



Review

EEG-neurofeedback for optimising performance. III: A review of methodological and theoretical considerations



John H. Gruzelier*

Goldsmiths, University of London, UK

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ABSTRACT

In continuing this three-part review on validation of EEG-neurofeedback for optimal performance evidence is first provided for feedback influences on the CNS, the integration of EEG with fMRI methodology as well as anatomical correlates. Then whereas Parts I and II reviewed the considerable behavioural outcome gains and evidence for their feedback causation, part III lays bare the not inconsiderable methodological and theoretical conundrums. Cardinal assumptions amongst practitioners about specificity of topography, behavioural outcome and frequency bands are critically examined. The hitherto mostly neglected nature of feedback learning is reviewed including evidence of within- and between-session and successive baseline learning; the enduring impact on the tonic EEG; implications for experimental design, individual differences and the trainer–participant interface; distinguishing between the learning and mastery of self-regulation; connectivity, ratio, unidirectional and multimodal feedback protocols. A thorough grounding in human neuroscience plus interpersonal skills are considered prerequisites for scientific advancement and ethically sound practice.

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* Department of Psychology, Goldsmiths, University of London, Lewisham Way, London SE14 6NW, UK. Tel.: +44 20 8 2992203.

E-mail address: j.gruzelier@gold.ac.uk

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1. Introduction

As Parts I and II (Gruzelier, 2014a,b) of this review have shown there is now substantive evidence in support of cognitive, affective and performance enhancement following neurofeedback in healthy subjects, termed the optimal performance field. The sources of validation that were considered consisted of controlled group comparisons favouring neurofeedback training, which was mostly coupled with evidence of neurofeedback learning indices, and in some studies affirmative correlations were reported between indices of learning and outcome gains in support of mediation/causation (Parts I and II). The gains in cognitive and affective outcome have encompassed sustained attention, orienting and executive attention, the P300b, memory, spatial rotation reaction time, complex psychomotor skills, implicit procedural memory, recognition memory, perceptual binding, intelligence, wide ranging aspects of mood and well-being, and performance in music, dance and acting including domains of creativity, communication/presentation and technique. Evidence of mediation through correlation with feedback learning was found with sustained attention, P300b, working memory, mental rotation, motor procedural learning, psychomotor skills, fluid intelligence, expert ratings of music and acting performance, and anxiety in performance. There has been a diversity of trajectories in achieving these gains with protocols including those drawn from the clinical neurofeedback domain such as training the sensory-motor rhythm (SMR) theta/beta ratio, the beta-1 ratio and the theta/alpha ratio termed alpha/theta (A/T) training. These have been extended with protocols drawn from contemporary cognitive and affective neuroscience including the up-training of gamma, upper-alpha (alpha-2), frontal midline and posterior theta, or the down-training of alpha, posterior theta, and theta EEG maxima, all with or without inhibiting other frequency bands (inhibits).

In Part III of this review general methodological and theoretical issues will be briefly considered with recommendations for research and practice. But first, in order to supplement the behavioural outcomes reviewed in Parts I and II and inform what follows, the impact on the central nervous system from EEG-neurofeedback will be outlined. This includes TMS and fMRI assisted studies, the simultaneous recording of EEG and fMRI, intracranial power density training, as well as morphological correlates. While covering the CNS impact, as in Parts I and II there will

be incidental mention of features such as specificities of training bandwidth topography, and outcome, as well as learning functions, before these specificities and learning issues are considered at some length in the following sections and addressing all three parts of the review.

2. Central nervous system underpinnings

2.1. Corticospinal excitability and intracortical inhibition with TMS

Direct evidence for an impact of EEG-neurofeedback on central mechanisms first arose from transcranial magnetic stimulation (TMS) methodology (Ros et al., 2010). A newly developed paired-pulse TMS procedure was chosen involving bilateral hand motor evoked potentials (MEPs) in response to TMS delivered to primary motor cortices. MEP amplitude represents the strength of transmission and corticospinal excitability, while paired-pulse MEP parameters give estimates of short latency intracortical inhibition and facilitation, coupled with neuronal circuitry (Lazzaro et al., 2008). Two neurofeedback protocols were chosen – alpha (8–12 Hz) amplitude suppression and SMR (12–15 Hz) amplitude training, both without inhibits. TMS was delivered before and twice after neurofeedback at 3–15 min and at 15–27-min. Eyes open EEG (C3,4) was recorded and analysed for DC and standard spectral bands from delta to high gamma (60–120 Hz). Twenty-four dextral participants were randomly assigned to one of the two protocols delivered in a 30-min session (Ros et al., 2010; Ros and Gruzelier, 2010).

Neurofeedback learning was achieved in the one session (see Section 3.3.1.2 for other one-session outcomes). As shown in Fig. 1, learned alpha suppression was seen in both hemispheres, and the greater the reduction in the post-session resting alpha amplitude, the greater was the learned suppression during training. Effects spread beyond the alpha band and spread topographically. Enhanced SMR amplitude was only seen in the trained hemisphere towards the end of the session, necessitating a cautious interpretation of the outcome of the SMR training, and which was done here without inhibits. The post-session impact of SMR training also varied according to the degree of enhancement, but without a spread of facilitation beyond the SMR band, demonstrating training band specificity, these features are outlined in the section on specificity (Section 3.1).

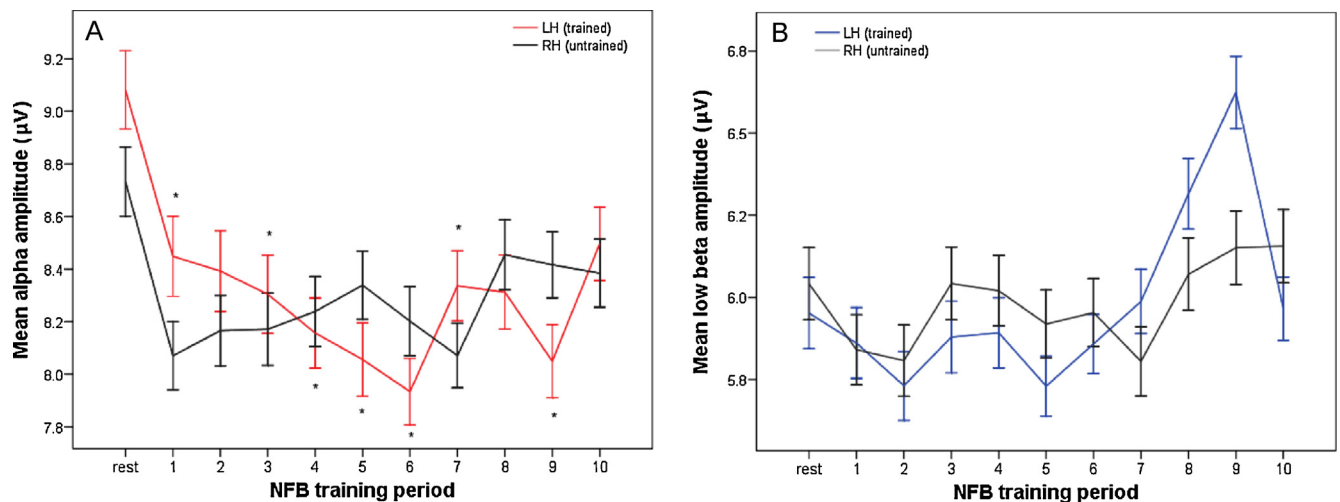


Fig. 1. Within session mean bilateral amplitudes for alpha and SMR protocols together with resting baseline (Ros et al., 2010).

Neurofeedback was found to be an effective modifier of the TMS parameters. Firstly, corticospinal excitability increased by 135% in the alpha trained hemisphere around 20-min later. Secondly, intracortical inhibition was disinhibited by 174% immediately, and this was found to be sustained by 165% at the 20-min assessment only in the trained hemisphere. Thirdly, the within-session alpha desynchronisation learning coefficient was positively associated with corticospinal excitability 20-min after neurofeedback, and with a counterpart in high gamma amplitude augmentation across the session. SMR synchronisation was also positively associated with corticospinal excitability at 5-min after training, and nonsignificantly so at 20-min, with no effect on intracortical inhibition. Similarly the more suppressed was the EEG spectrum as a whole the higher was the corticospinal excitability 20-min after neurofeedback. Fourthly, path analysis disclosed that it was the effect of neurofeedback on the tonic resting EEG that mediated the influences of neurofeedback. Finally, DC potential training coefficients in each protocol disclosed stronger relations with the alpha group, in whom those participants with the most consistent negative shifts in DC potentials were those with the greatest decreases in the paired-pulse measures of intracortical inhibition, and with the greatest increases in intracortical facilitation, in keeping with DC negativity representing excitation.

The results were interpreted in favour of neurofeedback influences on brain plasticity, with effects outlasting the training epoch for 20 min. Long-term potentiation (LTP) would be a possible candidate (Cooke and Bliss, 2006), while a decrease in cortical GABAergic transmission would follow the concomitant reduction that was found in the intracortical inhibition index (Hallett, 2007). The relations between both trained alpha suppression and high gamma desynchronisation were consistent with evidence associating alpha desynchronisation with excitation. As a candidate neuromodulator, noradrenaline facilitates alpha desynchronisation, increases corticospinal excitability and reduces intracortical inhibition, enhances LTP, and is released during attentive behaviour as in neurofeedback learning.

2.2. Alpha suppression, fMRI and attention

Further elucidation of central influences was sought from fMRI coupled with assessments of attention through an auditory oddball task with probes about unrelated thoughts, i.e., mind-wandering. These were obtained before and after a single 30-min training session of alpha suppression with an eyes-open resting EEG

baseline recorded from nineteen electrodes (Ros et al., 2013). Thirty-four participants were randomised to alpha desynchronisation (8–12 Hz) at Pz, or to the sham feedback of another person's successful session.

As before learning was successfully obtained in the single session. There was an immediate and sustained desynchronisation with a return to baseline at the end. In contrast, in the control group changes were irregular with progressive synchronisation from period four to ten, near to and no different from the baseline. The alpha within-session desynchronisation correlated positively with reductions in theta (4–8 Hz) and beta (12–25 Hz) amplitudes, indicating a spread of the training effect, and in keeping with a signature of selective attention and alerting (Fries et al., 2001; Fan et al., 2007). Furthermore the alpha reduction was topographically global, in keeping with arousal regulation rather than sensory processing (Schurmann and Basar, 2001).

Notwithstanding that the resting EEG baseline recordings before and after did not differ on average, there were individual variations in the direction of change such that baseline alpha global changes following training were found to be positively correlated with the within-session reduction in alpha amplitude calculated as a percent of baseline, importantly a result not found in the sham group, as shown in Fig. 2. In other words short-term plasticity change due to neurofeedback was associated with longer-term plasticity effects. While in some participants desynchronisation was sustained beyond the training, in others there was a return to synchronisation, or even a rebound beyond pre-training levels. This individual difference would be worth elucidating further together with the changes in other dependent variables, and examined through a course of training (see also Rosenfeld et al., 1997).

Importantly for the experimental group, the global reduction in resting state alpha and theta power (but not delta and beta), was positively associated with a reduction in mind-wandering, though multiple regression analysis implicated alpha only. Although no evidence was provided for group differences in mind-wandering, there was a predicted association between the changes in resting alpha amplitude and mind-wandering following neurofeedback. Scatter plots of these relations for both groups again disclosed that changes could be in either direction, with less mind-wandering associated with desynchronisation, and more mind wandering associated with synchronisation, in support of an arousal and attention inward-outward relation. Neurofeedback learning strategies disclosed that focussed visual attention was the most popular,

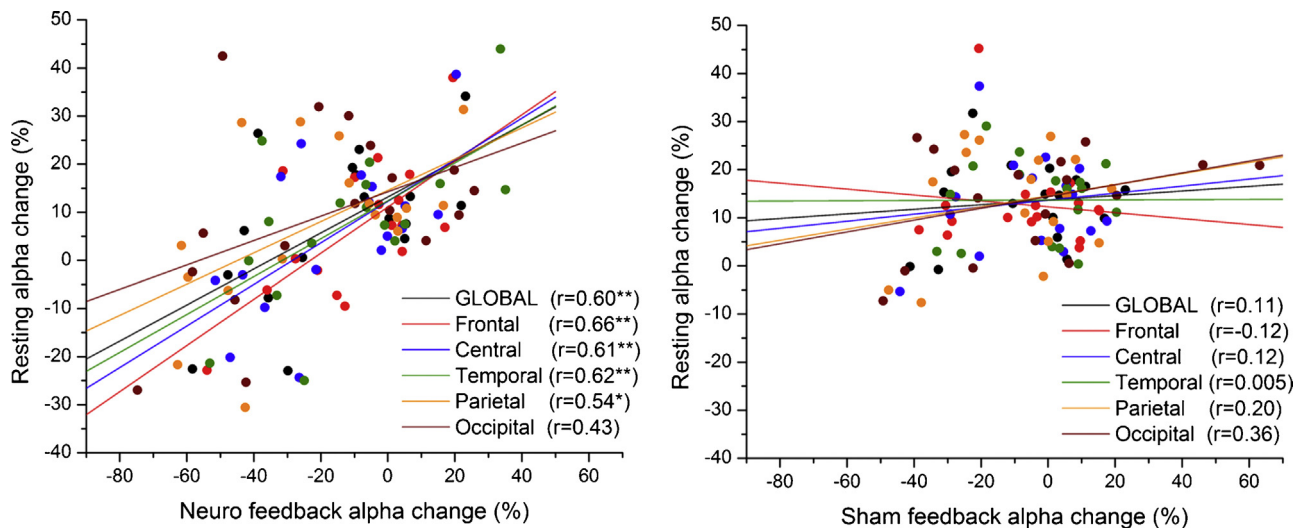


Fig. 2. A scatterplot of the change in resting alpha amplitude (μV) before and after neurofeedback as a function of the % change during the one session of neurofeedback (Ros et al., 2013).

and self-rating of state anxiety was found unrelated to the alpha changes.

Turning to the main thrust of their report, the impact of neurofeedback on neural networks, the fMRI auditory detection procedure disclosed a salience detection, intrinsic alertness network, with a dorsal anterior cingulate cortex (dACC) focus, in keeping with reports of Seeley et al. (2007) and Clemens et al. (2011). Importantly, following neurofeedback the connectivity within this network was increased when the fMRI was performed 30-min after training. Furthermore the increase in connectivity showed significant positive correlations, both with the degree of alpha suppression and the reduction in mind-wandering during the detection task. Consistent with these relations, in the control group an increase in mind-wandering was associated with reduced salience-network connectivity. Additionally a resting state, 'task-negative' Default Mode Network (DMN; Christoff et al., 2009; Hlinka et al., 2010; Mantini et al., 2007; Mason et al., 2007) showed the opposite relations from the salience network between connectivity and both mind-wandering and the alpha baseline changes (Hlinka et al., 2010; Jann et al., 2009; Mantini et al., 2007; Moore et al., 2012). In other words, the higher the alpha synchronisation, the more frequent the mind-wandering and the stronger the DM network connectivity; relations also found in the control group. Consistent with the effect of alpha desynchronisation on cognition, neurofeedback training resulted in a positive relation between improved reaction-times to the mind-wandering probes and the frequency of mind-wandering.

The authors concluded that the first neuroimaging evidence was provided showing that alpha-band desynchronisation directly induced reinforcement of dACC connectivity within the salience network, and this correlated with less mind-wandering. Further, aspects of this report have been replicated in patients ($N=21$) with post traumatic stress syndrome (Kluetsch et al., 2014). In an uncontrolled study alpha amplitude desynchronisation was successfully learned, and this time there was a significant post-training rebound for the group as a whole. Investigating effects on mood, while there was no effect on state anxiety, there was an increase in calmness (Thayer, 1967), and this correlated positively with the degree of 'homeostatic' rebound. Additionally the rebound was positively correlated with increased functional connectivity in both the salience and default mode networks.

2.3. Simultaneous EEG and fMRI disclose alpha/theta networks

Alpha/theta (A/T) feedback networks have been examined with simultaneous EEG and fMRI (Kinreich et al., 2012). Thirty subjects were firstly given a single 15-min session of theta/alpha ratio (Oz,1,2) enhancement. They were classified according to whether or not they could elevate theta over alpha a third of the time, a putative index of a deep state of relaxation (Part II, Section 1.2.3 or 1.2.4). In ten participants in each achiever group the time in crossover correlated congruently with a parasympathetic index derived from heart rate variability assessment (II, Section 2.3). The A/T protocol was then repeated twice in the fMRI scanner, with feedback now individualised on the basis of the three derivations with the highest T/A amplitude outside the scanner, and selected from eight posterior electrodes (Oz1,2; Pz1,2; CP1,2). Pooling the two scans, five of the subjects achieved the learning criterion in both scans and five failed to do so, giving for each group twenty scans for comparison. When comparing high versus low periods of the T/A ratio, three networks were disclosed: (i) a T/A ratio network consisting of medial pre-frontal cortex (right) and supplementary motor area (left), both positively correlated, and cerebellum (left) and brain stem (right), negatively correlated; (ii) a theta network including the posterior cingulate cortex, medial prefrontal cortex and primary visual areas, all with right-sided maxima; (iii) an alpha network involving the left-sided visual cortex and amygdala and the right-sided ventromedial prefrontal cortex. These three networks were respectively attributed to emotion regulation, attention allocation, and sensory-attention-emotion regulation.

Utilising these data Meir-Hasson et al. (2013) applied signal processing and machine learning methods to obtain what they have called an 'EEG Finger Print', whereby a single EEG electrode may be modelled to target brain foci, including deep brain subcortical loci such as the amygdala. They utilised data from a resting alpha study (Ben-Simon et al., 2009) involving the opening and closing of eyes every 30-s for 3-min (the Berger effect). In four subjects with primary visual cortex area V1 as the alpha region of interest they estimated the best individualised predictor from the eight posterior electrodes of Kinreich et al. above. Then using their data they tested the method's efficacy with the right amygdala as the region of interest. In seventeen/twenty subjects the left parietal (P3) derivation was the best predictor of the right amygdala, with activated frequencies ranging from theta to gamma, and

with individual variation. In testing the medial prefrontal cortex as the region of interest Fz was the best predictor, and frequencies ranged between theta and beta. The amygdala was found to be correlated with a bottom-up network involving perception, learning and emotion, while the medial prefrontal cortex was correlated with a top-down network.

A promising approach has been provided with which to refine EEG protocol electrode placement, and the conjoint methods can enable a higher temporal resolution than can be produced by fMRI.

2.4. Dual feedback tasks with simultaneous EEG and fMRI recording

Zotey et al. (2014), also with simultaneous EEG recording during fMRI found suggestive evidence showing that, when aided by a positive emotion induction task, participants ($N=6$) could accomplish dual fMRI and EEG feedback tasks, one regulating left amygdala activation as found previously (Zotey et al., 2011), and the other regulating the EEG frontal beta-2 (21–30 Hz) asymmetry (F3,4, Section 3.3.4.2).

They raised the possibility that the combined methodology may be more effective in modifying emotional regulation than either performed separately, facilitating the design of feedback protocols where the EEG could approximate the effects of fMRI.

2.5. LORETA intracranial power density training

Three exploratory studies of neurofeedback have been conducted with intracranial power training with inverse solution low resolution electromagnetic tomography (LORETA) based on nineteen electrodes. Cognitive outcome measures are reported in Part I. The first report established the feasibility with six subjects. The intracranial current power density ratio between beta-1 (16–20 Hz) and alpha-1 (8–10 Hz) was recorded from the anterior cingulate cognitive division within Brodmann area 32, and was fed back via visual and auditory feedback (Congedo et al., 2004). Three subjects received six sessions involving six 3-min trials and the other three received twenty sessions of three 15-min trials. In order to assess volitional control, at the end all subjects received eight 3-min trials on four trials of which they were instructed to obtain as much reinforcement as possible, and on the other trials to obtain as little reinforcement as possible. While the individuals displayed considerable variability, there was a significant increase in beta-1 power across sessions for the group as a whole, and volitional learning was significant in 3/6 subjects.

In the second study (Cannon et al., 2007) the potential of the topographical specificity of LORETA for elucidating central involvement in neurofeedback learning processes was examined. Beta-1 (14–18 Hz) was trained in the same anterior cingulate region, while concurrent effects were examined in seven anterior and parietal regions of interest, along with executive function outcome measures. Eight participants received thirty sessions over ten weeks involving 16-min training within a 40-min session. Changes in the anterior cingulate had a long latency and were not seen until 8–12 min of training. There was correlational evidence of a beta-1 network of influences between anterior cingulate, bilateral dorsolateral prefrontal cortex and right post-central gyrus. Beta-1 current density was higher in anterior regions relative to the anterior cingulate. The results supported the importance in neurofeedback learning of executive functions and of a right fronto-parietal attention network, and with a gating role posited for the anterior cingulate cortex. Increases in beta-2 were also found, and these had a posterior topography, perhaps attributable to the sensory feedback, and if so, implying frequency specific activity/functions. Here correlations with the EEG would have aided interpretation of the training mediation in the absence of a

control group. Turning to the post-training resting EEG, perhaps the most striking longer lasting increase in activation was found in the right inferior temporal region.

This exploratory study was extended (Cannon et al., 2009) by improving the spatial specificity of LORETA with a head model informed by magnetic resonance imaging. Three beta-1 groups were compared with twenty sessions of training. One targeted the anterior cingulate as before ($N=8$), and the others the left ($N=3$) and right ($N=3$) dorsolateral prefrontal cortices. Activity was concurrently examined in the right postcentral gyrus, the left and right supramarginal gyrus and the cuneus. Here EEG was examined throughout the spectrum from delta to a broad-band 'beta' (12–32 Hz). With seven regions, each with its own pattern of activity, plus five EEG bands and the three training groups the results were complex. In brief, evidence of an anterior locus was replicated, and here this was independent of the training site, likely due to the demands on the frontal lobes for the learning process. Turning to network interrelationships, with the trained beta-1 frequency, while there were interrelations between the cingulate and left frontal training sites, each site otherwise had its own pattern of interrelationships across regions, and these varied with frequency band. While there was cognitive improvement, interpretation of this was hampered without a control for task repetition.

Valuable first steps have been provided for replication, and further attempts would be advanced by the addition of a priori hypotheses about frequency and network relations with a choice of cognitive outcome measures that would allow a test of hypotheses, and together with a constructive replication approach relating back to the previous intracranial studies. A first controlled clinical study with this methodology has been undertaken (Maurizio et al., 2013).

2.6. Anatomical correlates

Recording EEG over the sensory-motor cortex with a brain computer interface (BCI), single-session design Halder et al. (2013) compared anatomical correlates in those participants with a low versus high aptitude in controlling 8–15 Hz amplitude activity. In those with the higher aptitude the structural integrity and myelination quality of deep white matter structures such as the corpus callosum, cingulum, and superior fronto-occipital fascicle was found to be higher.

Enriques-Geppert et al. (2013) reported the morphological correlates of up-training midline frontal theta, a rhythm originating from the midcingulate cortex, and implicated in a range of executive processes including action monitoring and task demands (Mitchell et al., 2008; Cavanagh et al., 2011; Onton et al., 2005); incidentally all processes are necessary features of eyes-open neurofeedback training. This anatomical investigation was done in conjunction with methodological studies (Section 3.2.2.5; Enriques-Geppert et al., 2014). In the nineteen participants their individualised theta peaks within the 4–8 Hz range were based on pre-training cognitive task performance. The midcingulate, independent of frontal cortices, was found to be associated with the dynamics of within-session learning (see Fig. 3a). These disclosed an immediate short latency increase in the first 5-min block, which was sustained until the final sixth block, after which there was a return to baseline. It was this facility, described as a 'responsiveness to training', which correlated with the volume of the midcingulate cortex and the underlying white matter and its concentration. However, there was no relation with learning across sessions which followed a conventional learning curve, see Fig. 3b. The dynamics of within- and between-session learning are considered further in Section 2.2.2.4 in relation to the putative cognitive role of the midcingulate.

Dynamical changes within sessions

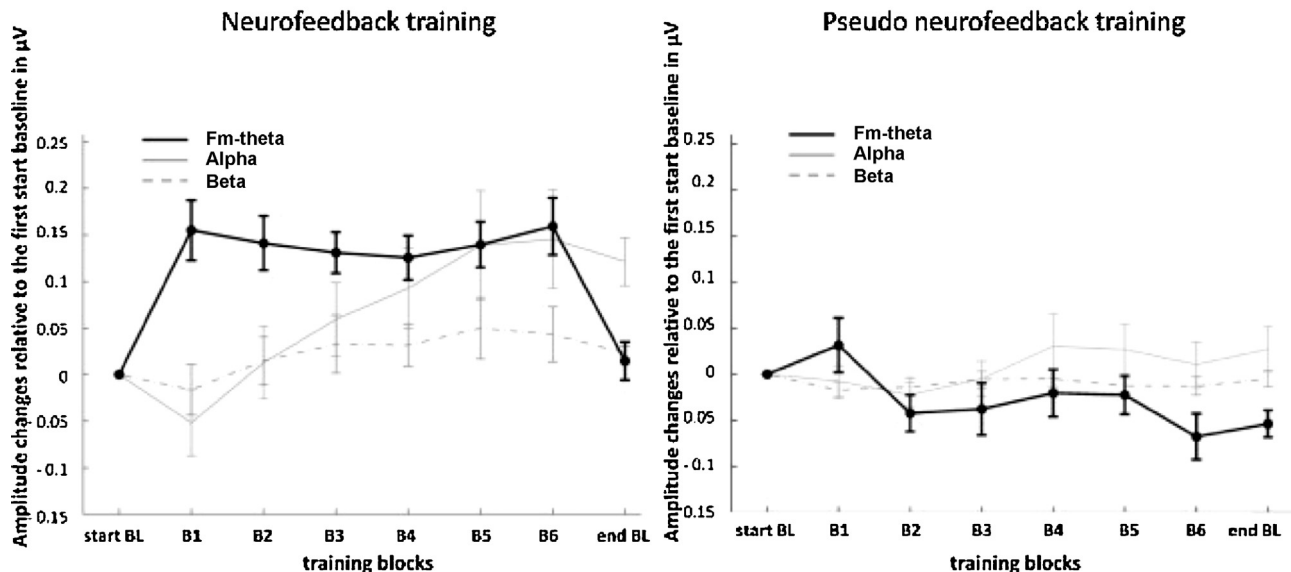


Fig. 3. Within-session averaged theta amplitudes together with baselines (Enriques-Geppert et al., 2014).

2.7. Concluding CNS investigations

Important first steps have been illustrated by the various CNS methodologies.

- (i) Direct evidence was provided through TMS of the influence on brain plasticity of one session of alpha amplitude suppression and to a lesser extent SMR amplitude enhancement, which in the case of alpha was in evidence for up to 20 min after training.
- (ii) In an fMRI study one session of alpha suppression, aside from benefits for attention, directly induced reinforcement of dorsal anterior cingulate cortex networks, networks with affirmative behavioural correlates.
- (iii) Networks underpinning the A/T protocol were also elucidated by conducting training in the fMRI scanner with simultaneous EEG recording. Application of advanced signal analysis and machine learning led to the prediction of the best electrode location for A/T training, an important advance.
- (iv) In a further innovation separate fMRI and EEG feedback tasks were trained simultaneously, with putative practical advantages accruing from the dual task method including refinement of EEG protocols, as well as a focus on connectivity training through feedback protocols. And of theoretical importance, light was shed on networks that disentangle feedback learning from the self-regulation process once learned.

Neural networks were additionally informed by intracranial power density LORETA training also with alos potential for targeted EEG training. Of theoretical importance, in supporting a systems approach to neurofeedback, intracranial neurofeedback was shown not only to enhance functional networks that were related to the region of training, but disclosed that the strengthened network connectivity involved several spectral frequencies. In other words it was not the case that current density was increased selectively in the training region and in the spectral frequency band that was trained. This indicated a non-specificity of both the training band and topography, and challenges basic theoretical assumptions of practitioners in the field outlined in the next section.

The evidence regarding specificity relating to bandwidth and to topography, together with the specificity of behavioural outcome,

will now be reviewed in Section 3.1. The above studies have also served to introduce, as did Parts I and II, different forms of learning, including learning within and between sessions, and the impact of learning on the baseline tonic EEG; these issues will be outlined in Section 3.2.

3. Theoretical issues

3.1. Specificity

Three of the cardinal theoretical assumptions inherent in the practice of neurofeedback concern issues of specificity. (1) *Frequency band specificity*: the assumption of a separation of the training outcome from the chosen band from adjacent flanking and other spectral bands. (2) *Topographical specificity*: the selection of electrode placement according to assumptions about localisation of function in relation to the behavioural or neurophysiological processes to be modified. (3) *Outcome specificity*: the choice of bands for training based on their putative psychophysiological salience for outcome in terms of presumed cognitive/affective performance correlates.

Specificity may be contrasted with an alternative view which posits that only a nonspecific generalised learning process is trained, so that faster-wave neurofeedback protocols are interchangeable acting on a generalised principle such as the ability to shift mental states at will (Norris and Currier, 1999), or 'brain training' as enshrined in popular contemporary culture.

How does the accruing evidence support the assumptions of specificity? Evidence was detailed in passing when the focus was on the cognitive, affective, performance and neurophysiological sequelae. In summarising here, it will be seen that the scant evidence is mixed; there is emergent support for both generalised and specific effects.

But first, an innovative and informative two-experiment methodological study by Salari et al. (2013) is summarised, which is the only one to consider all three aspects of specificity. With a primary interest in gamma recorded from the lateral visual cortex (PO7,8), their first experiment examined the specificity of training gamma activity (30–45 Hz) within the EEG spectrum, along with topographical specificity, and the effect of high versus low gamma

amplitude on object detection and object recognition. In the second experiment gamma was contrasted with alpha (8–12 Hz) training.

In brief, in experiment I following three weekly gamma training sessions the results were as follows in twelve/twenty participants: (i) Relative to a passive visual fixation baseline gamma enhancement peaked in the 30–45 Hz training range, in support of a discrete role of gamma in visual perception (e.g., [Hanslmayr et al., 2007](#)), but enhancement extended beyond the training band to a broad gamma band (28–116 Hz), perhaps reflecting a generalised process such as attention ([Tallon-Baudrey et al., 2005](#)); (ii) Topographically the effect was specific to the training electrodes, recorded from a twenty-eight array; (iii) Concerning behavioural outcome, within sessions after each of eleven blocks there was a 6-s display signifying success or failure, during which a scrambled image could be presented for detection in those epochs where the gamma elevation was in the bottom or top third of the individual's capability. Detection was found to be superior with high gamma trials, and the presented images were also better recognised 10 min afterwards in a surprise old/new recognition memory task. Band specificity regarding outcome was also examined by comparing the pre-stimulus EEG spectrum for hits and misses irrespective of high/low gamma epoch. Significant effects were confined to the gamma range (34–40 Hz), and were not found in either the alpha (8–12 Hz) or beta (20–30 Hz) ranges.

In experiment II with a similar design and twelve new subjects, band specificity was examined further by improving spatial precision with sLORETA and with fifty-eight active electrodes. An added innovation was alternating the gamma training with alpha training within subjects. The results were as follows: (i) Specificity of the training band was also found to characterise alpha training. Within the alpha blocks alpha (8–12 Hz) amplitude and not gamma (circa 40 Hz) amplitude was enhanced within subjects, and vice versa in the gamma blocks, and this differential band specificity extended to the pre-stimulus visual detection EEG, as had been found for gamma in experiment I. (ii) Whereas gamma was topographically specific to the lateral occipital lobe, alpha was more widespread extending from the occipital to the parietal lobes, and was maximal in the superior parietal lobe. (iii) Object detection favoured gamma (mean 81) over alpha (mean 74; indicating that alpha synchronisation did not impair detection overall), whereas with object recognition there was an equivalence between the bands.

In conclusion, there was band specificity between gamma and alpha, and informatively these specificities were demonstrated within subjects, attesting to their validity. There was evidence of gamma topographical specificity in line with gamma having a putative focal distribution, whereas alpha was less topographically specific. There was no cognitive specificity with regard to recognition memory, but there was a preferential effect of gamma over alpha on object detection.

These results will be referred to the other findings below (Section 3.1.1). Importantly Salari et al. have demonstrated for the first time that band specificity could be modulated within sessions within subjects. The within subject methodology is to be commended, assuming there are no carry over influences from one band to another (see Section 3.1.1). Furthermore, as the authors conclude: “the actual study introduces a new method that combines neurofeedback with an adaptive stimulation. The results demonstrate the value of this method for a highly selective modulation of gamma band activity that follows disentangling the functional relation of pre-stimulus gamma and alpha band activity for visual object processing” (p. 8).

3.1.1. Frequency band specificity

Specificity of bandwidths has acquired the most abundant source of information, and therefore presents the more challenges in its comprehension and integration. Conventionally the choice

of training bandwidths follows theoretical assumptions about the cognitive/affective correlates of EEG bands, or again simple practitioner pragmatic assumptions about a single deviation from a normative data base. Outcome recordings may be done immediately before the last training session, afterwards as a post-training baseline, during an outcome task, or some time later, which may provide a follow-up. The review follows these distinctions.

3.1.1.1. Band specificity within and across sessions. To date only a few investigators have reported the full spectrum or flanking or other selected bands. [Keizer et al. \(2010a\)](#) with a focus on gamma training in one of two experiments (Pt I, Section 2.3) presented the full EEG spectrum making an important methodological advance. Participants were required to augment gamma (36–42 Hz) amplitude while inhibiting SMR/beta (12–20 Hz) amplitude. With training at Oz there was an absence of band specificity. Not only was there an increase in gamma extending from 30 to 60 Hz, but this was coupled with reciprocal changes in frequencies which were below the beta inhibit training band. It is possible that this may have been a by-product of the attempt to inhibit 12–20 Hz activity, notwithstanding, both of the non-specific effects were functionally consistent with an increase in arousal. The simultaneous inhibiting of SMR/beta prevents a direct comparison with the gamma training of [Salari et al. \(2013\)](#), who in their first study had also found that training 30–45 Hz amplitude led to an increase in a broad gamma (28–116 Hz) range.

Yet in Salari's follow on study, which contrasted the enhancing of gamma with the enhancing of alpha within subjects, there was band specificity for gamma training which did not influence alpha, and vice versa. Specificity has been reported for SMR/beta amplitude training in the elderly ([Staufenbiel et al., 2013](#); Pt I, Section 4.2.3), in whom there was non-specificity in the training of gamma (36–44 Hz) with extension to the 12–20 Hz range. In contrast beta-1 LORETA training demonstrated non-specificity with a marked impact on beta-2 ([Cannon et al., 2009](#)).

Also reporting the full spectrum [Ros et al. \(2010, Section 2.1\)](#) disclosed further evidence of non-specificity when comparing SMR (12–14 Hz) amplitude enhancement with alpha (8–12 Hz) suppression. Firstly, the effects of facilitation with the SMR and suppression with alpha both extended from theta to high-beta, and in the case of alpha extended to the gamma band as well. Secondly, a unitary process was endorsed through positive correlations between theta, alpha, low beta, and high beta amplitude (<25 Hz) at the $p < 0.01$ level, within a range of $r = 0.5–0.9$ ([Ros and Gruzelier, 2010](#)); indicative of SMR enhancement increasing spectral power overall and alpha suppression lowering spectral power overall. Thirdly, there was an inverse relation between high-gamma mean frequency (60–120 Hz) and alpha amplitude, such that the greater the alpha desynchronisation the higher was the gamma amplitude. This denoted arousal functional congruity as both an increased gamma amplitude and suppressed alpha amplitude indicate functional activation. Functionally the gamma/alpha relation has affinity with the results of Keiser et al. above, and possibly with Salari et al's demonstration of alpha and gamma band specificity, while Ros et al's non-specificity of SMR training has been supported by [Schabus et al. \(2014\)](#) who also found that SMR amplitude training enhancement extended to a broad beta band (16–25 Hz).

Non-specificity was also found in a subsequent single-session study of [Ros et al. \(2013, Section 2.2\)](#) focussing on alpha power where the trained suppression of alpha extended to the theta and beta-1 flanking bands. Here the arousal continuum model does not fit all of the data; a model which is increasingly seen to be an oversimplification as the cognitive properties of oscillations come under renewed scrutiny (see also Section 3.3.4.4). Here it cannot account for both the suppression extending from theta to alpha where

suppression of slow waves signifies activation, and the suppression of the faster beta waves where suppression signifies deactivation.

Non-specificity had also characterised the trainability of midline-frontal theta. [Enriquez-Geppert et al. \(2014, and see section 2.2.2.4 on learning\)](#) found that power increased across sessions in all the three bands they recorded – theta, alpha and beta (>21 Hz), though with the greater impact on theta amplitude followed by relative alpha amplitude. At the same time within-sessions there was a short latency theta training effect which coincided with a more conventional, positively accelerated alpha amplitude learning curve, and with no effect on beta. In support of across-session nonspecificity, [Nan et al. \(2012; Pt I, Section 2.2.2\)](#) in training alpha-2 amplitude also found enhancement across sessions from theta to sigma frequencies.

3.1.1.2. Baseline specificity. Turning to baseline carryover effects, notwithstanding the above mixed evidence mostly in favour of band non-specificity within and across sessions, there is some evidence of specificity in across session baselines.

[Zoefel et al. \(2011\)](#) found specificity in baseline EEG following upper-alpha amplitude training. Contrasting alpha-1, alpha-2 and beta-1 pre-training active baselines, when changes in saturation of a coloured square were counted in the first and last (fifth) session, only alpha-2 was reliably enhanced, in line with specificity of the alpha-2 training protocol. With a similar design, but adding a passive resting baseline, [Escolano et al. \(2011\)](#) found that upper-alpha amplitude training specificity held for the active baseline, in support of Zoefel et al. In contrast the passive baseline showed a spread of activity to include lower-alpha, see [Fig. 4](#).

Similarly with midline theta training, baseline levels in both theta and alpha amplitude increased with no advantage to theta over a pseudo training control group ([Enriquez-Geppert et al., 2014](#), and see Section 3.2.2.5 on learning for further considerations).

3.1.1.3. Specificity following training. In the two-study investigation with musicians ([Egner et al., 2004](#)) posterior hypnagogic A/T training led to replicable reductions in beta-1 amplitude in bilateral frontal locations, and to a left frontal reduction in SMR amplitude. In the first study, training to increase SMR amplitude at C4 led to relative alpha decrements at left frontal sites along with prefrontal decrements in SMR activity, a decrement also found in the second study which was located in the right parietal region (the disparity in locus may follow differences of experimental design). EEG outcomes were recorded up to two weeks after the completion of the ten week training courses.

[Becerra et al. \(2012\)](#) reported that following down-training theta maxima (Part, Section 4.2.2) in addition to frontal reductions in theta power there were left lateralised increases in alpha power. Additionally [Bernier et al. \(2006\)](#) from a single session of successful up-training of the ‘sigma’ band (11.6–16 Hz) reported a noticeable but non-significant increase in slower frequencies (4–10 Hz) whereas there was no immediate post-training carryover on sigma amplitude.

All of the limited evidence of effects that have followed training is in favour of non-specificity; the training of one band has led to changes in another band.

3.1.1.4. Concluding frequency band specificity. The evidence is complex with regard to bandwidth specificity, and, in addition to the training band, the neurofeedback process itself and its non-specific accompaniments will call on a range of processes such as learning, attention, motivation, effort, reinforcement monitoring, etc., which may invoke a number of bands. Non-specificity was the more prevalent outcome, though interestingly less so with successive baseline carryover, which is the more enduring goal for feedback learning.

The field would be advanced by experimenters routinely recording the full EEG spectrum in order to elucidate the bandwidth specificity question, and to examine the range of learning indicators (Section 3.2). Where the full spectrum has been recorded a complex picture of non-specificity has emerged including: (i) global downward shifts in power independent of the arousal properties of individual bands ([Ros and Gruzelier, 2010](#)), (ii) reciprocities between fast and slow wave bands in accordance with an arousal continuum ([Keizer et al., 2010a; Ros et al., 2010](#)) and empirically compatible with the specificity that [Salari et al. \(2013\)](#) observed between gamma and alpha training.

The reporting of the full spectrum following training would do much to advance understanding of the neurofeedback process itself, as well as the diverse cognitive and affective processes involved in EEG neurofeedback, together with their spectral band correlates. This would also inform the understanding of the sometimes contrary dynamics in shifts of EEG power that occur with task engagement (Section 3.2.2). Thus a full spectrum analysis should become an essential requirement for future studies, ideally coupled with a fine grained analysis of the various learning parameters (Section 3.2.1.1) when aligned with the spectral bands and the behavioural tasks with putative relevance to the spectral sub-bands.

As will be seen the behavioural outcome gains can be stronger for the training band and/or correlate with the training band indicative of a specificity of behavioural outcome, even where frequency non-specificity rules.

3.1.2. Frequency band specificity and cognitive/affective outcome

There is some evidence of neurofeedback protocol cognitive/affective specificity. From a theoretical standpoint this to some extent should be anticipated given the putative difference in behavioural correlates of the EEG bands. Sources of evidence arise from: (i) comparisons between adjacent band protocols, (ii) comparisons between slow and faster wave protocols, and (iii) from examining behavioural relations with spectral bands flanking the training bands.

In comparing adjacent SMR (12–14 Hz) and beta1 (15–18 Hz) amplitude protocols ([Egner and Gruzelier, 2001](#)) a reduction in continuous performance commission errors was found associated with SMR but not with beta-1 ratio training, and there was a counterpart in self-report ratings of calmness which were increased following

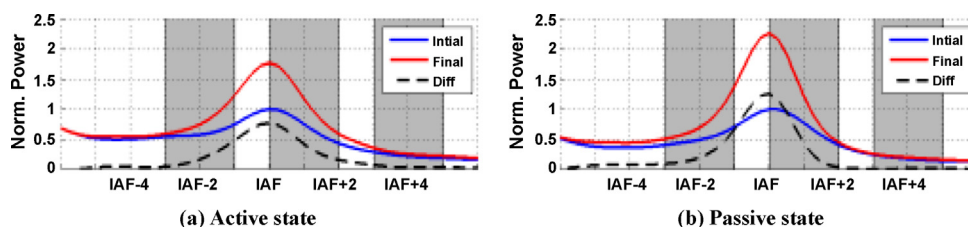


Fig. 4. Frequency spectra comparing active (a) and passive (b) baseline power in μV , with the first and fifth session and difference between them ([Escolano et al., 2011](#)).

the SMR and not the beta-1 protocol (Gruzelier, 2014c). In contrast the two protocols found common positive correlations with the P300b amplitude and with tiredness ratings. In a constructive replication with the addition of a more complex attention task (Egner and Gruzelier, 2004a,b), whereas behavioural measures of attention did not differentiate the groups, except for a reduction in reaction-time variability following SMR training, increased P300b amplitudes were found only with the beta-1 protocol.

The calming effects of SMR training should facilitate sustained attention and a reduction of impulsive errors of commission, properties which might also be expected to hold for bands lower in the spectrum than 12–14 Hz. In fact A/T training in children (Gruzelier et al., 2014a; Pt I, Section 2.1.1) was found to improve sustained attention by reducing errors of commission. Then in the case of trainee eye surgeons randomised to SMR or A/T amplitude ratio protocols (Ros et al., 2009; Pt I, Section 2.1.2), gains following SMR training in the skills lab included more efficient surgical skills, a more modulated performance, as well as a reduction in anxiety. These cognitive and affective benefits were shared with those doctors showing the stronger A/T learning.

In contrast, comparisons between the SMR ratio recorded centrally and alpha/theta hypnagogic training with posterior recording, and conducted with eyes open and closed respectively, have in a series of music studies produced evidence of differential outcomes. Whereas A/T training has resulted in wide ranging benefits for advanced and novice music performance in five comparative, controlled music studies (Egner and Gruzelier, 2003; Gruzelier et al., 2014a,b, 2013b), the benefits from SMR training have been restricted to novice music performance putatively because of the lower-level abilities involved in novice performance (Pt II, Section 3.2).

Comparisons between divergent protocols have included parietal alpha-2 and frontal theta, with up-training versus down-training amplitude respectively (Hanslmayer et al., 2006). Mental rotation was improved by increasing parietal upper-alpha and not by decreasing frontal theta. In the case of fluid intelligence Keizer et al. (2010b; Pt I, Section 2.3) found that increasing gamma (36–44 Hz) and inhibiting beta (12–20 Hz) amplitudes led to a high frequency spread of activity (16–60 Hz) going beyond the training band and overlapping with the inhibit band, which correlated positively with a fluid intelligence outcome measure. Congruent with this outcome a low frequency band (2–4 Hz) correlated in a negative direction with intelligence. Familiarity and recollection in recognition memory have also been separately enhanced by gamma and beta-1 training respectively (Keizer et al., 2010a).

In conclusion there is support for specificity of behavioural outcome from comparative protocol studies (Egner and Gruzelier, 2003, 2004a,b; Hanslmayer et al., 2006; Keizer et al., 2010a,b; Gruzelier, 2014c; Gruzelier et al., 2013b, 2014a,b; Salari et al., 2013). On the whole differential outcomes were consistent with the differing neurophysiological properties. At the same time there were commonalities of outcome between contrasting protocols in some instances (Ros et al., 2009; Gruzelier et al., 2014a) and which also made sense from a cognitive perspective. To further this line of investigation certain comparative studies stand out as in need of investigation: contrasting alpha-2 up-training with up-training the SMR amplitude; clarifying alpha's role by comparing alpha-1 and alpha-2, or even a threefold alpha classification (Klimesch, 1999); investigating the two classes of posterior theta suggested almost half a century ago (Vogel et al., 1968; Schachter, 1977).

Certainly feedback learning as a methodology allows for manipulation of selected rhythms and so allows elucidation of their psychological properties through a fine grained analysis. The within-subject methodology of Salari et al. (2013) has particular value in this regard.

3.1.3. Topographical specificity

In guiding the choice of training electrode site, perhaps the most fundamental principle that neurofeedback practitioners have observed is presumed localisation of function, and this has been based on a strict localisation, cortical neuropsychological model, one that has deep historical roots in a strict localisation versus holism school of thought (Boring, 1929), wherein holism is more abstract and is a precursor of a dynamic functional systems perspective. Practitioners are encouraged to perform a resting baseline topographical EEG so as to compare each individual with a commercial database, which they pay for. This is the so called 'qeeg' practice. The aim is then to normalise deviations from the database. As yet the validity of this practice has not been determined, but more critically the strategy is mostly at odds with a dynamic systems functional network perspective that governs the EEG spectrum (Varela et al., 2001; Roy John, 2002; Basar, 2011).

In illuminating this strict localisation misconception, the study of Becerra et al. (2012; Pt I, Section 4.2.2) is informative, because in adopting a 'qeeg' protocol approach in a thirty-session study of down-training theta in elderly participants, importantly they documented the outcome on various EEG bands and the topographical EEG. Firstly, the down-training of 'excessive' theta, with the electrode derivation determined by z-score analysis from a diversity of electrodes (F4, C3, C4, P3, F7, F8, T6) disclosed, after thirty sessions, post-training reductions in theta, as well as increases in alpha. Secondly, these manifestations were frontal; they did not coincide with the majority of training locations. Clearly the widespread 'qeeg' practitioner practice requires validation studies, and, as will be seen in Section 3.3.2.2, the one reported application with students was a failure.

On the whole there is little support for topographical specificity from the experimental studies, apart from Salari et al.'s gamma non-specificity result. This serves now to introduce the evidence that a frontal locus is the strongest locus showing changes following training, though this is not an exclusive locus. Even posterior training predominantly leads to stronger frontal than posterior effects. Importantly, while the executive processes involved in learning through feedback will involve the frontal lobe and will be manifest during training, the long-term effects will outlive the actual learning of self-regulation and will represent the mastery of learned self-regulation (Section 3.3.4.1). The frontal locus may well represent top-down thalamo-frontal EEG regulatory influences (e.g., Roy John, 2002), hypothesised speculatively here to follow the mastery of the learned self-regulation.

A frontal long-term locus was first reported by Egner et al. (2004) up to two weeks after a course of ten sessions, when the topographical EEG was measured as an outcome assessment of central and parietal training in the two music performance studies (Pt I, Section 2.1; Pt II, Section 2.1). In the first study those musicians randomised to neurofeedback were all trained with three protocols: SMR (12–15 Hz, C4), beta-1 (15–18 Hz, C3), and alpha/theta (A/T; 8–11 Hz/5–8 Hz, Pz), and in the second musicians were randomised to one of the three: SMR (Cz), beta-1(Cz), or A/T (Pz) training. Specific associations were examined between learning indices and the changes in absolute and relative spectral topography in the eyes-closed resting state. Partial correlation analyses disclosed that the long-term effects were predominantly anterior, with the more replicable ones following A/T training. A/T training over the parietal midline in the first experiment led to beta-1 reductions at prefrontal scalp sites, while in the second experiment analyses of relative power changes confirmed the beta-1 reductions in bilateral frontal locations, and as well disclosed a reduction in SMR activity in the left frontal region; none of the outcomes involved the slow wave training bands, but all indicated a lowering of arousal. Anterior effects were also found from SMR training over sensorimotor cortex in the first experiment, which took the form of

decrements in SMR activity in prefrontal scalp regions, along with relative alpha decrements at left frontal sites. At the same time SMR training resulted in posterior changes in the second experiment with a reduction in SMR activity in the right parietal region.

Turning to the dynamics during a course of training, a frontal bias was found amongst a more complicated outcome and with more complex protocols but essentially contrasting gamma with beta-1 delivered in eight sessions (Keizer et al., 2010a, I, Section 2.3). Results pertaining to the frontal bias could be summarised as follows: (i) only frontal within-session learning followed the beta-1 protocol training from central-occipital/frontal electrodes; (ii) posterior Oz gamma training led to frontal learning shown both in gamma across-sessions and in the beta-1 band within sessions; (iii) coherence between midline occipital and frontal electrodes in gamma was increased across sessions and within the last session by both gamma and beta-1 protocols, while coherence in beta was also increased, but only by beta training; (iv) Oz-Fz coherence increased within the first session as a result of both gamma and beta-1 training. This was in keeping with both frontal involvement in learning and gamma involvement in binding at early stages of the learning process.

Investigations with elderly participants have also confirmed the importance of the frontal sequelae of neurofeedback. Angelakis et al. (2004) reported that between thirty and thirty-five sessions of alpha peak training in three subjects resulted in frontal changes in the EEG and not at a posterior training POz site. Similarly, as already mentioned in the elderly participants of Becerra et al.'s (2012) study, post-training reductions in theta and increases in alpha were frontal irrespective of the electrode derivations. In both these reports with older subjects the frontal effects could be interpreted as consistent with frontal involvement in the cognitive improvements following training (Angelakis et al., 2004; Becerra et al., 2012). Fz gamma training in the elderly on the other hand has had widespread effects with enhancement seen frontally, centrally and parietally (Staufenbiel et al., 2013), evidence contradicting any focal outcome of gamma training.

Topographical specificity has also been challenged from a behavioural perspective. The effects of C3 versus C4 neurofeedback on word (left hemisphere) versus non-word (right hemisphere) training activated asymmetric hemispheric control circuits which modify widely distributed hemispheric networks (Barnea et al., 2005). Similarly lateralised alpha suppression training at C3 in the one-session TMS study of Ros et al. (2010, Section 2.1) led to bilateral effects (C3, C4), though SMR amplitude C3 training led to homolateral effects. In a subsequent one session study (Ros et al., 2013, Section 2.2) alpha suppression was topographically global. In participants with insomnia (Schabus et al., 2014) lateralised broadband SMR amplitude C3 training also resulted in bilateral enhancement, though not with same gain at C4 as was found at C3, the training site.

A focus on topography was provided by Cannon's LORETA assisted studies (Section 2.5) with the disclosure of distributed networks (Cannon et al., 2007, 2009). Beta-1 (14–18 Hz) training in the anterior cingulate within Brodmann area 32 disclosed networks with frontal involvement, posited to be due to demands on episodic and semantic memory, as well as to diverse memory processes and visual attention. While beta-1 current density was higher in pre-frontal cortex, the accompanying increases in beta-2 had a posterior topography, perhaps reflecting an association with the perceptual nature of the feedback.

In conclusion, it should come as no surprise to those of us schooled in the brain functional system networks, rather than in a strict localisation perspective, that the effects of EEG spectrum neurofeedback training on the whole were not restricted to the region of training. While many neurofeedback clinicians proceed on a simplistic strict localisation view, and train the learned-control at

that electrode site disclosing deviations from a normative data base, the effects of training are likely to be more generalised, in keeping with a functional system perspective. However, the simplistic strict localisation view is deeply embedded in scientific consciousness dating back to phrenology, in contrast to the realistic but complicated functional system perspective. A simplistic strict localisation (q EEG) view, is likely to address only processes in superficial cortical layers or discrete thalamo-cortical loops, and with putative clinical relevance to cortical neuropsychological disorders.

Having said that, a study of up-raising alpha power in tinnitus patients with a procedure that visualised alpha power with source space projection analysis targeting the primary auditory cortex more focally, has provided support for strict localisation, and with a beneficial clinical outcome (Hartmann et al., 2014). Without going in to clinical details, data from twenty-nine scalp electrodes were projected on to eight regional dipole sources feeding back those from bilateral auditory cortex to the participants who were trained to increase alpha, which was hypothesised to be desynchronised abnormally in tinnitus patients. Broadband alpha power was enhanced in the right but not left auditory cortex which was accompanied by an increased outgoing connectivity to adjacent right-sided cortex, and this was paralleled by, though not correlated with, the increase in alpha power, a possible outcome of lateral inhibition. In left-sided auditory areas there was less ingoing connectivity and this was unrelated to local power changes, a possible reflection of an association between an increase in inhibitory alpha power and decreased functional connectivity (Jensen and Mazaheri, 2010).

Another methodological perspective is offered by the successful training with two participants of regions of interest with MEG (Florin et al., 2014). The theta/alpha ratio with eyes open was trained in eight sessions with activity fed back from regions associated with mental imagery – aspects of dorsal superior parietal lobe, anterior/posterior central sulcus, and the pre-supplementary motor area of the dorsomedial frontal cortex. Reliable-over-session training-region-of-interest effects were reported in both subjects differing in topography, anterior in one and posterior in the other, with possible relation to the chosen imagery which differed for the two subjects – ‘a self-centred motor imagery strategy’ in the first and a more abstract observer position in the other. More robust, anatomically specific training was achievable apparently than with the EEG having taken into account individual differences which putatively were governed by individualised imagery.

3.2. The nature of EEG-neurofeedback learning

An even more critical issue than specificity is the importance of appreciating that the training of neurofeedback is complex, requiring a skilled participant-trainer interaction, along with the need to monitor the learning process carefully.

Before reviewing the state of the evidence for the various protocols in turn, what can be deduced about the form of learning curves? As reviewed in Parts I and II, in total there are more than thirty optimal performance reports that have formally examined learning indices, with some providing illustrations. There are presently a number of options for monitoring rate of learning, and research is at an early stage. The main forms of learning are illustrated in order to orientate the reader before reviewing the evidence. These include learning across sessions, within sessions, and learning evinced in successive pre-session baselines.

3.2.1. Across session

In Fig. 5 is an example of across-session learning from SMR/theta/beta-2 ratio training (Gruzelier et al., 2010).

In using mainly a standard approach in our SMR ratio amplitude studies we typically found across-session learning curves as

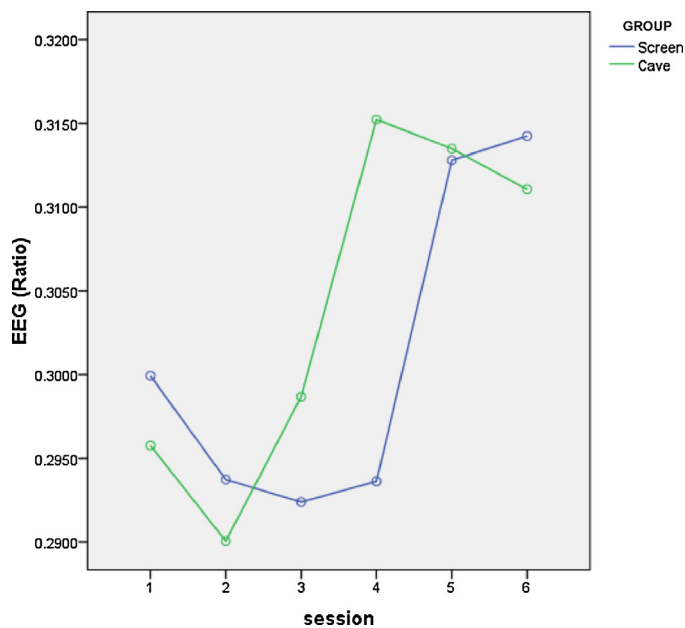


Fig. 5. SMR ratio amplitudes (μ V) between sessions (excluding session one) comparing 3D (reactor) and 2D (laptop) training contexts (Gruzelier et al., 2010).

reflected in the two functions shown contrasting a conventional 2D with a 3D training context. As can be seen, once mastery of the SMR ratio was achieved over the initial sessions, cumulative learning followed with a positively accelerating function reaching a plateau between the 4th and 6th session, (a first familiarisation session was not included in the figure). The asymptote was reached roughly a session earlier with the more immersive 3D context, and coincidentally with the acknowledgement through self-ratings that the aimed for state was achieved (Pt II, Section 3.1.3). A closely similar learning function was reported by Keizer et al. (2010b) with gamma ratio training where the aim was to increase the gamma amplitude while maintaining or inhibiting a broad beta1 (12–20 Hz) range, whereas a comparison group was trained to do the opposite. Here in the gamma group there was a marked increase between the 5th and 6th sessions at which time a plateau was reached.

3.2.2. Within session

Within-session learning is complicated by the generalised reduction in power and desynchronisation in the EEG spectrum that may occur as the subject adapts to the task in hand, as shown in Figs. 1b and 2, and see Dempster and Vernon (2009), along with other apparent dynamics of adjustment such as an odd, inexplicable short-latency reversals in lateral asymmetry training (Peeters et al., 2013, Section 3.3.4.2). There is also a report of an upward short latency effect, departing from conventional within-session learning functions through an asymptote reached in the first session with both frontal gamma (Fig. 4) and frontal midline theta (see Enríques-Geppert et al., 2013).

3.2.3. Baseline Increments

It follows that if the goal of neurofeedback is to modify the tonic EEG (e.g., Hanslmayer et al., 2006; Ros et al., 2013), then learned changes should be manifested in the pre-training EEG baselines of successive sessions. However, with a few exceptions progressive changes in baseline have only been examined recently. Zoefel et al. (2011) and Escolano et al. (2011; Fig. 6) have reported a carry-over to the pre-training baseline of five daily sessions of within/across session upper-alpha learning from parietal chain placements. Zoefel et al. found that training led to a linear increase in amplitude

within/across sessions, and the baseline was higher in the fifth session than in the first session, while a stronger effect was found by Escolano et al. with an active compared with a passive baseline.

3.3. Individual protocols

The evidence for the various forms of learning will now be summarised for the neurofeedback protocols individually. Where behavioural outcome was not examined the reports are described as methodological studies. If there was a successful cognitive, affective, performance outcome, a description of gains will be found in Parts I and II, along with correlational evidence in support of mediation between outcome gains and neurofeedback learning indices.

3.3.1. Alpha training

Beginning with eyes-open alpha training, this was the first of the EEG protocols to receive attention following Kamiya's (1968,69) pioneering work, giving rise to a body of early investigations (see Vernon et al., 2009), and recently replicated (Frederick, 2012). In one of the more recent methodological studies three alpha (8–12 Hz, Pz) learning indices – amplitude, percent time, and integrated alpha, were examined both within and across ten weekly sessions (Dempster and Vernon, 2009). Twenty-five participants were examined in a single group design with sessions divided into two equal segments consisting of five periods. Within-sessions and in each 7.5-min segment all the three measures showed an initial desynchronisation below baseline, followed by significant increases returning and with a nonsignificant rise above the session baseline. That learning did occur was observed by an increase in alpha amplitude across sessions and importantly by an increase in baseline amplitude. The initial desynchronisation would be consistent with an external direction of attention (Klimesch, 1997) as is required in engagement with feedback, contrary to the inward direction of attention and an inhibition of distracting stimuli accompanying alpha synchronisation which was the training goal. The use of the conventional alpha band may also hamper learning given evidence of different behavioural properties of alpha-1 and alpha-2 (Klimesch et al., 2007; Bazanova and Vernon, 2014; see also Dekker et al., 2014).

All other investigations of up-training amplitude have focussed on alpha-2 and have the advantage of validation through outcome assessment (see Parts I and II). The evidence is mixed regarding learning indices, with the majority of evidence favouring across-session learning. With elderly participants Lecomte and Juhel (2011) reported that four sessions of transverse-central alpha-2 training while inhibiting theta led to between-session but not within-session learning. Similarly Nan et al. (2012) established between-session learning but failed to achieve significant within-session learning with sixteen subjects receiving central-midline upper-alpha training for twenty sessions within fifteen days.

Amplitude enhancement sustained during the post-training tonic EEG was first reported in a single session study (Hanslmayer et al., 2006) of fronto-parietal alpha-2 versus theta reduction. Cumulative effects of learning on successive baselines has also been seen in alpha-2. As mentioned above Zoefel et al. (2011) found a linear increase throughout five daily sessions of posterior alpha-2 training, though the only statistically significant effect reported was an increase in the pre-training baseline in the fifth session when compared with the first, following the exclusion of non-learners. Similar but stronger results were reported by Escolano et al. (2011) when comparing an active baseline with the same design of five daily sessions of posterior (PzOz) alpha-2 training. The active baseline involved counting changes in the saturation of a target for 5-min, supplementing an eyes-open passive baseline. The results

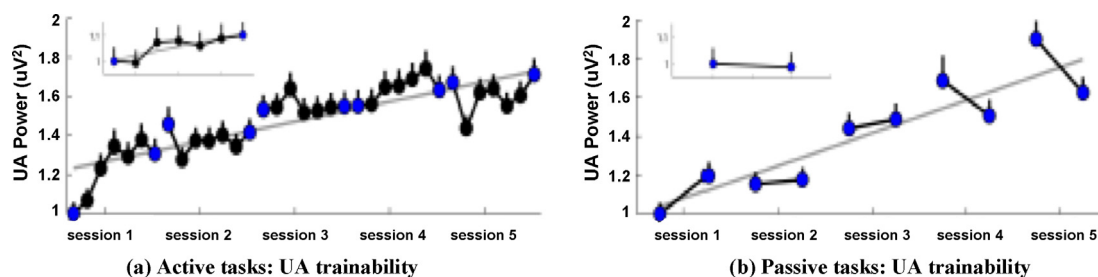


Fig. 6. Alpha-2 normalised power (a) within sessions plus pre- and post-session task active baselines and (b) pre- and post-session passive baselines, across all five sessions, with insets showing the within session averages (Escalano et al., 2011).

after excluding 3/9 whose amplitudes did not increase are plotted in Fig. 6. The type of baseline was found to be critical, for only with the active baseline were regression lines for each subject significant, and pre-active baselines were higher when comparing session five with session one. Within-session analyses were nonsignificant, though these were in the expected direction.

In contrast, learning effects have been reported with a similar active-baseline, but in conjunction with within-session rather than across-session learning. López-Larraz et al. (2013) trained upper-alpha amplitude (IAF in a 2 Hz bin within the range 7.5–12.5 Hz) from the motor cortex (central and centroparietal chains). Five subjects were given five daily-sessions consisting of five blocks of 5-min duration. All subjects disclosed positively accelerated linear gradients within sessions in alpha-2 amplitude as a ratio of the first session baseline obtained in an active state. There was a within-session average increase of 34%, and an increase from the pre-training to the post-training active baseline of 79%. On the other hand group across-session learning was irregular.

Alpha desynchronisation training, as shown in Figs. 1a and 2, has been effective in one-session studies (Ros et al., 2010, 2013; see also Kluetsch et al., 2014). However, baseline assessment has been complicated by rebound effects (Ros et al., 2013), as mentioned earlier (Section 2.2).

There has been a single report of training alpha with eyes closed. In a methodological study Cho et al. (2008) examined 8–12 Hz parietal midline training to auditory feedback for eleven weekly sessions with reference to a resting eyes-open baseline. They found evidence of between-session learning and carryover to the eyes-open baseline, while within sessions learning was confounded by an alpha synchronisation surge with eye closure.

In conclusion, there is clear evidence of eyes-open alpha synchronisation learning, especially for upper alpha, with learning demonstrated in all cases either across sessions or in baselines, preferentially an active baseline, or both between sessions together with baselines. Within-session learning, demonstrated in only one study, may be complicated by attention outward which accompanies alpha suppression and is a fundamental requirement of setting in motion the feedback learning procedure. This may be why alpha desynchronisation feedback was effective in just one session (Ros et al., 2010, 2013), but there may be baseline rebound complications, at least in single-session studies. Another complication surrounds the likely cognitive/affective differences between lower and higher alpha frequencies in what is a spectral band that is poised in the EEG spectrum between opposing slow wave versus fast wave 'arousal' sequelae; when broad-band alpha training is undertaken these alpha-1 and 2 properties may well collide. Another development will be to train other indices, aside from power, for effects on optimal performance such as those outlined by Bazanova and Vernon (2014) and see Dempster and Vernon (2009, Section 2.2.2.1), and as has been suggested in a pilot study with alpha peak frequency in the elderly (Angelakis et al., 2007) and see Pt I, Section 4.2.1.

3.3.2. Alpha/theta training

In low arousal states with eyes closed, as in A/T training (Pt II, Section 1.2), on the whole there has been more difficulty in demonstrating across-session than within-session learning when training; the use of self report arousal scales may inform this, e.g., Gruzelier (2014c). When one considers that the aim is to induce hypnagogic stage I sleep, much will depend on the state of the subject when they attend for training. The 'depth' and magnitude of the theta/alpha ratio tends to fluctuate, and does not readily show a smooth progression across sessions, so that carry-over to pre-session baseline measures may not be recommended as a learning index. While difficulty in showing within-session learning might be anticipated when healthy participants fit into their crowded schedules half-hour neurofeedback sessions with the aim of achieving stage I sleep in 15 min, in our experience increasing the theta/alpha ratio is typically achieved, to include children excused from class to attend sessions (Gruzelier et al., 2014a).

Examples of A/T learning curves are shown in Part II, Section 1.2.4, Fig. 1 and outcome gains in Part I, Sections 2.1.2, 3.1 and Part II, Sections 2, 3. The following reports found evidence of both within-session and across-session A/T learning (Raymond et al., 2005a; Ros et al., 2009; Gruzelier et al., 2014a,b, 2013b). Others found only within-session learning (Egner et al., 2002; Egner and Gruzelier, 2004a,b; Raymond et al., 2005b), while Egner and Gruzelier (2003) used a composite within/between session measure; though until the emergent complexities of learning are under better control, separate indices may better inform the field in general.

3.3.3. SMR training

Considering first the studies that included theta and beta-2 inhibits when elevating the sensory-motor rhythm, both within- and across-session learning has been demonstrated (Ros et al., 2009; Gruzelier et al., 2010, 2013b), while within-session without across-session learning has been reported (Vernon et al., 2003), as well as the converse (Gruzelier, 2013b). Furthermore successful learning in children was found with the SMR/beta-2 ratio and not the SMR/theta ratio (Gruzelier et al., 2014a).

The dynamics of both bands in the ratio proved to be important, as found earlier (Ros et al., 2009; Pt I, Section 2.1.2). In a methodological study of SMR (12–15 Hz)/theta (4–7 Hz) ratio training de Zambotti et al. (2012) have plotted the learning functions showing the separate contributions to the ratio. For eight weeks a group of eight participants was given twice-weekly sessions divided into five 3-min periods and after each period the strategy used was ascertained with the successful one fed back at the end of the session. The SMR/theta ratio and SMR and theta amplitudes were all calculated as a percent of each session's baseline instead of referenced to session one, which likely compromised across-session baseline learning and the generality of the results. They found an increase across sessions in the learning ratio, both when referenced to baseline and when independent of baseline.

The increase in ratio over sessions was underpinned by an increase in SMR amplitude, consequent on a fall to below the session baseline, a fall which then lessened across sessions. This was coupled with a substantive drop in theta amplitude reaching a maximum in the first session, and remaining constant on average; as discussed above (Section 3.2.2) an initial reduction in power is a common occurrence. When absolute SMR/theta ratios independent of baselines were plotted there was a noticeable increase in the last two sessions, but when examining the successive session baselines the ratio was found to decline. Interpretation would have been guided by examination of the full spectrum, the post-training EEG, and the within-session learning data which was unaccountably omitted. The use of an anterior FCz placement rather than the conventional Cz placement also complicates interpretation, both as it involves central midline theta which has different functional properties to posterior theta (Pt I, Section 2.4), and is at a distance from the sensory-motor strip which underpins the sensory-motor rhythm.

Turning to SMR learning without inhibits, this has led to successful between-session learning (Doppelmayr and Weber, 2011; Berner et al., 2006; Schabus et al., 2014), and somewhat slow learning in a one-session report (Ros et al., 2013). As outlined in Part I, Section 2.2.4, Hoedlmoser et al. (2008) reported that despite evidence of across-session learning there was no cumulative impact of ten sessions of SMR C3 amplitude training on pre-training baselines, however, there was an increased frequency of sleep spindles and a shorter EEG sleep latency in a post-training nap. Similarly a follow-up with insomnia patients (Schabus et al., 2014) found evidence of cumulative across-session SMR learning but no impact on the resting EEG, though there was an impact on the post-training sleep EEG with increased spindle frequency.

Thus a demonstration of SMR learning with and without inhibits has been mainly successful, and SMR training has been consistently successful in achieving outcome gains (Part I, Section 2.1). A controlled comparison of training with and without inhibits would make a useful contribution to further applications, while baseline learning warrants further study.

3.3.4. Theta training with eyes open

To date there are few studies training theta in the waking state, though recent interest in up-training amplitude has followed evidence of frontal Fz recording, the anterior cingulate origins and cognitive correlates including among executive functions action monitoring and cognitive control.

Following twelve sessions of up-training of frontal midline theta with gamma and delta inhibits successful between-session learning together with cognitive gains (Pt I, Section 4.2) were found equally in an elderly community sample and students (Wang and Hsieh, 2013). Importantly the theta ratio increased across sessions and there was a carry-over to the pre-session baselines in theta amplitude, with the elderly disclosing improvements in attention and recognition memory. Within-session learning was not examined, and as such was unable to illuminate the within-session results from a complex methodological study (Enriques-Geppert et al., 2014) which was reported earlier in Section 2.6 regarding anatomical correlates of within-session training (Fig. 3; Enriques-Geppert et al., 2013). Dynamics of learning were examined in thirty-one participants randomised either to training frontal midline theta averaged from Fz, FC1, FC2, FCz, FC2 and Cz, or to pseudo feedback given to matched participants. Theta frequency, conceptualised as phasic theta, was individually determined during four executive function tasks. Participants were given eight 30-min sessions over two weeks, four per week, with sessions divided into six 5-min trial blocks. Learning was assessed by measures of amplitude and percent increase relative to session one. In interests of training-band specificity the spectrum was reported from 3 to 20 Hz.

Interestingly, as was shown in Fig. 3, theta amplitude showed an immediate increase which reached a plateau, returning to baseline post-session, whereas in the control group it declined, significantly so by the last block and carrying over to the post-session baseline. Training was not band specific, and a more conventional within-session learning function was found with alpha amplitude, which in the experimental group took the form of a linear increase sustained in the post-session baseline. Despite the decline in theta amplitude in the pseudo-theta feedback control group, there was across sessions in both groups with an increase in theta, alpha and beta amplitudes (the three bands examined), occurring more so with theta and alpha in the experimental group, and with both theta and alpha carrying over to successive session baselines in both groups.

Such a short latency peak, reaching an immediate asymptote within sessions, and giving the appearance of instant learning, is directly in line with midline frontal theta indexing action monitoring and may represent a nexus of factors including learning, self-regulation, as well as non-specific issues such as attention and effort, but perhaps most central of all action monitoring. The fact that it was within-session learning and not between-session learning that correlated with cingulate morphology (Enriques-Geppert et al., 2013) supports this inference. However, one would suppose that the same non-specific factors would operate within sessions in the control group, especially as the groups did not differ in subjective ratings of commitment or motivation which declined in both groups, though the control group reported less difficulty, paradoxically perhaps, given their lack of success within sessions. Complimenting the pre-training cognitive assessments with post-training assessments may have helped clarify the outcome.

Turning to posterior theta amplitude up-training, Reiner et al. (2014) in a theta (4–7 Hz)/beta (18–22 Hz) one-session controlled study reported that individual variation in learning was positively correlated with gains in speed of performance of a finger-thumb apposition test which correlated with the theta/beta amplitude after one, after two and after six nights of sleep, see Fig. 7.

Turning to down-training theta amplitude, in a comparative protocol study Vernon et al. (2003) compared SMR ratio training with down-training midline central theta amplitude with broad alpha band and delta amplitude inhibits. Whereas the SMR ratio was successfully trained within sessions and led to cognitive gains, theta ratio training was unsuccessful. Instead the alpha inhibit was enhanced within sessions, a likely contributor to the compromise in training-down theta.

Perhaps in support of the confounding influence of the inhibits on theta down-training, successful training down of theta without inhibits was achieved in a single session in ten/eighteen subjects (Hanslmayer et al., 2006), but without a cognitive or EEG impact in contrast to the outcome with alpha-2 training. The null result was complicated by the subjects also receiving enhancement training of upper-alpha in a counterbalanced design, both recorded from the combined frontal and parietal chains. A further discussion of inhibits is found in section 3.6.4.

In concluding, up-training theta, both anterior and posterior, offers intriguing possibilities for future research. Rather than abandoning down-training theta, more research is clearly required when considering distinctions made earlier (Vogel et al., 1968; Schachter, 1977) between two types of posterior theta, one of low, irregular amplitude with the classical association of tiredness, and the other of higher amplitude associated with attention. Consider too the finding that in a single case clinical study of cognitive disorganisation coupled with anhedonia following long-term recreational drug abuse, it was the reduction in theta (Cz) when combined with SMR ratio training that correlated with ratings of clinical recovery (Unterrainer et al., 2013a,b).

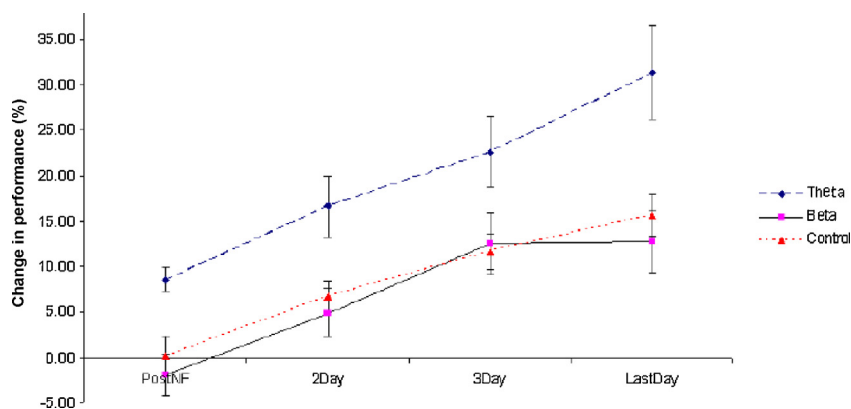


Fig. 7. Percent improvement in instrumental learning after a single session of training up posterior theta as a function of consolidation after sleep in the course of a week (Reiner et al., 2014).

3.3.5. Gamma training

Across-session learning has been demonstrated with gamma (Keizer et al., 2010b), as was shown in Fig. 6. With an occipital midline placement and up to eight sessions, increasing gamma (36–44 Hz) without increasing beta (12–20 Hz) was compared with a group trained to do the opposite. Across sessions gamma increased in the experimental group reaching an asymptote on the 6th session, whereas the comparison group was unsuccessful. Within-session learning was not reported. In a second experiment without inhibits both across- and within-session learning were demonstrated (Keizer et al., 2010a). Gamma feedback was from the occipital electrode as before while beta feedback was from the average of occipital and frontal electrodes. Between-session learning at Oz was again successful and was found at the frontal Fz non-training site, but examination of within session changes disclosed learning only in the last session at Oz. In contrast beta-1 training, where feedback was the average of both frontal and occipital derivations, disclosed no evidence of learning across sessions at either Oz or Fz, though there was evidence of frontal within-session learning. 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. This was a complex pattern of results showing a lack of correspondence in learning between and within sessions, and in changes in connectivity.

The potential importance of gamma training for cognition in the elderly led to an extension of this research. Staufenbiel et al. (2013) compared eight sessions of Fz gamma (36–44 Hz) with broad band low beta (12–20 Hz) training. Eyes-open EEG was examined before and after the training course across frontal, central and parietal chains, and frontal and central chains within sessions. Within-session learning was demonstrated in both groups. Gamma training increased both gamma and beta amplitudes whereas beta training demonstrated specificity. In contrast there was no evidence of gamma learning across sessions and with only a tendency following beta training. In neither group was there an impact on the post-training resting EEG. This contrasted with successful gamma enhancement across sessions as demonstrated by Salari et al. (2012, Section 3.1).

The cognitive gains (Keizer et al., 2010a,b; Salari et al., 2013) support the value of gamma training for enhancing performance, even though the dynamics of learning currently are not always clear.

3.3.6. Concluding comments on learning indices

At this early stage in understanding the processes involved in neurofeedback training and self-regulation (Section 3.3.4.1) it

would be helpful always to report learning functions within sessions, between sessions and with successive baselines. The last is especially important for theoretical reasons given that the object of the exercise is to create enduring changes.

When considering the calculation of learning indices and coefficients, there is sufficient evidence to suggest that immediate adjustment to the learning context may lead to contrary changes, which if included say in a coefficient will dilute the learning estimate. It is important to look at the data first. Then the evidence and theory relating to neurofeedback's impact on tonic changes in the working brain suggest that a more useful baseline condition is an active rather than a passive one. While the consideration of technical matters relating to learning coefficients is beyond the scope of this review, in referencing ratios to baseline it might be better to use the baseline of an early reliable session rather than using a constant adjustment to each session's baseline. This would allow the participant a sense of achievement, aside from the fact that an asymptote may be reached after four or five sessions, as seen in Fig. 5, which also has the potential for leaving the participant feeling compromised.

Studies comparing protocols will clarify the behavioural correlates of bands and assist in elucidating outcome specificity. Such studies are in the minority, and largely consist of comparisons between SMR ratio and A/T, and to a lesser extent beta-1 training, and see a comparison of 'theta/beta' and SCP training in ADHD (Leins et al., 2007). Comparative studies have methodological strengths. They allow for a control of the majority of non-specific confounds, and with faster-wave protocols with open eyes they allow for comparisons to be made within individuals within sessions (e.g., Salari et al., 2013, Section 3.1) which have particular advantages for validation.

Especially important would be comparisons, all with individually adjusted frequencies (Section 3.3.2.4), between the adjacent alpha-2 and SMR bands, and adjacent alpha-1 and alpha-2 bands, not only because of potential flanker leakage confounds but also potential cognitive/affective commonalities; Klimesch (1999) has also considered alpha to be subdivided in three. Similarly comparisons within the beta-gamma range are required; surely the loose and prevalent usage of 'beta' to apply to the spectrum above alpha-2 must be abandoned. Theta also requires elucidation. To reiterate, relating learning measures to behavioural and CNS outcome assessments is a useful guide to the impact of learning, which in turn informs the appropriateness of a learning index.

3.4. Learning perspectives

3.4.1. Experimental design

Intervention studies offer practical challenges and requirements which impact on learning. In terms of compliance a ten-session

intervention study with one, two, or possibly three pre- and post-assessment sessions, with one day devoted to a full cap EEG, could give a total of sixteen laboratory visits. This would lead in a modest study comparing two protocols and a participatory control group with ten subjects per group to four hundred and eighty sessions independent of dropout rescheduling. Aside from practicalities of timetabling the availability of experimenter, subject and laboratory, everyday vicissitudes inevitably lead to rescheduling, and intervals between sessions may impact on rates of learning. For practical reasons, in order to avoid long gaps between sessions due to vacations, studies are often scheduled around terms and semesters, omitting exams and pre-examination stress. One implication can be a difficulty in arranging follow-up assessments as participants move on; follow-up is highly desirable requirement for future studies. Another is the need to keep the session duration within practical limits, which inevitably precludes a full topographical EEG during training sessions; the latter would elucidate the development of the learning and self-regulation processes (Section 3.3.4.1). These issues impact on experimental design. Resources for a dedicated study will be of heuristic importance to trace the development of learning and mastery.

3.4.1.1. Number of training sessions. How many sessions are optimal? Training sessions with healthy subjects have ranged from one to thirty-five, and a majority of investigators have been successful with eight–ten in controlled studies. To consider numbers of sessions and successful behavioural outcomes with protocols including SMR, Beta1, A/T, alpha2, gamma: eight sessions benefitted attention and working memory (Vernon et al., 2003), perceptuo-motor skills (Ros et al., 2009), perceptual integration (Keizer et al., 2010b), perceptual integration and recognition memory (Keizer et al., 2010a), and cognitive creativity (Gruzelier, 2014c); ten sessions benefitted attention (Egner and Gruzelier, 2001, 2004a,b), music performance (Egner and Gruzelier, 2003), mood ratings (Raymond et al., 2005b; Gruzelier, 2014c), dance performance (Raymond et al., 2005a), declarative memory and sleep (Hoedlmoser et al., 2008); seven–ten sessions advanced acting performance (Gruzelier et al., 2010); five sessions benefitted mental rotation (Zoefel et al., 2011), though Doppelmayr and Webber (2011, Section 3.3.2.3) found that not until sessions twenty-six to thirty was there a significant increase from baseline in a study benefitting mental rotation and RT.

In children attention, music performance and well-being benefitted from ten sessions (Gruzelier et al., 2013a) and their recognition memory from twenty sessions (Barnea et al., 2005).

In the elderly a successful outcome was obtained with thirty and thirty-one to thirty-five sessions (Becerra et al., 2012; Angelakis et al., 2007), but not with four sessions (Lecomte and Juhel, 2011).

All in all guided by the empirical evidence to date eight – ten sessions would be the suggested guide for young healthy participants, and more sessions in older participants.

3.4.1.2. One session learning and outcome gains. As has been noted, learning may be achieved in a single session with protocols including training up alpha-2, SMR, and posterior theta, as well as alpha desynchronisation and left temporal slowing, summarised in Table 1.

Further, one session can produce not only evidence of learning, but also evidence of cognitive and affective outcome gains in the short term, including archery skill, mental rotation,

over-night memory consolidation, music performance, calmness and reduction in mind wandering (Table 1), as well as in instrumental learning lasting throughout a week (Reiner et al., 2014). Influences on the central nervous system post-training have included the tonic EEG, sleep spindle frequency, cortico-spinal excitability, and increased functional network connectivity.

Correlational evidence from a single session of neurofeedback learning of mediational influences have been demonstrated with mental rotation, mind wandering, calmness, procedural learning, cortico-spinal excitability and functional connectivity in default mode and salience networks, and indirectly with a sleep study where a trained increase in a broad 'SMR' sleep spindle band (C3/4) carried over to the first half of the night in stage 2–4 NREM sleep, a period during which the sleep spindle incidence correlated positively with declarative memory (Berner et al., 2006).

In some experiments (Hanslmayer et al., 2006; Berner et al., 2006) the one-session learning facility may have benefitted from the selection of participants on the basis of prior evidence of their ability to raise alpha through neurofeedback (though as seen later, Section 3.3.1.2, neurofeedback learning is not a generic facility).

While one cannot anticipate durability of outcome enhancement following one session, and concluding a null outcome about learning potential would be premature, one session experiments have practical advantages in addressing some research questions and by recruiting larger groups of subjects which allows an increase in statistical power compared with the labour intensive smaller scale studies.

3.4.1.3. Inter-session interval. Historically the impact of inter-session interval on learning has revolved around massed versus spaced practice, but this has been largely based on motor skills with practice distributions within twenty-four hours. From the reviewed evidence (e.g., Donovan and Radosevich, 1999) there would appear to be little to go on when considering neurofeedback learning, where intervals typically range from twice a day to once a week. Three outcome studies to date inform this issue, but only incidentally. Reiner et al. (2014; Pt I, Section 2.4.3) reported a complex outcome from a single session of posterior up-training including a delayed gain in just under a week (Fig. 7), which implicated a late consolidation of procedural learning at a systems level, aside from synaptic consolidation. Ros et al. (2009) with trainee microsurgeons found the better surgical skills in those who in the second half of the eight-session training course managed appointments for SMR ratio training with a shorter inter-session interval – 4.8 days versus 8.5 days in the remainder. In contrast Schabus et al. (2013) in a sleep study reported benefits for patients from SMR amplitude training who came more infrequently. However, the retrospective analyses of individual differences (Ros et al., 2009; Schabus et al., 2013) may have reflected other contingencies that led to attendance. An important research question is to determine the ideal intersession interval for an individual, and whether this should vary during a course of training.

3.4.1.4. Control or comparison groups. Here no approach is free from some limitation. There is a saving of time, especially pertinent when more than one protocol or group is under study, by including a non-intervention control for practice effects that might impact on outcome assessments. However, the inactive no-training control has the obvious limitation of not controlling for non-specific influences including motivation, training context dynamics and so on, which are of particular importance in a single protocol investigation.

Pseudo feedback has proved effective, with slow wave training in particular. A potential limitation concerns non-contingency and whether awareness of the failure to learn reduces motivation. This awareness may be somewhat less present in alpha/theta

Table 1

Reports showing successful one-session learning with protocol and beneficial cognitive/affective and CNS effects. 'r' indicates affirmative correlations.

Report	Protocol	Cognitive/affective	CNS
Landers et al. (1991)	Left temporal temporal slowing	Archery skill	–
Hanslmayer et al. (2006)	Alpha 2	Mental rotation (r)	Tonic EEG
Berner et al. (2006)	SMR	Declarative memory r with NREM spindle frequency	Spindles NREM
Bazanava et al. (2007)	Alpha 2	Music performance	
Ros et al. (2010)	Alpha suppression	–	Cortico-spinal excitability (r) intracortical inhibition tonic EEG
	SMR		Cortico-spinal excitability (r) tonic EEG
Ros et al. (2013)	Alpha suppression	Mind wandering (r)	Salience network and default mode network connectivity (r)
Kluetsch et al. (2014)	Alpha suppression	Calmness (r)	Salience network and default mode network connectivity (r)
Reiner et al. (2014)	Posterior theta	Procedural learning (r)	–
Ros et al. (2014)	Alpha suppression	Implicit memory procedural learning	

training where deep relaxation is inevitable in a majority of subjects, and indeed participants in one study experienced the same level of relaxation as the experimental group despite non-contingency of reward and without the enhancement of the theta/alpha ratio (Egner et al., 2002). Despite the potential limitation of risking motivation pseudo feedback has been used effectively with faster-wave protocols.

Another approach involves random frequency bins where the control group receives the same training as the experimental group save for changing the training band randomly across sessions. This was adopted originally by Hanslmayer et al. (2006). By choosing frequencies both above and below the alpha-2 training frequency of the experimental group, this strategy putatively would allow a cancelling out of differential effects, say between slow wave and fast wave learning arising from the flanking bands. This assumes that the behavioural correlates of the flanking bands differed, an assumption that requires demonstration given the wide ranging enhancements in outcome gains across the spectrum, e.g., theta versus beta-1 versus gamma up-training. More risky is the choice of random bands that are at the one, higher end of the EEG spectrum, especially when one takes in to account the evidence of non-specificity evincing a spread of activity across bands (Section 3.1.1), and when considering one-trial learning capabilities as well (Section 3.3.1.2).

3.4.2. Individual differences in learning

There is a notion in the field that about a third of participants fail to learn. On the other hand of the forty or so controlled optimal performance studies that have demonstrated affirmative outcomes following a course of training, as distinct from a single session (Parts I and II), a majority have not reported non-learning; possibly because in many instances group advantages in favour of a protocol may have not encouraged looking further at the data set. Certainly there are differences between individuals in how successful they are in their learning achievements. This individual difference in outcome gains has been examined by subdivision into high versus low ability on the basis of learning indices, or on the basis of the magnitude of outcome gains. As reviewed in Parts I and II this variation has assisted in providing evidence of mediation through correlation between better learning and superior outcome gain, and covering a diverse range of processes. There is also the implicit assumption that non-learning is a generic factor, an assumption which is likely to be misconceived.

3.4.2.1. Is feedback learning generic? Given the diversity of processes underpinned by spectral bands, with anatomical correlates capable of demonstration, the likelihood of a generic learning facility is unlikely. As outlined in Part I, Section 2.2.1, Hanslmayer et al. (2006) trained participants ($N=18$) in a counterbalanced design to raise alpha-2 and lower theta power from F3, Fz, F4 and P3, Pz,

P4 combined, with both bands individually adjusted. There was a single session with separate 20-min blocks of trials separated by cognitive tasks. Nine subjects had successful alpha learning and ten successful theta learning, but, only four in the alpha group were in the theta group. Though an incidental finding, this indicates that feedback learning (or at least its speed) is not a generic facility and likely varies with protocols. This awaits systematic study and has important clinical implications in treating the individual.

3.4.2.2. Learning failure. There has only been one report of a failure in learning overall (Logemann et al., 2010), but the approach to protocol choice and analysis might account for its failure. An individualised protocol based on z scores obtained from a pre-training topographical EEG was chosen, which, as has already been mentioned (Section 3.1.3), is popular in clinical domains but remains invalidated (and see for application with the elderly (Part I, Section 4.2.2)). The experimental group was compared with a sham control group in a double-blind evaluation. While exact details were not given as to the individualised protocol choices, in ten participants the goal was either to elevate one band within a range of 11–18 Hz with one or two slow or fast wave inhibits, or in the remaining four participants to inhibit slow and/or fast wave bands. It was hypothesised that the z-score determined training of the diverse topographical derivations would have a common influence in normalising students with high scores of impulsivity and inattention. These diverse protocols were pooled within groups without consideration of whether they were effective in demonstrating learned control. After sixteen of the planned thirty 22-min sessions, groups were compared with EEG, a stop signal task, a reversed continuous performance task and with questionnaires. Results showed that in the participants who were blind to group inclusion, there was no trend towards a beneficial effect of neurofeedback. The authors opined that the results might indicate a possible lack of effect of neurofeedback when one accounts for non-specific effects. However, at the very least, this claim would require evidence that learning took place, while the pooling of the diverse protocols for group analysis, their lack of validity and atheoretical basis, and potentially the double-blind procedure, were likely to mask effects on outcome. Furthermore the outcome was at odds with the clear majority of evidence above, not to mention evidence of one-session learning. If learning is not being achieved over the early sessions then the approach is lacking in some way.

It is of fundamental importance that learning is scrupulously monitored throughout and adjustments made to learning contingencies where necessary, which may be documented.

3.4.2.3. Predicting learning. There has been one useful two-experiment methodological initiative (Weber et al., 2007) attempting to predict across-session learning ability on the basis of the early sessions of an SMR amplitude protocol (C3,4). The

inhibits 'chosen to exclude artefacts' were low theta (3–5 Hz), beta 2 (22–30 Hz) and gamma (45–60 Hz). In the first experiment participants ($N = 13$) received twenty-five daily sessions with eight 3-min blocks, and in the second experiment ($N = 14$) thirty sessions of five 5-min blocks. Reward thresholds were individually adjusted daily. In the two samples only 7/13 and 6/14 provided evidence of learning according to their learning criterion of an 8% increase between sessions 1–2 and the last five sessions, coupled with a mean SMR amplitude increase across the twenty-five sessions. In the first experiment, after introducing smoothing over successive blocks of three sessions to overcome intraindividual variance in the EEG, it was not until the eleventh session that learning was predicted. Using medians, and with the first three sessions as a baseline, the percentage increase of eight successive subsequent blocks (up till session eleven) was obtained and the standard deviation subtracted. Using this formula for predictive purposes, all participants in the second experiment were correctly identified as learners or nonlearners, while for the first experiment only one participant, a learner, was misclassified and would have been correctly classified at the thirteenth session.

This is a welcome strategy, but the generality of the outcome is limited by the high incidence of non-learning and the slow rate of learning achieved in those who did learn, for as this review indicates the majority of SMR studies have achieved successful post-training outcomes in the majority of participants and with fewer than eleven sessions and some with one-session learning.

3.4.2.4. Individual adjusted frequencies. There is good evidence that the delineation of spectral bands varies between individuals and varies with age (Klimesch, 1999). Klimesch has promoted an individual adjusted frequency method which has been adopted in some neurofeedback studies (e.g., Bazanova et al., 2007; Raymond et al., 2005a,b). While Escolano et al. (2011) adjusted the upper-alpha band each day in a study of five consecutive daily sessions. As yet no direct comparisons have been made between training with and without this adjustment in order to assess its value for neurofeedback. The adjustment makes good sense and should be widely adopted, and for further discussion see Bazanova and Vernon (2014).

3.4.2.5. Personality and individual differences. Differences in learning ability have been elucidated with personality inventories in two studies. Hardman et al. (1997) in examining the ability to shift slow cortical potential negativity recorded frontally from hemisphere to hemisphere in students found that Introverted Withdrawal characterised those students with the stronger rightward shifts, a directionality in keeping with hemispheric personality differences (Gruzelier, 1996).

Witte et al. (2013) found that Locus of Control informed the facility with which students learned to elevate the SMR amplitude. Locus of control assesses whether internal or external agencies preferentially control one's behaviour, with in their study a particular reference being made to technology. Interestingly confidence in controlling technical devices actually hampered neurofeedback learning. This was interpreted as being in keeping with the sensory motor rhythm signifying a relaxed attentional focus, so that a detached attitude to mastery rather than one of active striving was the more effective in promoting learning. Such an attitude should be a fundamental rule in training neurofeedback learning.

3.4.2.6. Differences in sustaining attention; 'less is more'. Of relevance for considerations of experimental design, participants may soon exhibit evidence of learning but fail to sustain learning throughout individual sessions due to a falloff in sustaining attention. This first came to light in elucidating the lower achievers among some schizophrenic patients (Gruzelier et al., 1999). While

all of the twenty-four cooperative outpatients whose symptoms were in relative remission were found to be capable of learning to shift their lateral asymmetry in slow cortical potentials from hemisphere to hemisphere, within-session analyses indicated that those with the poorer overall performance in learning, while not demonstrating a problem in learning per se, were unable to sustain their learning ability in the last block of each of the ten training sessions. The sessions were too long for them. This was in keeping with poorer sustained attention, often held to be a characteristic of schizophrenia.

Similarly Ros et al. (2009) basing their group division on the degree of gain in microsurgical technique in trainee ophthalmic surgeons, found that in the lower technical improvement group there was a 10% fall off in the later sessions in the SMR/theta ratio. This was found to be due to an increase in theta amplitude, whereas the training goal was to inhibit theta amplitude.

Tiredness is a largely unrecognised feature of neurofeedback learning. Self ratings of high achieving music conservatoire students administered the Thayer Activation-Deactivation scale (1967) before and after 15-min SMR ratio and beta-1 sessions, administered in a counterbalanced order, disclosed that Tiredness increased following each 15-min protocol whereas Calmness ratings were differentially affected and were improved by SMR ratio training (Gruzelier, 2014c).

The length of neurofeedback sessions has been guided by the received wisdom that after about 20-min fatigue sets in for the majority. When individual differences are taken into account it is quite likely that some participants will tire more quickly than others. The analysis of periods within sessions should ideally be an ongoing process, guiding the choice of the optimal session length for the individual, and adapting it where necessary. Individual differences in speed of learning have not been investigated but this also is likely to be informative; some investigators have set out to demonstrate learning over hours?

3.4.3. Conclusion

The striking incompatibilities between existing studies in the incidences of non-learning compel a close consideration of training practices in general, as well as the likely differential impact of learning schedules on protocols. This section has considered practical design issues that will inform learning for the individual such as the number of sessions, intervals between sessions, and individual adjusted frequencies which should become a necessary design feature. Then there is the yet to be investigated need for top-up consolidation of learning in some cases.

Individual differences in learning will be informed by consideration of variations in speed of learning, build up of fatigue within sessions, motivational differences within and across sessions. Personality differences are likely to prove to be an heuristic aid for designing learning schedules along with sex differences yet to be investigated, and the impact of the menstrual cycle (Muravleva et al., 2012).

One can anticipate, now that necessary validation work is well underway and which has understandably been of a nomothetic nature, that idiographic approaches will increase (see Unterrainer et al., 2013a,b) bringing a keener appreciation of individual differences in order to achieve more effective learning for the individual and more effective scientific outcomes overall. This will likely be stimulated by the needs of the clinician given the predominantly practitioner applications of neurofeedback.

3.5. The participant's brain

3.5.1. Trainer-participant interface

What may sometimes be wanting, perhaps more so in non-clinical studies, is the vital ongoing interface between the trainer,

the participant and their EEG. This should be done through a flexible adjustment of threshold, and the monitoring of the participant's motivation, tiredness and capabilities. This is to ensure that learning is achieved and that agency is facilitated and maintained. As should be abundantly clear from this review, the field is at too early a stage to recommend automatised training overall, should that be desirable, at least with faster-wave protocols. Similarly the ideal-world requirement of double-blind training is undesirable at this early stage of demonstrating and understanding the dynamics of neurofeedback learning, and should take precedence of experimental design considerations that may compromise learning.

Clinical skills may favour engagement. In patients compromised by intractable epilepsy [Stermann \(1996\)](#) has estimated that across studies, involving a total of one hundred and seventy-four chronic epileptics, eight-two percent benefitted in seizure control from neurofeedback. And this high percentage did not in addition include those who were capable of learning but who found no relief from their epilepsy. If learning is inferred, at least in a majority, the question arises how is it that some laboratory studies report high numbers of non-learners, and one study reported no learning after sixteen sessions. While it is true that more sessions are typically given in the clinic, there is substantive evidence of learning in the laboratory in up to ten sessions (Section 3.3.1.1, [Table 1](#)).

The participant-trainer interface is critical and is insufficiently appreciated. [Glannon \(2013\)](#) in a special issue in *Brain Topography* on 'clinical and ethical implications of neuromodulation techniques' writes informatively on this, which has in important respects equal relevance to nonclinical studies. "While the effects of NFB on brain activity and perception are partly due to unconscious conditioning mechanisms, this does not imply they are beyond the subject's control. Besides, the subject in NFB must consciously initiate the process in learning how to manipulate the information before unconscious conditioning takes over. The critical first part involves conscious cognitive effort. Equally important, how effectively the subject uses NFB to modulate brain activity depends on how well the practitioner trains him to do it. So, as with BCIs, the interaction between the subject and the practitioner is critical to the success or failure of the technique and to restoring and maintaining the subject's agency and autonomy." "Using information about the brain to modulate its activity involves more than the practitioner explaining and the subject knowing about the mechanical and neurophysiological features of the technique. It is a biopsychosocial process. The interaction between the learner and trainer is a social encounter formed by beliefs and expectations ([Benedetti, 2011](#)). How the trainer motivates and in stills confidence in the subject in making him believe that he can modulate brain activity can make a significant difference as to whether the subject can achieve these goals. Conceived within a biopsychosocial model, the role of the trainer is critical in effecting a therapeutic outcome and thereby promoting the agency and autonomy of the subject" ([Glannon, 2013](#), p. 8).

3.5.2. Phenomenological report

Phenomenological report, a data source often overlooked ([Piffer, 2012](#)), may also be a useful guide to validating learning. As mentioned (Section 3.2.1.1) there was a close parallel between the session in which the learning asymptote was reached and the session when participants consciously identified the state in which they could exercise control retrospectively, here of the SMR/theta/beta/ratio, see [Fig. 5](#). The question posed was "At what stage did you recognise the mental state we were seeking in you?" Furthermore the one session lag between the two groups distinguished by a 3D versus a 2D training context was paralleled by a lag in the perceived control of the EEG. Phenomenology can also shed light on outcome improvements as seen with elite music performance ([Edge and Lancaster, 2004](#); [Gruzelier, 2009](#); Part II) and

in school children with well-being and the transfer to classroom, school and home ([Gruzelier et al., 2014a](#)).

Self-report ratings about application to the neurofeedback learning process such as attention, mood, motivation and so on may also inform individual differences in learning between participants, while within sessions they may elucidate variability and outlying performance. Phenomenological reports when obtained with school children were in favour of transfer ([Gruzelier et al., 2014a](#)) supporting ecological validity, which is routinely examined in ADHD research through parent and teacher ratings, and is a necessary requirement of therapy.

3.6. Process and procedural initiatives and clarification

3.6.1. Fractionation of learning from mastery

Though the review has on the whole disclosed extensive evidence of congruent learning functions for the various protocols, by no means is learning reliably disclosed within and between sessions and between baselines. Furthermore differences have been shown in the form that learning has taken, as well as in methods of calculation, not considered in this review. However, it likely that some differences will become explicable when the training process is deconstructed. 'Learning' in the neurofeedback field, where it is not simply the elephant in the room, is being treated as a global concept, and requires refinement through fractionation.

The differential effects of positive versus negative feedback on frontal theta (4–8 Hz) versus beta (18–24 Hz) amplitudes have been examined by [van de Vijer et al. \(2011\)](#) from feedback-based response learning with a button-press time-estimation task. They found that reward valence was differentially associated with the two bands. Frontal theta predicted learning following feedback, but in line with involvement in cognitive control and reinforcement-learning after errors (e.g., [Cavanagh et al., 2010](#)) frontal theta was of higher amplitude after negative feedback. Frontal beta predicted learning after both positive and negative feedback, and was of higher amplitude after positive feedback, in line with the notion that it represents maintenance of a status quo ([Engel and Fries, 2010](#)). Connectivity was also increased following negative feedback, with theta as the carrier in a larger network signifying adjustment between right lateral prefrontal, medial frontal and sensorimotor sites (see [Cavanagh et al., 2010](#)).

Of critical importance is the need to isolate learning from what is the ultimate goal of training the mastery of self-regulation, as well as from the non-specific variables. As yet there has been little attempt in EEG-neurofeedback studies to unravel these processes. Separation may be assisted by including transfer trials where the feedback of reward is excluded, or conceivably by contrasting trials before and after learning has reached an asymptote. While transfer trials have been conventionally included in slow potential feedback as a validity marker (e.g., [Strehl et al., 2006](#)), and [Cannon et al. \(2009\)](#) included transfer trials in their intracranial LORETA studies, as yet transfer has not been subjected to a differential process analysis from either learning or from self-regulation trials without reward.

In this regard there is an informative fMRI feedback study of [Haller et al. \(2013\)](#). They set out to differentiate neurofeedback learning from self-regulation. Twelve participants were taught in four weekly sessions to regulate activity in the auditory cortex through feedback, and later to self-regulate without feedback, and there was a counting backwards control for the cognitive demand in self-regulation. A data driven approach disclosed that the initial learning phase led to gradual connectivity changes in a widespread network, which became more restricted during the transfer phase. Of seventeen functional networks, in five of them connections with the auditory cortex hub were modified during learning. These related to the brainstem, higher-level vision for tracking feedback

and attention, and low-level visual, insular and working memory areas. Self-regulation was differentiated from learning, firstly, by connectivity decreasing between the auditory network and the high level vision areas and attention regions which was consistent with the reduced attentional demands following mastery. Secondly, there was an absence of those changes in connectivity that were concerned with working memory, introspection and reward during learning.

3.6.2. Connectivity training

In the afore mentioned report among Hallet et al's conclusions the regulation of brain connectivity was endorsed "as an explicit target of neurofeedback training for future applications." fMRI has cast light on networks and a functional-systems perspective of brain dynamics, which necessitates a more sophisticated approach to neurofeedback. As yet little research has been undertaken in examining or training connectivity in EEG neurofeedback, though the approach is being undertaken by practitioners. Connectivity examined with EEG coherence methods as an outcome of neurofeedback was reported by Keizer et al. (2010a). Coherence between Fz and Oz disclosed, inter alia, important temporal oscillatory dynamics in the learning process, but was not the main thrust of the report. Cannon et al's intracranial training assisted by LORETA also cast a light on beta-1 and beta-2 as network carriers.

Lateral asymmetry training offers one approach to connectivity training. Hemispheric asymmetries of function have a venerable history (e.g., Corballis, 1987) with implications for psychopathology (e.g., Gruzelier and Flor-Henry, 1979; Gruzelier, 2002). In fact the potential of neurofeedback for schizophrenia drew the writer into the neurofeedback field (Gruzelier et al., 1999). Hardman et al. (1997) as a prelude to the patient study demonstrated that students with ten sessions of training were capable of shifting the frontal (F3,4) asymmetry in slow cortical potentials in either direction. Adopting this within-subject bidirectional strategy, in a feasibility study schizophrenic symptomatic patients were found to be capable of learning to shift slow cortical potential central (C3,4) asymmetries in either direction with just ten sessions of training. In one patient, on returning after a three month psychotic episode, learning was found to be saved on the very first session (Gruzelier et al., 1999).

Most asymmetry training has focussed on putative valence differences between the frontal lobes on a simplistic left-positive, right-negative axis, and with a particular focus on negative affect in depressive disorders with some affirmative results (e.g., Rosenfeld et al., 1995; Baehr et al., 2001; Choi et al., 2011), and see dual imaging feedback (Section 2.4). Unidirectional changes in two student studies have been compared by allocating students to rightward versus leftward asymmetry frontal alpha asymmetry groups. Allen et al. (2001) with a mixed outcome gave (alpha (8–13 Hz) frontal (F3,4)) asymmetry training to eighteen dextral women for five consecutive days along with daily mood self-ratings bookended by ratings of emotive film clips combined with EMG recording from cheek muscles (positive affect) and brow muscles (negative affect). Only five in each group exhibited learning. There were preferential effects in the rightward group in relation to learning, ratings and the film clips, whereas learning in the leftward learners was limited. Peeters et al. (2013) in a single session similarly administered alpha (7.8–13.1 Hz) F3,4 training to dextral women ($N=40$) allocated to leftward and rightward groups. While the group asymmetry changes were the mirror image of one another, the results were difficult to fathom, for in the first five-min block both groups showed an unexpected asymmetry shift opposite to the training goal, which reversed across the next four blocks followed by a significant return to baseline. The effects extended frontally to theta and beta-1, but they were topographically specific in so far as they were not found centrally (C3,4) or parietally (P3,4).

One impression from these asymmetry studies is that SCP training may be more easily learned than frontal alpha training. Connectivity neurofeedback holds particular promise for the future, and Sacchet et al. (2012) have demonstrated its potential with MEG with a potential role in BCI control.

3.6.3. Multi-modal brain imaging feedback

The combined methodology of fMRI and EEG can elucidate the nature of EEG-neurofeedback's impact on the central nervous system (section 2), especially connectivity in networks (Kinreich et al., 2012; Ros et al., 2013), and with guides for EEG-neurofeedback therapy (Kluetsch et al., 2014). This aside, modelling with fMRI (Meir-Hasson et al., 2013) can inform EEG electrode placements, and in turn the EEG can inform a higher temporal resolution than those of fMRI. In fact Zotev et al. (2014) have proposed that following their demonstration of dual modality feedback tasks, the tasks may be more effective in combination than either one administered separately. Certainly when in tandem with fMRI and following initiation of a therapeutic improvement, as has been demonstrated with fMRI-neurofeedback in intractable depression (Linden et al., 2012), EEG-neurofeedback could follow fMRI-neurofeedback informed by the fMRI regarding electrode site(s) and protocol.

The combined methodology and opportunities for integrative therapy hold exceptional promise, and the combining with other imaging modalities will also be instructive.

3.6.4. Ratio deconstruction when training multiple bands simultaneously

Where ratios between EEG bands are trained, exploring learning in the various bands individually can be informative (Vernon et al., 2003; Gruzelier et al., 2013a). In many instances, as with delta, theta, beta2 and gamma, there has been a tendency to view the bands simply as an aid to minimising the occurrence of movement and muscle artefacts? This is to overlook their cognitive and affective significance, information which can provide a useful guide to the facilitation of learning, and more critically perhaps, as a source of insight regarding impediments in the learning process.

Considering SMR ratio training as one example, along with the increase in SMR amplitude the aim is to decrease theta and high beta. High-beta activity is important because inter alia it indexes an activated state associated with over-arousal, tension and anxiety, in line with the inverted-U relation between arousal and performance – the Yerkes-Dodson 'law' (Lindsley, 1952). This is antithetical to the SMR state which governs a relaxed attentional focus. In fact a reduction in fast beta band activity in frontal scalp regions was found to be the long-term outcome of A/T training (Egner et al., 2004), and was entirely congruent with the induction of deep relaxation, hypnagogia, and stage I sleep. Research on the behavioural significance of the beta band is regaining attention, and as such will plug a gap in much contemporary neurofeedback practice and research (e.g., Fries et al., 2001; Haenschel et al., 2000; Özgören et al., 2005; Nikulin and Brismar, 2006; Ritter et al., 2009; Jenkinson and Brown, 2011; van de Vijver et al., 2011; Athanasiou et al., 2014), for its role as an activation index is an oversimplification.

The implications of training down theta are not well understood. Consider the implications of inhibiting theta in the eyes-open state. With eyes open the generators of theta are complex with at least a thalamo cortical system associated with arousal such that the more prevalent theta becomes the more tiredness and drowsiness, and with fronto-limbic theta circuits having positive associations with behaviour. Vogel et al. (1968) and Schachter (1977) have reported two different types of posterior theta, one that is of low irregular amplitude associated with drowsiness, and another of higher amplitude associated with attention. In the eyes closed state evidence from A/T training studies suggests that anterior and posterior theta have different generators (Egner and Gruzelier, 2004b).

SMR ratio and A/T neurofeedback were compared in a single-case treatment study also combining psychotherapy in a student suffering psychological disintegration and anhedonia following long-term drug misuse (Unterrainer et al., 2013a,b). Correlations were obtained between the various spectral bands and psychiatric ratings. Highly significant correlations were found across the ten sessions between practitioner ratings and theta recorded during SMR ratio training in the direction of the poorer the mental state, the higher the eyes-open theta amplitude, while no relations were found with eyes closed theta during the A/T protocol.

Positive outcome gains can be forthcoming from SMR ratio training without completely successful theta inhibit training, as was found in school children (Gruzelier et al., 2013a). Furthermore, as outlined in Part I, Section 2.1. SMR training does not require inhibits. Indeed the field would profit from a comparative study of SMR training with and without inhibits. Deconstruction may be informative in other ways too. Whereas Vernon et al. (2003) reported that a group assigned to SMR ratio training disclosed successful cognitive gains, the group assigned to theta/alpha/delta ratio down-training showed no evidence of learning. But consideration of theta and alpha amplitudes separately indicated that though the aim was to elevate theta amplitude and suppress alpha amplitude, what had occurred was successful alpha enhancement which was the opposite to the training goals (Section 2.2.1).

It behoves trainers and investigators to be vigilant and monitor learning in ratio bands simultaneously, and for investigators to relate differential effects to outcome.

3.6.5. Tonic EEG

The majority of evidence suggests that it is the tonic EEG that is altered by neurofeedback, and this is in the theoretical direction of the trained enhancements, though not necessarily in the trained band or location. Hanslmayer et al. (2006) found that the successful learning of up-training SMR amplitude transferred to the post session EEG, but not during the subsequent cognitive assessment, implying carry-over of learning to the tonic not to the phasic EEG. Ros et al. (2010, Section 2.1) found that a path analytic statistic determined that it was the effect of neurofeedback on the tonic EEG that mediated the training influences on TMS paired-pulse parameters.

This conceptualisation may have a bearing on experimental procedures and their outcome. To give one example, in setting out to train-up midline frontal theta Enriques-Geppert et al. (2013) sought a marker of phasic theta in view of the rhythm's correlates with executive control. Innovatively they based this individually-adjusted theta band on recordings taken during pre-training executive function tasks. This phasic rather than tonic theta estimate may have had an impact on the complex results (Section 3.2.2.4).

The alteration of the tonic EEG by training also informs learning indices such as within-session and across-session baseline ratios, and the choice of the tonic baseline selected (Section 3.1.2.2). Escolano et al. (2011), with alpha-2 training, by comparing an active with a passive resting baseline found band specificity only with the active one (Fig. 4), confirming Zoefel et al.'s (2011) finding.

3.6.6. Directional training strategy

All of the behavioural gains from EEG-spectrum training reported in Parts I and II have been predicated by unidirectional training predictions. The choice of the up- or down-training of a particular band or ratio was based on contemporary neuroscience, or on evidence of beneficial clinical outcomes. These predictions have bypassed the historical interest in associating learned control with the capability of being able to regulate a rhythm, both upwards and downwards. Indeed what sense would bidirectional training make if the prediction was that a unidirectional change

would enhance performance? In order to say improve memory, would one set out to both improve and impair it?

Conceivably in a pathological context, one could certainly envisage that a regulatory mechanism was at fault, and formulate a specific hypothesis that bidirectional training could be advantageous. For example, this could be reasoned with regard to hemispheric imbalance in schizophrenia, where there is evidence of syndrome-dependent leftward and rightward lateral shifts (Gruzelier, 2002) which psychotropic drugs normalise or reverse (see for review Gruzelier et al., 1999).

In the context of methodology and validation, bidirectional training has important properties. It provides the opportunity for dissociation; enabling the potential demonstration of how training in one direction may enhance an outcome while training in the other may impair it (e.g., Salari et al., 2013), or doubling dissociation where tasks are chosen that have opposite effects. Dissociation is especially effective when examined within subjects where it is free from individual difference confounds that may cloud the interpretation of group effects.

Accordingly bidirectional training has important virtues regarding questions of validity, but its application for functional enhancement requires a more considered approach.

3.6.7. Is conscious awareness necessary?

Self-efficacy is the primary goal in feedback learning. While it is commonly considered that conscious realisation is involved, and indeed introspective awareness of the state sought in training has been found to be tied temporally to the session in which the learning curve reached an asymptote (Fig. 5), consciousness may in fact not be a prerequisite. Clearly in A/T training, the participant in reaching stage I sleep is not fully conscious of the theta/alpha cross-over state realised. Furthermore it is not an altered hypnagogic state that is being recognised and produced in performance. Analogously the state of flow in performance is not totally at the will of the performer. A consideration of protocols to include animal studies has led Birbaumer et al. (2013) to view neurofeedback as learning an implicit skill and involving the cortico-basal-ganglia-loop. They concluded that neither explicit mental strategies nor instructions were required for BOLD control in successful fMRI feedback. Furthermore mental strategies may retard learning (Hardman et al., 1997), for participants instructed to use positive and negative emotions to facilitate frontal asymmetry shifts were found to be less successful than those who accomplished lateral shifts without given strategies. There is much to be said at this stage, while the issue is unresolved, to let participants 'go on their own journey'.

4. Conclusion

While much has now been achieved in providing a foundation for EEG-neurofeedback, and there is an impressive array of outcome gains from controlled studies in the optimal performance field (Parts I and II), and to some extent in the clinical field, it would be foolish to conclude that a foundation of knowledge has been realised enabling textbooks to be written. But given the history of the field no doubt they will be written at this infantile stage, for sundry reasons. While many studies found outcome gains, it must not be overlooked that null results in many of these studies were also commonplace from assessments that on theoretical grounds should have improved too.

It surely must be apparent that on numerous counts a highly complex picture is emerging. Consider the variety of learning indices extant in order to establish that neurofeedback learning has actually taken place in a given study? What should be the ultimate goal in demonstrating learning? Between session learning or progressive learning in pre-session baselines, or learning at

follow-up, and at what stage is learning established – when a plateau is reached, or later at some point of its reinstatement, or during transfer trials, and so on? For undisclosed reasons learning may sometimes be slow; in the SMR amplitude study of [Doppelmayr and Weber \(2011; Pt I, Section 2.1.3\)](#) it took 26–30 days for learning to differ from baseline. Furthermore one healthy group receiving reduction in the theta/beta ratio training, a protocol successful in ADHD trials, failed to learn? Then consider the individual differences in disclosing evidence of learning, and in the time taken to achieve it. What are the appropriate training-session scheduling contingencies in order to optimise learning and to be economical of time and a client's finances. Also there are considerations of what protocol to select for what process is to be targeted, and what inhibits to use or should they be dispensed with, and where to position the electrode(s)? Intensive research is required to hone protocols for maximal effect and efficiency, while observing learning theory principles ([Sherlin et al., 2011](#)).

The behavioural significance of EEG oscillations is now receiving deserved attention, but until recently it attracted only a handful of dedicated researchers. If a tiny fraction of the resources channelled to event-related potential research, or even just to the P300, had been devoted to elucidating EEG rhythms we would be further ahead, but currently we are at the foothills of understanding the significance of brain oscillations. As has been repeated throughout, the underlying heuristic in interpreting the EEG spectrum, one of an arousal continuum: low arousal/slow rhythms to high arousal/fast rhythms, and with implications for performance that follow the classical inverted-U curve of the relation between performance and arousal, e.g., inattention, optimal attention, impulsive attention ([Lindsley, 1952; Duffy, 1957](#)), is outmoded. These premises are simplistic when considered in the context of contemporary neuroscience (e.g., [Varela et al., 2001; Roy John, 2002; Engel and Fries, 2010; Basar, 2011](#)), and in the context of the dynamics of neurofeedback reviewed here and the diversity of outcome gains – consider the consequences of training posterior theta up or down for one example. While ‘arousal regulation’ is indeed a fundamental property, it does not convey the intricacy and complexity of spectral oscillatory functions. There is not the scope to review this, but the young scientist should be aware that fashions of what is, and what is not, important in science may wax and wane for non-scientific reasons.

If one thing is certain, at this stage a comprehensive grounding in neuroscience is required to understand and implement a menu of protocol options with participants, a requirement that from an ethical standpoint calls into question a majority of contemporary training courses. This grounding should be coupled with interpersonal skills, for at the participant-trainer interface we are dealing with a biopsychosocial process ([Glannon, 2013](#)). That particular interface is critical for the success of the self-regulation learning process. As with hypnosis, while there are fundamental differences in hypnotic susceptibility which advantageously were historically known about from day one, by elucidating the course and stages of hypnotic induction ([Gruzelier, 2006; Oakley et al., 2007](#)) those processes that facilitate, and conversely those that handicap the hypnotic induction process could be determined and acted on; an experienced therapist knows that an unresponsive participant is rather rare. The same is likely to be true of neurofeedback learning once the underlying processes are disclosed, and non-learning relegated to history.

Among important next steps will be tracing the development of the learning, self-regulation and transfer processes on a session by session basis for which a full topographical EEG and other imaging methods will be required. Then there is the demonstration of enduring transfer to the real world. Typically the representations of brain waves in training the participant has been in the form of traces, histograms, computer games or entertainment DVDs,

unrelated to the context of the cognitive, affective, behavioural or clinical outcome. An ecologically relevant and immersive learning context is of potential value, as demonstrated in our training of actors with a computer rendition of an acting space, which additionally they learned to exert control over, and this control was programmed to be contingent on the mastery of their SMR ratio enhancement ([Gruzelier et al., 2010](#)). Furthermore the degree of immersion showed small but preferential benefits through comparing a 2D with a 3D rendition of the theatre auditorium, advantaging the latter.

Once resources are forthcoming it will be necessary to estimate the long term consequences of optimising performance, as shown with ADHD ([Gani et al., 2008; Gevensleben et al., 2009](#)), as well as the consideration of top-up training, yet to be voiced. Leading researchers in ADHD neurofeedback trials are only too aware that it has been ‘a long and winding road’ ([Arns et al., 2014](#)), and will continue to be so for the foreseeable future – heterogeneity bedevils traditional and evolving clinical nosologies, and ADHD is no exception. While integrative therapy, which must surely be the future, has yet to be explored systematically in conjunction with EEG-neurofeedback.

While the ‘EEG-biofeedback’ field has re-emerged as ‘EEG-neurofeedback’, with an exponential growth in publications in the last two decades ([van Boxtel and Gruzelier, 2013](#)), this is but a first step, though this step has provided demonstrable evidence of validity and mediation, along with important outcome gains covering a wealth of domains in the optimal performance field to accompany the growing evidence of benefits from clinical trials. But as this review has set out to lay bare, there are as many questions as answers. Recommendations for future research have been given throughout; the review has focussed on general principles and not issues such as feedback sensory modality, or learning contingencies, which while of central importance are not reported comprehensively or investigated systematically enough to provide the basis for review, and the same goes for technical issues such as advances in artefact rejection.

Notwithstanding, the optimal performance studies in this three-part review represent a renaissance in the EEG-neurofeedback field through a comprehensive second generation of work. On the basis of this any prevalent scepticism about neurofeedback may be put firmly to rest, and dissolve embarrassment that has led to hiding behind the BCI label, or ignoring EEG-neurofeedback altogether, or unthinkingly dismissing it out of hand. These are all attitudes encountered amongst reviewers in the Society of Applied Neuroscience (SAN) special issues on Applied Neuroscience and on Neurofeedback, of which this special journal issue is one (see also *Biological Psychology*, 95, January 2014, Neurofeedback; *International Journal of Psychophysiology*, Applied Neuroscience: Empirical and Methodological Studies on Psychobiology, Development and Pathology, in press). However, this is but a foundation on which to build in order to advance the field, and in order to realise the promise of such noninvasive and relatively cheap methodology for optimising function in health and pathology and with the promise of important pedagogical applications. Though the behavioural outcome and methodological studies raise more questions than answers, there is no denying the potential outcome gains, and not to overlook the inherent strategies for advancing scientific understanding of brain oscillations by providing controlled approaches for their manipulation.

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