numbered i–ix).

SMR ratio training has been correlated with outcome in three of the seven studies (Egner and Gruzelier, 2001; Ros et al., 2009; Schabus et al., 2013).

(i) In the earliest report (Egner and Gruzelier, 2001) a positive impact was seen in a reduction of impulsive errors ($r = -0.79$, $p < 0.001$; see Fig. 1; Section 2.1.1) contributing to an enhanced d-prime in a continuous performance task, and in an enhanced P300b ($r = 0.49$, $p < 0.06$), see Fig. 2.

(ii) The reduction in impulsive errors was theoretically consistent with a subsequent study showing correlations between SMR learning and outcome (Ros et al., 2009). Ros et al. (2009) with junior doctors found a correlation between SMR learning and the pause time in between microsurgical tasks in a simulated cataract operation ($r = 0.72$, $p < 0.019$; Section 2.1.2). This was in keeping with a more modulated performance, and was associated with more efficient surgical skills following SMR training.

(iii) The third source of SMR correlational evidence was from a sleep study (Schabus et al., 2013) showing inter-correlations between SMR learning and memory improvement over night ($r = 0.40$, $p < 0.027$; Fig. 5a and b), and increased sleep spindle frequency (13–15 Hz) in NREM sleep ($r = 0.38$, $p < 0.038$). These relations supported the sensory-motor rhythm affinity with sleep spindles and the role of sleep in memory consolidation (Niedermeyer, 2005; Schabus et al., 2004).

(iv) Beta1 enhancement correlated with the amplitude of the P300b in auditory detection ($r = 0.55$, $p < 0.05$, see Fig. 2 (Section 2.1.1), in support of increased arousal (Egner and Gruzelier, 2001).

(v) When training gamma (36–44 Hz) without increasing 'beta' (12–20 Hz) Keizer et al. (2010a) reported a correlation ($r = 0.82$, $p < 0.05$) between fluid intelligence and a broad beta/gamma band (16–60 Hz), see Fig. 7 (Section 2.3).

Upper-alpha has demonstrated mediation links in two studies.

(vi) Hanslmayr et al. (2006) reported that one session of training to increase upper-alpha and decrease theta led to improvement in spatial rotation which correlated with the gain in upper-alpha ($r = 0.41$–0.55, $p < 0.05$; see Fig. 6).

(vii) Nan et al. (2012) reported that upper-alpha training correlated with gains in a working memory task: digits forwards ($r = 0.501$, $p < 0.05$), digits backwards ($r = 0.543$, $p < 0.05$).

Finally theta up-training at Pz, both with eyes closed and with eyes open has been correlated with cognitive and affective outcome.

(viii) Training the theta/alpha ratio with eyes closed, Ros et al. (2009) in the micro-surgical skills study reported that elevation of the ratio was positively associated both with the improvement ($r = 0.64$, $p < 0.047$) and overall efficiency in technical psychomotor skills ($r = -0.52$, $p < 0.06$) as well as with a reduction in performance anxiety ($r = -0.66$, $p < 0.053$). Here the group who elevated the theta/alpha ratio shared the post-training outcome benefits with the group receiving SMR ratio learning; the latter incidentally included down-training theta with eyes open.

(ix) Reiner et al. (2013) found that training-up posterior theta with eyes open correlated with gains in procedural learning following one, two, and six nights of sleep ($r = 0.64$–0.66, $p < 0.01$) but not immediately after training (0.33, ns). From this it was inferred that the theta synchronisation protocol facilitated memory consolidation processes in sleep. Benefits for memory consolidation following sleep have also been shared with SMR learning as found by Schabus et al. (2013), in this case an SMR protocol without theta inhibits in contrast to the conventional SMR ratio protocol which shared benefits with theta training (Ros et al., 2009). The parallels between the contrasting theta protocols and SMR training are not understood.

One cannot necessarily infer from an absence of reportage an absence of learning because there has not been a tradition of considering this. There is also the proviso that because the understanding of the nature of neurofeedback learning is by no means a clear cut, well trodden issue, it is at an early stage and learning may have eluded measurement. For example, learning as in a carry-over to successive pre-training baselines may have gone unnoticed (Gruzelier, in preparation, Part III). The failure to find learning may be a reasonable inference when no cognitive/affective advantage has been disclosed as in the up-training of theta in the report of Vernon et al. (2003). Additionally attribution of learning to the neurofeedback process per se may not always be the case, when to give an example, learning falls away within a session once training stops, and there is no incremental increase across sessions either during training or in successive pre-training baselines. This example may reflect a process incidental to learning such as concentration or effort in attention in the feedback process.

While the number of studies is small, such evidence is a methodological advance for the neurofeedback field in general, one which has been seldom encountered in the more populous clinical literature.

5.3. Validation conclusion

As has been documented in this review successful validation within this re-emergent EEG-biofeedback domain has included diverse protocols: SMR and SMR ratio, beta1 and beta1 ratio, alpha/theta ratio with eyes closed, upper-alpha, alpha desynchronisation, gamma and gamma ratio, frontal theta up-training, posterior theta up-training and down-training theta EEG maxima. Approaches have arisen from contemporary neuroscience offering new opportunities in the clinic and the field. Validation has also included standard clinical protocols extending their repertoire and enriching their clinical potential, as exemplified by the feasibility of conducting neurofeedback with the elderly and the multiplicity of approaches applied: increasing high alpha power while inhibiting an increase in theta (Lecomte and Juhel, 2011), training-down individualised theta maxima (Becerra et al., 2012), training-up frontal midline theta with delta and gamma inhibits (Wang and Hsieh, 2013), training-up frontal gamma (Staufenbiel et al., 2013), and increasing alpha power while maintaining peak alpha frequency or vice versa (Angelakis et al., 2004). Their impact on cognitive and affective outcome in controlled studies with the elderly has included: executive functions, IQ and attention (Becerra et al., 2012) and recognition memory, orienting and executive attention control (Wang and Hsieh, 2013) (Fig. 8).

These laboratory and field studies with healthy volunteers have raised a host of methodological and theoretical issues that will stimulate research and assist in understanding the mechanisms underlying neurofeedback learning and the nature of the EEG and its cognitive/affective relations, which in turn will refine protocol implementation and real world applications. In Part III such issues will be enumerated further including inter alia the independence of training bands, behavioural outcome and topography, experimental design and issues surrounding what may be regarded as the elephant in the room – the fact that neurofeedback is a learning process that must be guided and nurtured.

In summary, the broad encompass of cognitive and affective outcome assessments from controlled studies has favoured: sustained attention, orienting and executive attention, the P300b, memory, spatial rotation, RT, complex psychomotor skills, implicit procedural memory, recognition memory, perceptual binding, intelligence and wide ranging aspects of mood and well-being.

The mediation links through correlations between neurofeedback learning and outcome gains have included: sustained attention, P300b, working memory, mental rotation, motor procedural learning, psychomotor skills, fluid intelligence and anxiety in performance.

There is now sufficient evidence validating the role of EEG-neurofeedback in enhancing function to dispel the lingering vestige of prejudice against the value of this EEG methodology. Meanwhile, neurofeedback for optimising function has materialised centre-stage in neuroscience through the advent of fMRI applications (Ruiz et al., 2013).

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