# Neurofeedback:
# Challenges, Applications, and Opportunities for Education

**by**

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## Abstract

This thesis reviews the current state-of-the-art in neurofeedback research and then goes on to consider three fundamental problems for the psychology of education: first, to what extent can the mind cause changes in the brain at will; second, to what extent can studies in neurofeedback be considered to have validity; and third, given positive outcomes for the first two, to what extent can students become more adept at neurofeedback. Opportunities of neurofeedback for education are contingent on addressing all three of these problems.

**Keywords**: Neurofeedback; EEG; validity; educational implication and opportunity; Educational Neuroscience; ENGRAMMETRON

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Blessings!

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## List of Acronyms

| | |
|---|---|
| ADHD | Attention-deficit hyperactivity disorder |
| APA | American Psychiatric Association |
| ASD | Autism spectrum disorder (or autism) |
| BCI | Brain-computer interface |
| BESA | Brain Electrical Source Analysis |
| EEG | Electroencephalograph |
| EMG | Electromyogram |
| EOG | Electrooculogram |
| FC | Frontal cortex |
| FFT | Fast Fourier Transform |
| fMRI | Functional magnetic resonance imaging |
| GSR | Galvanic skin response |
| IAF | Individual alpha frequency |
| IEP | Individual Education Plan |
| LD | Learning disability |
| LH | Left hemisphere |
| MEG | Magnetoencephalography |
| MMH | Monomethyl hydrazine (convulsion inducing chemical substance) |
| OC | Occipital cortex |
| OCD | Obsessive-compulsive disorder |
| RH | Right hemisphere |
| SMR | Sensorimotor Rhythm |
| TC | Temporal cortex |

# Chapter 1.

# Introduction

Is it possible that attending to one's own brain activity in various ways could open a new world of educational possibilities in the 21st century? After introducing and reviewing the state-of-the-art in neurofeedback in Chapters 2 and 3, this thesis addresses this question in the affirmative, with several important qualifications and conditions. Addressing this question in the affirmative also involves engaging some very difficult issues at the very heart of philosophy, science, and engineering.

Imagine that our minds really can control matter. Not in the sense of bending spoons, or levitating rocks, but by controlling the activity of our own body, such as raising an arm, or more to the point that concerns us here, by using our minds to change the activity of our brain in similarly deliberate and determined ways. As simple and straightforward as this may sound, it presents us with our first challenge. How is it that our minds can have an effect on our brains? This is a special case of the famous mind-body problem. For any opportunities that may exist for neurofeedback in education requires that it is possible for the mind to have a controlling effect on brain behaviour. This is *the problem of causality*.

So the first issue that we must address is whether the mind can exert a controlling effect on matter, and in particular, brain matter and the neuronal activity that it supports. This problem of causality is a philosophical problem, in that traditional and contemporary science assumes that our minds cannot be observed and measured in a third person sense; yet we all agree that we have one. Hypothesizing that a study of the mind can be operationalized scientifically by

observing and measuring brain and brain behaviour, this problem of causality regarding neurofeedback presents us with a second fundamental challenge for neurofeedback in education. If our minds do not affect brain activity, how can neurofeedback be taken seriously? This is *the problem of validity*.

So the second issue that we must address is whether research in neurofeedback is observing and measuring what we intend to observe and measure. The problem of validity directly implicates the manners, extent, and degrees to which minds can be shown to exert effects over brains and brain activity. Addressing the problem of validity is another important step in assessing research in neurofeedback. These first two problems, the problems of causality and validity, are addressed and considered in Chapter 4.

Given that it is possible for minds to have an effect on brain and brain behaviour, and that research in neurofeedback is observing and measuring what we intend to, what are the limitations of neurofeedback? If the mind can only make limited changes in brain activity at a slow rate of speed, such changes, accordingly, may be of limited value. This is *the bandwidth problem*, and it is addressed and considered in Chapter 5. Also considered in this chapter is the further question as to how one might best approach and attempt to resolve the bandwidth problem. Using EEG equipment and neurofeedback software developed in the ENGRAMMETRON, an experimental design is proposed which has the potential to shed light on the problem.

Identifying and assessing opportunities of neurofeedback for education are contingent on addressing the aforementioned three problems. If the mind has no causal effect on brain activity, then any perceived benefits of neurofeedback would be either illusory or must be attributed to other factors. Irrespective as to whether minds can exert causal effects on brain activity or not, if such effects cannot be operationalized, then the validity of studies in neurofeedback is still at risk. Assume that neurofeedback studies can be validated, then, opportunities for neurofeedback

in education could be vastly expanded—even if the mind alters brain activity in a manner such that the rate of information transfer could be expanded a little.

Taken together, this thesis identifies, articulates and addresses each of these three fundamental problems for research in neurofeedback and the challenges they present, in order to more readily identify and assess the potential opportunities for neurofeedback in education in the 21st century. By emphasizing major concepts and methodological issues of neurofeedback, pertinent questions such as "what is neurofeedback and why should it matter to education" as well as "what pitfalls, limitations and potentials of neurofeedback are there for education" are explored in Chapter 6.

A summary of the thesis is provided in Chapter 7. The problems of causality, validity, and bandwidth are discussed at the forefront. To extend the potential applications of neurofeedback as a technique for optimizing learning and behavioural prospects in educational settings, this thesis aims to:

1. provide better understanding of the foundations and the characteristics of brain behaviour via neurofeedback
2. examine existing evidence of neurofeedback applications in the scientific literature
3. explore both challenges and potentiality of neurofeedback research
4. employ neurofeedback as a practical research and learning tool via *ActiMatt* software
5. suggest implications of adopting the neurofeedback technique in educational settings

# Chapter 2.

# Observing 'Brain Waves'

To address the three fundamental problems of causality, validity, and bandwidth, for research in neurofeedback, it is important to first provide some background regarding neurofeedback, along with aspects of the brain and brain behaviour that are implicated in neurofeedback.

The attempt to solve the mind-body interaction, concerning the relationship between the mental and the physical, has been an enduring pursuit in human science. Throughout decades, philosophers, psychologists, and physicists suggest different theories to explain how the mind is related to the physical world of cause and effect that leads from genes and environment, to the mind and then to action. Without advanced technology, direct observation of the human brain is impossible. As a result, philosophers and scientists have long been relying on epistemology to develop theories and arguments in deducing causality between the physical and the nonphysical, with a hope to solve the mind-body problem in a pure rational manner. A credit to technological breakthrough in the early 20$^{th}$ century, renewal of interest in the relationship between the human mind and the physical body rekindled a revolutionary focus on studying mental phenomena such as attention, perception, memory, consciousness and thinking in general. Combined with technological advances such as electroencephalography (EEG), continuous brain electrophysiology can be measured in a finer grained and observable manner. Electrical activities of the human brain then can be linked to different mental states, cognitive processes, and accompanying behavioural performances.

Using EEG, neurofeedback may serve as an innovative technique that can be used to help bridge the gap between learning and teaching experience. Based on the assumption that different brainwave frequencies can exert different mental and behavioural effects, the ability to learn self-modulating or self-regulating electrocortical signals of a specific mental state may enhance subsequent performance of different tasks in a desirable manner. On the other hand, training on voluntary alteration of brain activities can facilitate conscious awareness of our mind-body interaction, thereby improving physical and mental fitness as well as well-being. By providing a neurophysiological account of self-regulative learning, research on neurofeedback may open up potential opportunities for reconciling these mind-body tensions and thereby offer a revolutionary force in education.

## 2.1. Electroencephalography (EEG)

To understand how neurofeedback serves as a technological innovation that works directly with the brain, it is helpful to understand how 'brain waves'—oscillations of electrical potential across different brain regions—are observed, measured, recorded, and displayed using electroencephalography (EEG). Although other methods, such as magnetoencephalography (MEG) and 'real time' functional magnetic resonance imaging (fMRI), can be used, they are more expensive and less practical to utilize at present, and hence we shall restrict our considerations to EEG.

EEG is a recording method to measure brain functioning via electrical activity of cortical nerve cells through electrodes attached to various locations on the scalp. It is an electrophysiological tool that is often used in contemporary neurocognitive research, and is by far the most commonplace tool used in neurofeedback research. In general, a raw EEG recording is comprised of a collection of neural oscillations in several frequencies that are contributing to varying degrees to the overall signals. After raw, unfiltered brainwave signals are recorded in a digital format, minute electrical activity coming from the scalp then can be amplified and transformed into

brainwave data (Demos, 2005). To extract information about the extent of unique frequency bands that is contributing to the overall power of a waveform, Fast Fourier Transform (FFT) is a common processing method applied to EEG recordings that is widely adopted in neuroscientific research (Pfurtscheller & Lopes da Silva, 1999). Due to geometrical organization and necessity for a strong overlap of temporal bioelectrical currents, EEG is generally assumed to reflect synaptic input and intracortical processing of excitatory post-synaptic activity of highly organized pyramidal neurons as the most dominant source (Pfurtscheller & Lopes da Silva, 1999). When oscillations from neural signals are picked up by electrodes placed on the scalp, EEG voltage measures display resonant behaviour of neuronal populations and fluctuations in different states which are caused by the spatiotemporally summed activity of large populations of neurons (Pfurtscheller & Lopes da Silva, 1999). By the advantage of its high temporal resolution in the range of milliseconds, EEG represents a relatively low-cost and robust measurement modality that offers real-time applications (Demos, 2005).

In healthy individuals, normative, consistent EEG patterns are generally observed (Demos, 2005). With EEG, a great opportunity for identifying neuro-correlates of different mental and behavioural states has been opened up. With its potential of displaying electrochemical reactions of distinct frequency bandwidths in the brain, EEG can yield observable and dynamic manifestations of neuronal processes throughout human development. By opening the door for researchers to observe electrical activities of the healthy human brain in vivo, EEG has become a valuable research tool for measuring brain functioning in a comprehensive and rigorous way.

### 2.1.1. EEG Frequency Bands and Behavioural Associations in Learning

To study the relationship between cortical activities and their behavioural or phenomenological associations, neurocognitive researchers divide rhythmic activity

in the brain within a certain frequency range that is distributed over the scalp or is related to a significant mental state. In general, cortical neurons fire in a rhythmic, or synchronous, pattern which leads to a variety of waveforms or frequency bands such as alpha, theta, beta, sensorimotor rhythm (SMR), delta, and gamma. In an alert state in healthy individuals, EEG normally records in the gamma frequency range, 40 Hz on average, from the cortex (Coben & Evans, 2010). This electrocortical frequency decreases to 8-12 Hz (alpha) during relaxed wakefulness and to 0.5-4 Hz (delta) during deep sleep (Coben & Evans, 2010). In conscious and vigilant states, electrocortical frequency often increases, respectively, to 4-8 Hz (theta) and 15-30 Hz (beta) in human adults (Carskadon & Dement, 2011). Relationship between recordings of the most commonly studied frequency bands and ongoing thinking and learning in existing neurocognitive literature will be discussed in the following section and respective neurofeedback issues will be considered further below.

### *Alpha*

Alpha (8-12 Hz) activity is found to be strongly correlated with attentional processing, working memory, and semantic memory, as well as retrieval from long-term memory (Basar, Basar-Eroglu, Karakas & Schurmann, 2001; Vernon, 2005). More specifically, the alpha band in a lower frequency range (8-10 Hz) reflects non-task related cognitive processes such as expectancy and attention, whereas alpha band in the higher frequency range (10-12 Hz) reflects task related cognitive processes such as memory processing (Klimesch, Schimke & Schwaiger, 1994). Although alpha activity is generally associated with a calm and relaxed state, event-related alpha activity can also facilitate associative mechanisms in different brain structures as a resonating signal in response to a specific sensory or cognitive input (Basar, Yordanova, Kolev & Basar-Eroglu, 1997). Note, however, that while organization and activation of state arousal is dominantly reflected in the alpha rhythm and sleep spindle, cognitive functioning is primarily reflected by EEG oscillations in both the alpha and theta range (Othmer, 2001; Klimesch, 1999).

### *Theta*

Serving as a coordinated response indicating alertness, arousal, or readiness to process information, theta oscillations play a prominent role in orienting to different stimulus during exploration and search (Basar et al., 2001). Theta (4-7 Hz) activity is also associated with higher cognitive functions and multiple cognitive abilities, including mnemonic and spatial information processing, recognition and episodic memory, spontaneity, and creativity (Kirk, 1998; Basar et al., 2001; Vernon, 2005). Mainly reflecting general activated state of arousal in both humans and animals, theta activity serves a basic role in cognitive processing which modulates in cortico-hippocampal interaction (Kirk, 1998).

### *Beta and SMR*

Both beta and sensorimotor rhythm (SMR) activities share overlapping frequency range in the human brain (12-30 Hz). Cortical arousal is governed by the beta (15-30 Hz) range in an active state that is important to arousal and attentional processing. Oscillation of this frequency band is associated with state of alertness, focus of thought, and attention in response to external orientation (Vernon, 2005). Compared to children's brain activity, higher dominant beta is often observed in a state of relaxed thinking in adults (Lubar & Lubar, 1999). SMR (12-15 Hz), a subdivision of the beta frequency band, consists of a comparatively complicated characteristic that overlaps with lower beta and upper alpha (10-14 Hz) in some studies (Vernon, Egner, Cooper, Compton, Neilands, Sheri, & Gruzelier, 2003). Primarily observed in the sensorimotor cortex, SMR activity serves as an internally oriented 'idling' rhythm that decreases during physical activity, as a sentinel to heighten mental vigilance and sustained behavioural immobility in response to action (Pfurtscheller & Lopes da Silva, 1999).

### *Gamma*

As an important building block of electrocortical activity, Gamma (30-42 Hz) band represents a universal code of central nervous system communication (Basar

et al., 2001). Oscillations of this frequency band are more synchronized, globally observed oscillatory activity over the scalp that is often associated with broad temporal binding of neurons across sensory modalities, and especially for sensory acquisition, as well as pre-motor planning (Ribary, 2005). A role of perceptual organization that underpins states of arousal and activation is evident in this band activity (Othmer, 2001). Gamma activity is found critical during problem-solving tasks for both adults and children to support planning, promote learning, and provide mental flexibility (Brown & Brown, 2000). As gamma is activated in the face of cognitive challenges, synchronous activity of this band appears to promote learning by facilitating information organization and allowing mental sharpness (Ribary, 2005).

### 2.1.2. Characteristic of EEG Frequency Bands: Dynamic and Multi-dimensional

Research also points to the significant of neurophysiological irregularities of EEG frequency bands and experiential associations that is based on disruption of ongoing thinking and learning in abnormal human EEG recordings. For instance, regardless of overall rhythmic delta, arrhythmic delta in higher amplitude is observed in wakeful adults following a traumatic injury, which leads to disruption of problem solving skills (Demos, 2005). In addition, asymmetrical alpha and dominant alpha frequency in above-average range can, respectively, serve as indicators of depression and anxiety (Demos, 2005). Moreover, excessively lower frequency theta waves is related to inattention, slow reaction, distractibility, and impulsivity in children with diagnoses of Attention-Deficit Hyperactivity Disorder (ADHD) (Demos, 2005). Furthermore, lower gamma activity is observed in individuals with learning difficulties, especially on problem solving tasks (Demos, 2005). Last but not the least, it is important to acknowledge that EEG frequency bands can vary considerably in each individual as a function of age, brain volume, cerebral injury, and neurological diseases (Klimesch, 1999).

As the research findings mentioned above suggest, the nature of EEG characteristics is not a static entity and which encompasses both positives and negatives. It follows that parameters of EEG frequency bands can be implicated with different cognitive functions and multiple aspects of learning and experience which emerge in various ways. Although distinct waveform patterns observed in raw EEG data appear to indicate a definitive neural activity that is associated with a particular function, neural activities can both operate in cohort, or shift between different waveforms, in order to optimize behaviour and performance according to the purpose of the task. For example, the observation of shifting from alpha to theta during a cognitive task suggests that mental preparation of different cognitive activities, such as attention orientation and engagement, can promote integrative functioning, thereby enhancing consequential behavioural performance (Basar et al., 2001). Although domination of one or more frequency bands is most commonly studied in research literature, it is important to keep the idea of a high flexibility of the cerebral cortex in our mind.

In addition to examining overall brain activity in a generalized manner, selectively distributed oscillatory networks of EEG bands across different brain structures and regions are also related to transfer functions of the brain as a whole. Therefore, behavioural and phenomenological associations of different frequency bands are multi-dimensional in nature, just as electrophysiological characteristics of the brain and functioning can be changed depending on the task and the context. As discussed above, scientific literature suggests that different EEG frequency bands are related to different mental processes. A dramatic increase of interest in contemporary research concerns the possibility of improving corresponding physical or cognitive behaviour starts to emerge, in which one possible technique that can be used is neurofeedback.

# Chapter 3.

# Neurofeedback

By promoting change at the cellular level of the brain through operant conditioning, neurofeedback is a comprehensive tool that empowers individuals to use their minds under volitional control. Brainwave patterns are first recorded as EEG data and detection of EEG brain signals are processed through a brain-computer interface that is set up for neurofeedback training (Huster, Mokom, Enriquez-Geppert & Hermann, 2014). After generating and extracting features of data signals, these signals can be used to quantify the strength of activity in a specific brain region, computation and representation of the signals convey information of relevant changes in brain states are "fed back" to the individual as a feedback loop (Huster et al., 2014). Based on the timing of the feedback signal throughout the entire feedback loop, voluntary alteration of brain states can be monitored in a quasi-continuous manner, and feedback signals can serve as immediate learning signal to be reward, as soon as the desired brain state is achieved (Huster et al., 2014).

Through the process of recording and reiterating biological data in real-time, neurofeedback can be conceived as a specialized version of biofeedback that intends to facilitate changes of brainwave signals related to subconscious or conscious neuronal activities of an individual. By using EEG to provide instant information as a feedback signal of dynamic physiological states, neurofeedback becomes a type of feedback training that offers an opportunity for an individual to learn and modify his/her own brain activity. EEG signals are measured from sensors, or electrodes, that are placed on the scalp while brain electrical signals are continuously recorded

while relevant components are extracted and fed back to the individual via online feedback loop in the form of audio, visual, or combined audio-visual information (Coban & Evans, 2010).

Based on the assumption that humans are able to exercise subconscious or conscious control over multiple aspects of physiology, neurofeedback allows participants to make beneficial alteration of brain activity as desired (Lubar, 1997). The advantage of providing immediate and continuous feedback is an opportunity for participants to learn and to engage in self-efficacious behaviour by fostering experience of self-regulating specific brain aspects on their own. In accordance with the embodied framework of cognition (see Rudrauf, Lutz, Cosmelli, Lachaux & Le van Quyen, 2003 for a comprehensive review), cognitive function that is subjectively experienced would be objectively manifested in brain behaviour as neural processes that are detected by EEG.

Taken together, neurofeedback opens up a great possibility for voluntary modulation of electrophysiological activity of the brain and, potentially, subsequent behaviour of an individual in an observable and measurable manner (Campbell & Handscomb, 2007). By establishing volitional learning of accessing and modulating the state of mind for future use, neurofeedback can serve as a powerful, non-invasive technique that provides convenient and meaningful values to both academic and research fields. Although neurofeedback is a comparatively young research paradigm, a background of neurofeedback with respect to its history and development will be briefly discussed in the following section.

## 3.1. History of Neurofeedback

The evolution of neurofeedback is a fairly recent development grounded on the cornerstones of scientific theory, technology, physiology, neurology, and psychology. Technological advances in the early years of the 20$^{th}$ century have

triggered a renewal of interest in the relationship between brain and behaviour. By pioneering innovative feedback training method on brainwave frequencies in 1963, Joseph Kamiya (2011) was the first researcher to demonstrate human's ability for alpha enhancement. During the training, an instrument was used to record the biological activity of alpha waves of trainees while participants received verbal reinforcement, whenever desired brain states occurred. In this experiment, Kamiya successfully trained volunteers to intentionally control their brainwave states by consciously identifying bursts of alpha activity to a significant degree over time. This study was the first to popularize the use of EEG signals in a feedback setup in which participants learned to control their own alpha waves. Based on the close relationship between alpha rhythm and relaxation state, alpha training has since been found effective in alleviating stress-related conditions in follow-up studies (Hardt & Kamiya, 1976).

Another groundbreaking experiment exploring the medical application of neurofeedback was published by Sterman, Wyrwicka and Roth (1969) soon after Kamiya's discovery. In Sterman et al.'s (1969) study, 50 SMR-trained cats were rewarded each time when increase of SMR was observed following neurofeedback training, and 10 of the cats demonstrated success of training to elevate SMR. In an unrelated research project requested by NASA, that was originally aimed at examining the relationship between toxic rocket fuels exposure and seizure disorder, all of the cats were injected with monomethyl hydrazine (MMH), a convulsion-inducing chemical substance in rocket fuel propellant. Unexpectedly, 10 successful SMR-trained cats that had coincidentally involved in a recent and unrelated neurofeedback study, as previously mentioned, were all resistant to seizure after injecting MMH. However, the remaining 40 non-SMR-trained cats developed seizures quickly following the injection. Overall results from the two studies, therefore, indicated a significant resistance to the convulsive effects of the chemical substance in the SMR-trained cats. Sterman et al.'s (1969) research thus

demonstrates the efficacy of SMR neurofeedback training and provides encouraging evidence of the beneficial effects of neurofeedback application.

In the same year, Thomas Budzynski and John Stoyva (1969), two pioneers in the field of biofeedback, invented the first surface electromyographic biofeedback training system for muscle tension in which participants were trained to regulate voluntary muscle activity. Rather than applying needle electrodes to isolate a single motor unit, skin sensors were placed over the frontalis, or frontal belly, muscle group. While results showed that participants were able to learn to reduce entire muscle group's activity on their foreheads, based on the electrical signals coming from their muscles and cerebral cortex, there were also muscle movement artifacts in the face, scalp, and neck which interfered with EEG recordings. This study on muscle activity has shed light for future neurofeedback research on investigating and refining potential artifacts.

By the late 20$^{th}$ century, neuroimaging techniques such as numerical analysis of EEG data and associated behavioural correlation had started to emerge. For instance, in the 1980s, development of normative databases of EEG data from multiple scalp sites opened up a possibility for comparing brainwave patterns of a particular individual to a sample population to provide a broader picture of the cerebral cortex in action (Budzynski, 1999). In the 1990s, a neurofeedback training program named EEG-Spectrum was developed (Othmer, Kaiser, & Othmer, n.d.). Moreover, as biofeedback studies demonstrate successful human ability to consciously control both the central and the autonomic nervous system, the power of neurofeedback has been publicized (Demos, 2005). By its great value of linking biofeedback modality with psychotherapy, neurofeedback can be employed as a dynamic psychophysiological training tool for self-regulating electrical signals in the cerebral cortex and individual muscles in a similar manner. Furthermore, the application of neurofeedback has even expanded its horizon as an innovative learning tool in gaming environment in contemporary research. For example, in a

video game called *Journey to the Wild Divine*, biofeedback signals are provided to players through animated graphics as a mean to consciously achieving relaxed and meditative states via multiple measures of physiological responses, including heart rate, respiration rate, and skin temperature (Du, Campbell, & Kaufman, 2010).

Over the past two decades, researchers have started to adapt neurofeedback as a new technology in various prospects such as medicine, mental disorders, cognitive processes, and peak performance training. As discussed below, applications of neurofeedback have gained increasing attention and significant impact in both clinical and research fields.

## 3.2. Contemporary Research on Neurofeedback and Applications

Since technological advancement of EEG and subsequent emergence of neurofeedback have opened up a possibility of self-modulating central and autonomic arousals, the idea of voluntary regulating changes in EEG rhythmicity in the human brain starts to germinate in both clinical and research practices. As an alternative to pharmaceutical medication for instance, neurotherapists start to explore therapeutic potentials of neurofeedback in remediating conditions which involve regulations of central or autonomic arousals. While some researchers aim at investigating neurofeedback as an effective treatment intervention of psychological disorders in clinical populations, others seek to examine the human ability of learning neurofeedback as a performance enhancement technique in general population (Cantor & Chabot, 2009; Doppelmayr & Weber, 2011). By providing a brief review of neurofeedback literature, we will see that the practice of neurofeedback as a prospective neurotraining application has evolved into two major branches, clinical and general populations, thriving side by side.

### 3.2.1. Clinical Population

The boom of psychological diagnoses in recent years has been a prevailing concern for both learners and educators. According to the British Columbia Ministry of Education (2012) report, almost 7% of public school students are diagnosed with behavioural difficulties and mental health issues; this rate has remained a steady trend since 2008. As described below, research on neurofeedback and its clinical effects on psychological disorders, such as behavioural or mental health conditions, have highlighted the treatment effect of voluntary conditioning parameters of EEG via neurofeedback. More specifically, neurofeedback has been shown to demonstrate positive clinical effects in stabilizing disruptions of central and autonomic rhythmicity, and provides dramatic impact on learning experiences such as attention, arousal, and affective regulations.

***Attention***

As an essential cognitive mechanism that is closely linked to consciousness, attention enables us to focus on relevant features of the external environment or to be directed to internal mental processes and outward actions (Gazzaniga, Ivry & Mangun, 2002). In regulating attention, neurofeedback has been found promising in remediating ADHD and related conditions, including Tourette syndrome, disruptive behaviour disorders, and conduct problems (Othmer, 2001). Particularly, intervention of neurofeedback has been reported to coincide with self-regulated normalization of the EEG frequency spectrum in ADHD and comorbid conditions, and effects of alleviating ADHD symptoms were even found comparable to the effects of medication in some adolescences (Coban & Evans, 2010; Rossiter, 1998). Treatment effect of attention regulation might be driven by the coupling of vigilance and attentional focus to physiological reaction (Othmer, 2001). If rhythmicity of EEG can be adopted as a marker for organizing neuronal firing to manage internal brain mechanisms, then the potential of restoring communication linkages between different brain regions via neurofeedback may serve as a fundamental remedy for

ADHD symptom clusters which subserve attentional focus, vigilance, habituation, and learning difficulties.

### *Arousal*

Often perceived as a global state of alertness such as sleep and wakefulness, arousal refers to the way in which alertness and attention is allocated depending on the level of physiological arousal (Coren, Ward & Enns, 2003). In regulating arousal, neurofeedback is effective in remediating conditions that involve de-regulations of central or autonomic arousal, including depression and anxiety, sleep disorders, photic epilepsy, and migraines (Demos, 2005; Othmer, 2001). Treatment effect of arousal regulation might be driven by the management of EEG rhythmicity pattern on arousal which governs attentional state (Othmer, 2001). By adjusting the timing properties of disrupted EEG rhythmicity, regulatory conditioning of neurofeedback training might be possible to regain nervous system stability thereby maintaining a balance of internal physiology and regulation.

### *Affect*

By reflecting an outward expression of internal emotions through facial expressions, gestures, and intonation, affect can influence various aspects of cognition and emotional regulation in a mutual way (Baron, Byrne & Watson, 2003). In regulating affect, neurofeedback has demonstrated success in remediating severe emotional dysfunctions such as autism (ASD), Asperger's Syndrome, and Reactive Attachment Disorder, as well as in regulating fundamental instabilities such as seizures, bruxism, anxiety disorder, panic disorder, bipolar disorder, schizophrenia, and obsessive-compulsive disorder (OCD) (Othmer, 2001; Demos, 2005). Treatment effects of affect regulation might be driven by raising the operative threshold of instabilities in the central nervous system (Othmer, 2001). By mediating communication pathways between subcortical nuclei and cortical regions, neurofeedback might be beneficial to modulate excessive EEG rhythmicity of the

limbic system that is thought to be primarily involved in governing feelings and emotions.

Taken together, empirical evidence has demonstrated a critical function of neurofeedback in normalizing mental and physical behaviours which exist in many clinical conditions. As Othmer (2001) suggests, psychological disorders may be conceived as "disorders of regulation" where psychopharmacology and neurofeedback, together, can act to restore appropriate psychophysiological and behavioural self-regulations. From a bioelectrical perspective, the human brain functions as a comprehensive control system that is also required to maintain its own stability. When self-regulatory processes go awry and hence indicate a loss of brain functional integrity, operant conditioning of EEG may play a significant role in remitting symptoms of mental and behavioural tensions.

### 3.2.2. General Population

While therapists in the clinical field use neurofeedback as an intervention tool for targeting abnormal EEG patterns in specific brain regions, scientists in the research field explore learning effects of neurofeedback on mental flexibility and personal growth of people in the public sector. According to the American Psychiatric Association (APA) (2000), the "general population" refers to healthy people without behavioural or degree of cognitive deficits, or learning difficulties (Doppelmayr & Weber, 2011). By inducing global changes in EEG patterns which lead to desirable changes in a specific state or aspect of behaviour, design of neurofeedback protocols aims at mirroring such optimal patterns of cortical activity in a particular frequency component and, in turn, enhancing corresponding performance of participants (Vernon, 2005). In other words, researchers in the scientific field study the potential benefits of neurofeedback practice on cognitive and behavioural activities in a range of human abilities, especially on attention, arousal, and memory, which are of great value in educational research.

### *Attention*

As previously mentioned, neurofeedback has demonstrated efficacy of regulating attention in ADHD and its comorbidities. To further examine the impacts of neurofeedback on attention measures in both electrocortical and behavioural manners, Egner and Gruzelier (2001, 2004a) designed an extensive study on the learned effects of SMR (12-15 Hz) and beta1 (15-18H z) training in healthy volunteers. By comparing pre- and post-training measures on a sustained attention task in the first study (2001), results showed that performance on measures of impulsiveness (e.g., reduced commission errors) and perceptual sensitivity (e.g., increased target detection) were significantly improved following both SMR and beta1 trainings. In a follow-up comparative experiment (2004a), improvements of perceptual sensitivity and impulsiveness were also evident in the SMR training group as compared to the control group. In addition, faster reaction time was observed in the beta1 training group compared to the control group, despite that this latter study failed to replicate remission of impulsiveness, as in the first study.

Taken together, the results suggest that SMR training may better enhance perceptual sensitivity, whereas beta1 training may better increase cortical arousal. Combining the two studies, the researchers concluded that learned regulatory control of both SMR and beta1 trainings can bring beneficial, although protocol-specific, impacts on cognitive integration of sensory input and facilitates higher-order attention processing. With the potentiality of improving attention, a student may be able to better mobilize his/her cognitive abilities such as being alert to instructions and linking new information to prior knowledge, thereby further promoting active learning and performance.

### *Arousal*

Since physiological signs of arousal often covary with the efficiency of sensory detection, vigilance decrement is closely linked to the level of arousal in the central nervous system in neuroscience research. Based on the assumption that

vigilance decrement in humans may be associated with a decreased arousal of the nervous system that can be reflected by increased theta activity, the relationship between learned regulation of theta (3-7 Hz) and detection behaviour in a prolonged monitoring task was investigated (Beatty, Greenberg, Diebler and O'Hanlon, 1974 ). In this experiment, healthy undergraduate students were required to complete a radar detection task after training on either suppressing or augmenting theta frequency band. While theta training was found to successfully induce spectral changes and discriminative control of EEG activity in both groups, an inverse relationship between regulation of theta activity in the occipital region and performance of detection efficiency was also observed. In other words, this study confirmed that less theta can lead to better subsequent task performance as demonstrated in the theta suppressing group in comparison to the theta enhancing group.

Taken together, the researchers concluded that theta rhythm can serve as a reliable indicator of arousal processes to determine vigilance efficiency in preparing, and in response to, action in monotonous conditions. In addition to the beneficial impact of neurofeedback training on arousal and performance, a prominent role of neurofeedback is also found effective on improving attention, behaviour and readiness to learn in primary school children with special educational needs (Foks, 2005). As a practical, innovative part of school-based provision, incorporating and extending the scope of neurofeedback into educational settings are, therefore, possible and valuable.

***Memory***

As interest in neurocognitive science continues to grow rapidly, research on examining the relationship between EEG oscillations and memory performance has also begun to explode in scientific literature. Wolfgang Klimesch, a notable researcher in this area, has presented ample evidence of double dissociation between EEG activity patterns and memory and cognitive performance activity

(Klimesch, 1999; Klimesch, Doppelmayr & Ripper, 1997; Klimesch, Doppelmayr, Pollhuber & Stadler, 2000; Vogt, Klimesch & Doppelmayr, 1998). One profound finding suggests that while small resting power and large test power in theta indicates good memory performance, the impact of alpha on memory performance works in an opposite manner (Doppelmayr, Klimesch, Schweiger, Stadler & Rohm, 2000; Doppelmayr, Klimesch, Stadler, Pollhuber & Heine, 2002). In other words, high alpha activities during idle state, and low alpha activities during test state, indicate good memory performance. On the other hand, higher alpha frequency is also positively correlated with various academic performance indices, such as memory capacities, mental flexibility, and intelligence abilities in high school students compared to age matched controls (Klimesch, Schimke, Ladurner & Pfurtscheller, 1990; Anokhin & Vogel, 1996).

In light of Klimesch's discoveries, related research on exploring the potential impact of EEG frequency training on memory performance started to emerge again in the mid-20$^{th}$ century with influential findings in neurofeedback literature. First, in alpha studies, the individual alpha frequency (IAF) technique, that is, individually determined alpha band is adjusted for each participant by using IAF as an anchor point for distinguishing a lower from an upper alpha band, can be adopted. While increase of relative amplitude in the upper alpha frequency range of healthy participants was found during active mental tasks, significant improvements in working memory as well as in short term memory were also observed when compared to control group (Escolano, Aguilar, & Minguez, 2011; Nan, Rodrigues, Ma, Qu, Wan, Mak, Vai, & Rosa, 2012). Second, in a theta study comparing healthy participants in different age groups, older participants showed better performance on working memory and attention following theta enhancing training (Wang & Hsieh, 2013). In addition, beneficial effects of higher executive functioning following theta enhancing training was also observed in younger participants (Wang & Hsieh, 2013). Third, in a SMR study examining similar cognitive aspects in healthy subjects, improved performance in tasks of cued recall, and of focused attention to a lesser

extent, were observed after eight training sessions (Vernon et al., 2003). This result suggests that semantic processing in working memory tasks can be facilitated following SMR training. Last, in a gamma study investigating the interplay between neural synchronization and cognitive processing, positive impact of gamma training was revealed in facilitating top-down control of episodic memory retrieval (Keizer, Verment and Hommel, 2010). In line with this finding, neurofeedback may help to aid neurocellular modulation through priming and preserving new synaptic connections (Nitsche, Roth, Kuo, Fischer, Liebetanz, Lang, Tergau, & Paulus, 2007).

In summary, neurofeedback research has provided supportive evidence on the cognitive and behavioural benefits for learners in diverse, educational contexts, ranging from mitigation of clinical symptoms that might have an impact on learning, to desirable EEG changes in a specific state or aspect of behaviour underlying cognitive and academic performances. When applying neurofeedback in training and research, however, we should beware of potential adverse effects, such as fatigue, headaches, anxiousness, and irritability due to prolonged training sessions, as recorded in the literature (Hammond, 2011). Citing beneficial effects of neurofeedback on cognitive and behavioural performance in literature, as well as the enjoyable training experience often reported by participants, Gruzelier (2014) suggests that applying neurofeedback-based program in school setting is certainly feasible.

# Chapter 4.

# The Problems of Causality and Validity

Regardless of a dramatic increase in applying neurofeedback as a possible intervention for treating multiple physiological and psychological disorders in recent years, critics dispute the effectiveness of training in healthy populations (Devlaminck, Wyns, Boullart, Santens & Otte, 2009; Egner & Gruzelier, 2001; Vernon, 2005; Guger, Edlinger, Harkam, Niedermayer & Pfurtscheller, 2003). As touched upon, data from both clinical studies and experimental research support the efficacy of neurofeedback trainings, and suggest the beneficial use of neurofeedback as an empowering tool for enhancing performance. However, a number of claims regarding validity, and especially on methodological limitations as well as interpretation of results, remain puzzling in the scientific paradigm. In a comprehensive review of neurofeedback literature for instance, despite that evidences in neurofeedback training studies have demonstrated its potentiality to enhance human performance in different aspects, including sports, cognition and performing art, Vernon (2005) claimed that

> [although] the reported association between specific patterns of cortical activity and particular levels of performance seems plausible to utilize neurofeedback as a tool to train individuals to re-create patterns of cortical activity in an attempt to enhance performance, however, it seems the plethora of claims regarding the use of neurofeedback training to enhance performance is matched only by the paucity of research showing a clear effect… whilst the findings [on positive effects of neurofeedback] are suggestive, a clear connection between neurofeedback training and enhanced performance has yet to be established (p. 362).

In order to effectively move forward from all the inconsistency and ambiguity in this field, it is important to solve the fundamental question; that is, what are the major problems, or challenges, in studying the effectiveness of neurofeedback as an authentic scientific approach? More specifically, how do we know that neurofeedback is doing what it is claiming, or what it intends to be doing? In other words, how do we know that neurofeedback studies are valid? The bulk of this chapter will focus on the problem of validity. However, it is important to consider an even more basic problem beforehand. A necessary condition for addressing the problem of validity in the affirmative is that the mind, consciously, subconsciously, or both, must be capable of exerting changes in brain and brain behaviour. That is to say, the mind must have some causal, or direct, effect on the brain in order for studies in neurofeedback to be valid.

## 4.1. Causality

The problem of causality in neurofeedback is a special case of the so-called 'mind-body problem'. The nature of this problem and any purported solutions to it are based on deep philosophical assumptions regarding the ontological nature of mind and body, or, as formulated by Descartes, *res cogitan* and *res extensa* (Campbell & Dawson, 1995). For Descartes, mind and body were two fundamentally different kinds of substances. If this is so, then a problem immediately arises as to how it is that these two substances, mind and material, can possibly interact. From a scientific perspective, this has been considered an intractable problem, given that mind has no extension in space, how could such a thing ever be observed, let alone measured. Hence, for many neuroscientists, the phenomenon of mind as an independent and separately existing construct remains beyond the purview of science. This has led to the modern view that 'the mind is what the brain does'. In other words, the mind as having any causal effect over the brain is rendered moot, as traditional humanist notions of volition, consciousness agency, and the

phenomenon we all have of lived human experience in general, are thereby delegated to the brain itself. Problem solved; or, is it?

Campbell (2011) presents the problem as follows:

> The term 'experience' and the effects thereof can be interpreted in many ways. From a materialist perspective, experience is what happens to the body, and the effects of that experience manifest as objective changes in body, brain, and behaviour. From an idealist perspective, experience is what we have. That is to say, it is, quite literally, what we experience as subjective beings—and the effects thereof concern effects pertaining to our state of mind. It is possible, in both cases, to believe that one of these views or the other is simply an epiphenomenon or illusion, or that never the twain shall meet. In cases where some degree of interaction is admitted between mind and brain, there is an issue of priority concerning exactly what is causing what. Do subjective changes in experience cause objective changes in brain, or vice versa? (2011, p. 9)

If the mind is just what the brain does, and the brain is just in essence a biological machine, how is it that humans experience themselves as having minds? Why is mind or the experience of having a mind necessary at all? Moreover, how is it that human experience is to be understood mechanistically in terms of brain and brain behaviour? Perhaps there is more to the nature of biological organisms than can be understood using deterministic and mechanistic thinking alone.

Be that as it may, it is undeniable that it is part of what it means to be human to experience the world in various sensorimotor and cognitive modalities, and if the mind, brain, or a mind-brain, irrespective of one's ontological commitments, the problem of causality basically amounts to the following (Campbell, personal correspondence): just as we are able, within our experience, to decide to use our hands, say, to type a sentence or to pick up a coffee cup, what are our abilities to alter the natural rhythms of our brains in deliberate and in predetermined ways, and what are the extent and limitations of those abilities? In order for neurofeedback to be valid, such ability must exist to one extent or another. The

problem of validity as an important step in assessing neurofeedback research will be discussed below.

## 4.2. Validity

Validity refers to the degree to which a particular use of a test is justified by evidence and judgments as well as decisions based on the test are accurate in representing data and information (Cozby, 2004). In other words, when a study is supported by available evidence to measure what it is intended to measure, validity of a study in a scientific design is strengthened. Consideration of validity is therefore as essential component for measuring and determining the quality of a study in relation to the nature of reality. In general, research can be evaluated in terms of four types of experimental validity: construct validity, internal validity, external validity and conclusion validity (Cozby, 2004). In the following session, the connection between neurofeedback research and validity issues of each type will be addressed and specified.

### 4.2.1. Construct Validity

Construct validity refers to the extent to which the operational definition of variables in an experimental design is adequate (Cozby, 2004). The fundamental question relies on whether the operational definition of a variable can actually reflect the true theoretical meaning of the variable. In neurofeedback research, experimental issues appear to threaten the validity of this type include inconsistent or non-specific EEG features as well as multiple cognitive domains of a behavioural outcome.

***Inconsistent or non-specific EEG features***

According to Zoefel, Huster & Hermann (2011), trainability, independency and interpretability, are three central elements which serve as critical criteria to be

met for determining the validity of neurofeedback research. In addition to demonstrate spectral changes of a chosen frequency band (trainability), neurofeedback training should exert spectral changes of a particular trained EEG band without affecting other frequency bands (independency) (Zoefel, Huster, & Hermann, 2011). Moreover, reliable improvement on cognitive abilities and behavioural performance should also be established in an applicable manner (interpretability) (Zoefel, Huster, & Hermann, 2011).

Although neurofeedback research has generally documented supportive evidence with respect to spectral changes and effects of distinct EEG frequency bands, closer inspection of the literature reveals that issues regarding independency remain in concern. For instance, in Beatty et al.'s (1974) study that is previously mentioned, spectral changes of theta ratio suggests the role of self-regulating theta in discriminative control of spectral activity and in subsequent vigilance performance. Without reporting changes of absolute theta level over time, however, it is not clear whether changes in theta ratio accompanying vigilance performance is also induced by changes in other EEG bands such as increase, or decrease, in alpha or beta (Vernon, 2005). In other studies that involved comparison of EEG changes based on spectra ratio, the problem of reporting unambiguous absolute values of spectral changes can be even more puzzling. In examining changes in alpha-to-theta ratio for example, either increasing alpha or decreasing theta, and vice versa, can lead to the same result of changes in the alpha-to-theta ratio. In addition, characteristics of EEG frequency components vary across scalp sites, such as alpha-to-theta training in frontal vs. posterior brain region, and provide pronounced differences of neurophysiological impacts on neurofeedback protocols and outcomes (Egner & Gruzelier, 2004b). The heterogeneous nature of EEG characteristics across scalp sites will be further discussed in the section on effect transferability.

Taken together, these findings suggest a diverse nature of EEG activity patterns overlapping with other frequency and brain regions. Future research can address the issue of independency by obtaining pre- and post-test measures of EEG baselines in multiple brain areas and corresponding behavioural changes in response to neurofeedback training.

***Multiple cognitive domains of a behavioural outcome***

As previously discussed, the criteria of trainability, independency, and interpretability should all be fulfilled in order to attain validity in neurofeedback research. In addition to the issue of independency, however, the problem of interpretability is also a concern.

In neurofeedback studies investigating sport performance, expert sportsmen often showed particular changes in EEG patterns prior to, and during, their performance. Further studies in the field have provided encouraging evidence of adopting neurofeedback training to mimic EEG patterns of expert sportsmen in novice sportsmen to enhance performance (Landers, Petruzzello, Salazar, Crews, Kubitz, Gannon, & Han, 1991; Hatfield, Landers & Ray, 1984; Salazar, Landers, Petruzzello, Myungwoo, Crews & Kubitz, 1990; Crews & Landers, 1993). Although the literature suggests positive impacts of neurofeedback training on sports performance in experts and novice in general, changes in a specific EEG band can be associated with different performance processes which are mediated in different brain areas. For examples, while karate experts show an overall increase in alpha at peak performance, significant increases in right-hemisphere alpha associated with decreased error has been found for expert golfers whereas left-hemisphere alpha has been observed in expert archers (Vernon, 2005).

Combining these results, which indicate that changes of alpha on sports performance can be inconsistent in both location and direction, hence suggest possible association of a particular EEG band with different underlying cognitive abilities and behavioural domains in sporting requirements. Since a behavioural

outcome often involves multiple mental abilities which require different cognitive domains, it is inconclusive to fully establish the role of neurofeedback that may be accounted for sport performance in terms of the degree of sporting requirements. Future research can address the issue of interpretability by providing a systematic investigation of neurofeedback impact on athletic training that involves standardized outcome measure of behavioural performance. In addition, cognitive assessment of multiple domains may be helpful to identify possible changes of EEG pattern in both spatial and temporal manner.

### 4.2.2. Internal Validity

Internal validity refers to the degree of ability to infer a causal relationship that exists between variables (Cozby, 2004). More specifically, whether a study has high or low internal validity depends on how strong inferences can be made when one variable causes change in the other variable. In neurofeedback research, experimental issues appear to threaten the validity of this type include individual variability, neurofeedback learnability, non-standardized training protocols, artifact, placebo or participant-experimenter interaction, as well as a lack of appropriate control conditions.

***Individual variability***

Adopted from an interactive perspective, the mind is related to the physical world of cause and effect that leads from physiological and environmental influences on the mind and on action, and vice versa (Campbell, 2011). If conscious control of brain physiology is possible to exert impacts on our mental and behavioural performance as suggested in neurofeedback literature, then, in a similar manner, mental and behavioural performance is also subjected to individual characteristics or variability underlying brain processes. In neurofeedback research, individual variability, or learner characteristic, concerns the ability of a learner to attain or maintain voluntary control of brainwave signals. Potential factors which

may influence the process of learning neurofeedback include: 1) mental/emotional state, 2) gender, 3) cognitive resource, 4) learning strategy, as well as 5) intention and motivation.

1) *Mental/emotional state.* The importance of mood in affecting brain signals and cognitive outcome has been widely documented in scientific research. For example, Bartolic, Basso, Schefft, Glauser and Titanic-Schefft (1999) conducted a between-group experiment in 60 right-handed women to examine the relationship of induced emotional states and cognitive task performance that is associated with the frontal lobe. While the euphoria-induction group showed better verbal-fluency performance that is linked to the left-frontal lobe, better figural-fluency performance that is linked to the right-frontal lobe was observed in the dysphoria-induction group (Bartolic et al., 1999). In addition to a particular emotional state, our ability to attain or maintain voluntary control of EEG signals is also susceptible to various factors underlying mental and emotional states, such as concentration, control of thoughts, relaxation, depression, anxiousness, frustration, distraction, and interruption (Curran & Stokes, 2003). In a post-training interview, verbal reports of these adverse experiences obtained from emotional participants were problematic to neurofeedback practitioners (Curran & Stokes, 2003). In addition, despite that neurofeedback training has demonstrated clinical effects on symptoms such as concentration, distraction, and frustration in individuals with ADHD, regression of these symptoms is observed soon after completion of treatment (Hammond, 2011). Taken together, these findings suggest that EEG activity can be influenced by changes in a variety of mental states and external factors. To guard from the potential effect of mental or emotional states, incorporating psychometric testing in neurofeedback training may be helpful to determine personality and emotional trait predictors related to responsiveness to EEG activity and corresponding performance.

2) *Gender.* In cognitive psychology literature on the one hand, EEG asymmetry has constantly been observed between males and females in a range of cognitive and emotion tasks. For example, males tend to outperform females on mental rotation and spatial orientation tests, whereas females tend to outperform males on tests of emotion and verbal memory (Roberts & Bell, 2000; Voyer, Voyer & Bryden, 1995; Davidson, Schwartz, Pugash & Bromfield, 1976; Volf & Razumnikova, 1999). In neurocognitive research on the other hand, sex difference is a variable factor that plays a dramatic impact on determining changes in EEG patterns, and mental and behavioural performance. For instance, while greater right-hemisphere activation of alpha during both affective and non-affective tasks was observed only in the female group, this group also showed greater flexibility of bilateral control during EEG training in self-generated cognitive tasks (Davidson, Schwartz, Pugash & Bromfield, 1976). Taken together, these findings suggest significant sex differences in EEG activity and cognitive performance. To guard from the potential effect of gender, further studies on brain electrophysiology and flexibility in controlling EEG activity between male and female may need closer investigation.

3) C*ognitive resource.* The ability to change EEG signals related to subconscious neuronal activities in neurofeedback opens up opportunity for changing dynamic physiological states, as desired, and making beneficial alterations of performance on different tasks where necessary. Note, however, that difficulty of performing tasks varies in terms of the cognitive resource required. For instance, mental effort that is reduced with practice, as a skill becomes a routine (Posner & Snyder, 1975). In other words, once automatic processing of a skill is acquired, mental fatigue is alleviated since performing mental operations of that skill no longer requires as much mental effort as before. During mentally depleting state, however, participants often report less effective control of automated brain activity, and further attempts of conscious control may lead to even more mental fatigue resulting in a higher depletion of cognitive resources (Kennedy, Adams, Bakay, Goldthwaite, Montgomery & Moore, 2000). Given that mental fatigue is especially

problematic on tasks which require quick response, as reported by experienced neurofeedback trainees, mental depletion can be detrimental when a skill is not fully automated in novice trainees (Kubler, Kotchoubey, Hintergerger, Ghanayim, Perelmouter, Schauer, Fritsch, Taub, & Birbaumer, 1999). To guard from the potential effect of cognition resource depletion, future studies can include tasks with a range of difficulties, starting from simple to complicated, while monitoring the amount of cognitive resource required to modifying brain signals for each task.

4) *Learning strategy.* By offering immediate feedback signals for an individual to learn self-modulating brainwave patterns, neurofeedback can serve as an operant conditioning procedure for achieving a desired particular mental or behavioural outcome. As a trainee learns to alter his/her brain activity and mental states via the feedback signal, continuous attempts to find and adapt mental strategies are employed simultaneously in order to control his/her brain states with respect to the instructions provided by a trainer. Note, however, that learners often adopt different strategies with different goals and tasks. Although mental imagery including both visual and audio aspects is found to be effective in producing positive reinforcement of brain activities, utilizing multiple strategies such as positive thinking and mental calculation for EEG self-regulation is reported in an alpha training study about short term memory (Birbaumer, Hinterberger, Kubler & Neumann, 2003; Nan et al., 2012). More importantly, different learning outcomes can follow even when the same strategy is adopted by different participants (Nan et al., 2012). In addition, the ability to acquire and to shift strategies can vary between learners. When a novice first attempts to produce EEG activities, the use of motor-imagery is mostly reported in the early stages of training. Although the need of motor-imagery strategy is often reduced as alteration of different frequencies of EEG activities becomes automated as training progress, occasional use is still evident in some participants (Curran & Stokes, 2003). Taken together, these findings suggest that mental strategies being adopted in neurofeedback to regulate brainwave activities can vary in scope and extent. To guard from the potential effect

of diverse learning strategies, attention should be paid in examining the effectiveness of different strategies use and/or in explicitly instructing participants to employ a particular strategy that is most appropriate for the purpose of the study.

5) *Intention and motivation.* Neurocognitive experiments often require the match of training modalities to a specific external objective such as neurophysiological functioning, mental fitness, and performance enhancement. One primary objective of neurofeedback training is to promote learning by self-controlling EEG activity, in the hope of achieving a desirable mental or behavioural outcome. In neurofeedback training, researchers' guidance for participants to conform to a specific set of procedures such as recommended mode, frequency and duration of controlling EEG activity is important. Neurotherapy is often required two to three times on a weekly basis, and training in traditional clinical trials can be intensive and involve a substantial volume, from 10 up to 60 sessions (Demos, 2015). Although healthy participants may need less frequent trials, they may also need to adhere to assigned mental activities, such as reading or relaxation exercises, on non-training days (Demos, 2015). To meet the goal and the intensiveness of neurofeedback training, self-engagement is a necessary condition. As motivation is crucial in mediating the learning process of guiding, determining, and sustaining self-control of EEG activity, discipline is an essential and integral element of any training program. Therefore, motivation throughout training sessions serves as a steppingstone for active engagement to help a learner on acquiring skill, mastering of task, building self-competency and achieving desirable outcome. According to research on constructivist learning theory, active engagement can bring positive reinforcement on permanent retention of an acquired skill in order to achieve mastery (Narli, 2011). As long training periods of neurofeedback is effortful, however, it is not surprising that a lack of motivation and poor participant compliance can be a problematic issue. The interest of the learner has been found to be a beneficial factor to determine performance gains by mediating motivation level, attention adjustment, automated processes, and mental strategies adoption.

However, participants who successfully responded to training nonetheless reported a lack of motivation and commitment to training sessions in a study which focused on assessing motivation and commitment of neurofeedback training (Enriquez-Geppert, Huster & Christoph, 2013). To guard from the potential effects of intention and motivation, brief and persistent assessments for long-term stability of training effects throughout training progress may be helpful to ensure both adequacy and effectiveness of training procedures.

***Neurofeedback learnability***

The ability to learn to modulate brain activity in a given frequency band is an indisputable prerequisite to induce neurophysiological, mental, and behavioural effects. Although neurofeedback research demonstrates a general success of training brain activity in different ranges of EEG frequency bands, a substantial number of participants who are unable to learn and show changes in modulating their brain activity over the course of neurofeedback training protocol prevails across studies (Hanslmayr, Sauseng, Doppelmayr, Schabus & Klimesch, 2005; Zoefel et al., 2011; Enriquez-Geppert et al., 2013; Doehnert, Brandeis, Straub, Steinhausen & Drechsler, 2008; Drechsler, Straub, Doehnert, Heinrich, Steinhausen & Brandeis, 2007). Various trait and state factors, such as hypnotisability, relaxation, motivation, attention, lethargy, and cognitive capacity, can interfere with the responsiveness, or the difficulty, of a learner to voluntarily changing EEG activity (Shaw, 2003; Pfurtscheller & Lopes da Silva, 1999; Gruzelier, Egner & Vernon, 2006).

The issue of an individual's ability to respond to voluntary changes of brain activity through feedback has captured research attention and brings tension to the practical field. For instances, a group of studies reported that about a third of the participants failed to demonstrate an ability to modulate EEG activity after extensive training of 36 to 40 sessions (Lubar, Swarwood, Wartwood, & O'Donnell, 1995; Fuchs, Birbaumer, Lutzenberger, Gruzelier, & Kaiser, 2003). Moreover, results from post-test measures of a continuous performance task indicated that non-responders

showed less improvement on attention in comparison to responders (Lubar et al., 1995). Furthermore, a complete lack of performance improvements with non-responders was observed in some studies (Hanslamyr et al., 2005; Drechsler et al., 2007). In spite of increasing attempts to prove that learning takes place during neurofeedback trainings by expanding cognitive and behavioural indicators of learner characteristics, uncertainty to identify reliable and predictive factors on a learner's capacity in response to neurofeedback training in a successful and accurate manner, therefore, is a non-trivial issue in terms of effectiveness and application.

On the positive side, a useful guideline in classifying responders versus non-responders during early stages of neurofeedback training has recently been published (Weber, Koberl, Frank & Doppelmayr, 2011). In addition, a major role of fronto-striatal circuits in governing neurofeedback effect has been proposed in another study that involved comparison of pre- and post-training (Levesque, Beauregard & Mensour, 2006). To guard from the potential effect of an individual's ability to respond to learning neurofeedback, detailed screening assessment such as neurological overview and psychosocial history, as well as experimental protocol including appropriate neurofeedback parameters, would worth considering.

***Non-standardized training protocols***

The idea of standardizing research approaches is a central criterion to maximize the quality and compatibility of studies, as well as to facilitate commoditization of custom experimental processes, in scientific community (Cozby, 2004). Considering neurofeedback training as an adaptive process of learning self-regulation on one hand, however, the rate of learning is different for each individual since every person is unique. Due to high investments in time and energy for different learners and trainers, designing the best, ideal training for each person can be exhausting. Considering the high complexity of interactions between brain and behaviour on the other hand, diverse training methods and procedures have

emerged across neurofeedback research groups in order to tackle the linkage between cortical oscillations and behavioural functioning. As a result, the process of developing and implementing technical standards of procedures and protocols to compare the effectiveness of neurofeedback studies between, and across, training approaches is difficult. Potential factors which might impose a lack of consistency in training protocols include: 1) training duration or number of sessions, 2) feedback modalities and signal presentations, 3) task, and 4) methods of measuring EEG frequency bands.

1) *Training duration or number of sessions*. Although literature points to a great potential of self-modulating conscious changes of EEG activities in humans, fundamental problems with respect to training protocols remain unresolved. In order to determine validity and specificity of beneficial effects of neurofeedback as a whole, systematic investigation of current training protocols across studies is needed. As mentioned previously, neurofeedback therapies in clinical setting normally range from 10 to 60 sessions. However, neurofeedback research have provided no solid guideline with respect to the requirements of training duration or number of sessions necessary for acquiring sufficient control over EEG signals. In general, Weber et al. (2011) suggested that the outcome of the first 11 training sessions could predict the later success of achieving EEG activity augmentation of a total of 25 training sessions. For healthy subjects who participate in prolonged training over the course of 20-40 sessions, 60% of participants were able to control changes of EEG components after 10-30 sessions (Kubler et al., 1999). In a study attempting to translate EEG into cursor movement on a computer screen over the course of training with 26-86 sessions, accuracy of EEG control by the final session was successfully improved for 90% with only 10-15 sessions (Wolpaw, Flotzinger, Pfurtscheller & McFarland, 1997). The length of time required to train a participant to acquire necessary control of EEG activity can further be facilitated by the use of pattern recognition method to increase initial discrimination for tasks pairing (Penny & Roberts, 1999). Taken together, these studies suggest that the ability to

acquire self-controlling changes in EEG is achievable, albeit the number of sessions required varies widely. To guard from the potential effect of training duration, future study can compare multiple training schedules or regimes with a variety of durations to strengthen experimental value of neurofeedback training protocols.

2) *Feedback modalities and signal presentations.* Sensory modality can be multifaceted and multi-situational in a way as it is subjected to individual differences in cognitive ability, learning progress, and development. As Mayer and Massa (2003) suggested, learning can be maximized by the use of complementary instructional presentations with multiple sensory modalities. However, adoption of feedback in various forms and modalities across studies may threaten consistency of measuring effectiveness of neurofeedback training as a whole. While most studies refer to a simple stimulus with either visual or auditory aspect, such as a presentation of a coloured square or tones in different pitch, the use of both visual and auditory feedback signals is observed in a majority of neurofeedback studies for people with ADHD, as well as in school setting (Becerra, Fernandez, Roca-Stappung, Diaz-Comas, Galan, Bosch et al., 2012; Enriquez-Geppert et al., 2013; Vernon et al., 2004; Joyce & Siever, 2000). Multi-stimulus feedback signals, such as thermometer displays and flying balloons, provided in stages of a training session can also be found (Gruzelier, Hardman, Wild & Zaman, 1999). Studies using complex stimulus suggest that increasing sensory modalities may enhance training outcome by increasing motivation and engagement (Subramanian, Hindle, Johnston, Roberts, Husain, Goebel, & Linden, 2011). In addition, presentation of feedback stimuli varies across neurofeedback studies in which feedback signals are updated ranging from continuous, or quasi-continuous updated periods between 100 and 400 ms, to an intermittent manner (Huster et al., 2014). Although feedback modalities, as well as signal presentations, are inconsistently presented and updated in different trainings, learners often report an enjoyable experience when learning neurofeedback, and especially when multiple sensory domains are involved (Joyce & Siever, 2000). To guard from the potential effect of inconsistency on feedback

modalities and signal presentations, future research can directly address this issue by comparing the effectiveness of different feedback modalities presented in periods which vary in order to determine an optimal training regime for different learners.

3) *Task.* Anderson and Sijercic (1996) have defined a classification scheme on differentiating EEG recordings according to different mental tasks. With a goal to elicit cortical hemispheric responses while participants' EEG were recorded in the meantime, five main cognitive tasks, including relaxation baseline, letter, mathematical, visual counting, and geometric figure rotation tasks, were performed. Results showed that accurate classification of EEG activity according to the five cognitive tasks identified can be obtained, which suggests the potential to choose a specific type of cognitive task according to a particular EEG frequency band of a study (Anderson & Sijercic, 1996; Keirn & Aunon, 1990). Due to the overlapping of mental abilities required for some of the tasks, the relationship between EEG activity and cognitive task employed, however, is more complicated than the classification scheme proposed (Keirn & Aunon, 1990; Anderson & Sijercic, 1996). More importantly, it is possible that the aforementioned cognitive factors are subjected to individual differences such as the preference for, and hence the effectiveness of, different cognitive tasks between participants (Pfurtscheller, Neuper, Guger, Harkam, Ramoser, Schlogl, Obermaier, & Pregenzer, 2000). In addition, multiple mental processes can be involved when performing a specific, or different type, of task. A number of questions with respect to the role of the type of tasks being used to successfully generate a particular EEG activity remain. For examples, what is the relationship between type of cognitive task and the level, or intensity, of EEG signal? Is/are there different characteristic(s) or other component(s) of a cognitive task involved to determine the level, or intensity, of EEG signals? Do cognitive processes required for the type of task provide a direct impact, or associative processes such as mental effort when performing the task exert an indirect impact, on EEG signals? Do the speed and the intensity of

generating an appropriate EEG signal mediated by different learning strategies? Does practice play a role in the generation of an appropriate signal to a specific type of task? To guard from the potential effect of types of task, future research can directly tackle this issue, a close match between the functionality of EEG activity of interest and the type of task being used can be warranted by building a broader range of reliable task measures of voluntary control of EEG activity.

4) *Methods of measuring EEG frequency bands.* As previously described, Fast Fourier Transform (FFT) is a commonly adopted computational tool for EEG training (Zoefel et al., 2011; Enriquez-Geppert et al., 2013; Brown & Brown, 2000). By extracting the power of a specific frequency band, FFT serves as a simple and straightforward technique for preprocessing and segmenting data in order to quantify the frequency of interest (Brigham, 1988). Due to the fact that raw EEG recording is a constellation of several frequencies with varying degrees of electric potentials, frequency of a EEG band may also be sensitive to alterations in neighboring frequencies when FFT is used to extract information. Although this computational technique allows researchers to compare each segment of raw power, different measures are used when examining a frequency band. While relative changes in baseline power of the same frequency measure is often estimated prior to a training session to compare changes of a single frequency following training, some studies mainly measure the ratios of target frequency bands relative to other frequency bands. By directly deriving EEG frequency bands based on values of a single frequency or on the ratio relative to other frequencies, simplicity and ease of usage for measuring EEG frequency bands can be maximized. However, these two methods may suffer from poor rater reliability since both outcome measure and result interpretation become harder when complicated experimental design with complex data is involved. Individual alpha frequency (IAF), as previously mentioned, is another method to measure EEG frequency bands. Rather than measuring EEG rhythmic activity based on frequency range defined in existing literature, IAF applies individually determined values of a single frequency

band as a dominant frequency in a given band. As critics argue that peak alpha frequency can vary to a great extent in healthy individuals, a need to define unique frequency range individually for each participant may be desirable (Klimesch et al., 1990). In addition, subdivision of a frequency band can be linked to different mental and behavioural outcomes, such as lower alpha frequency is related to attention where as upper alpha frequency is associated with semantic memory. As a result, other researchers suggest even finer measures of a frequency band with distinct components such as alpha 1 (6-8 Hz), alpha 2 (8-10 Hz) and upper alpha (10-12 Hz) (Klimesch et al., 1994; Klimesch et al., 2000; Doppelmayr et al., 2002). Taken together, multiple measures of EEG bands can lead to inconsistency in analyzing frequency features which make up raw EEG recording, thereby limiting the power of comparing effectiveness of a specific EEG band between, and across, training protocols. Future research is required to establish a consistent guideline of measurement of EEG frequency spectrum with respect to different mental and behavioural functions.

***Artifact***

In EEG research, artifact refers to interference of clean data in the perception or representation of cerebral activity due to peripheral information originated with the physiological or technical nature. While physiological artifacts are generated from the body (i.e., cardiac, muscle and eyes), environmental sources such as electrode movement and electrical interference account for technical artifacts. For instance, electrical signals generated from cardiac pulses can be measured up to a meter away from the body and mostly affect electrode connections to temporal and frontal sites (Thompson, Steffert, Ros, Leach & Gruzelier, 2008). In addition, electrical signals generated from muscle contraction can exhibit great amplitude of 100-1000 microvolt and obscure neural potentials of 10-100 microvolt on average (Thompson et al., 2008). Moreover, electrical signals generated from eye movements or eye blinks have been widely observed in EEG studies and primarily hinder electrode connections to the frontal area with peak amplitude of 50-200

microvolt that lasts for 200-400 ms (Thompson et al., 2008). Furthermore, electrode impedances and electrical noises from the environment might constitute challenging effects on signal quality (Thompson et al., 2008). By unintentionally generating unrelated signals that might contaminate target brain signals, peripheral electrical signals and the surrounding environment can provide detrimental impacts on data, regardless of careful monitoring of bodily activity while engaging in neurofeedback training. Although artifacts might be reduced or corrected by conducting signal processing of the data with computational software, such as basic digital filtering or multi-channel data processing after training, a considerable variation of detecting and rejecting artifacts in different software also exists (Thompson et al., 2008). To guard from the potential effect of artifacts, a thorough evaluation of methods for detecting and correcting EEG artifacts should further be explored. Appropriate methodological practices and accurate computational processing may also be helpful in minimizing the chance of obtaining contaminated feedback signals which interfere with learning outcome.

***Placebo or participant-experimenter interaction***

Placebo effect refers to the uncertainty of whether the observed improvement is caused by the actual treatment or by the perceived expectancies of a third factor involved (Cozby, 2004). In scientific research, placebo is a pervasive phenomenon that may bias the results of the study by drawing alternative explanations for results. More specific in neurofeedback research, participant-experimenter interaction may serve as a crucial factor in experimental design that can induce placebo, on the part of both participants and experimenters. As per participant's role on one hand, any feature that may inform participants of the purpose of the study can evoke self-fulfilling effect of response that may unconsciously motivate participants to be cooperative and conform to the hypothesis (Cozby, 2004). As per experimenter's role on the other hand, experimenters may not be aware of treating participants differently and encouraging participants to respond according to the purpose of the study (Cozby,

2004). In both ways, perception and expectation of experimental demands on the part of both participants and experimenters can severely bias the results of the study.

On the positive side, a previously mentioned pioneering study by Sterman et al. (1969) has offered strong evidence for disputing the possibility of expectancy effect in both participants and experimenters. Recall that this study has demonstrated the effectiveness of neurofeedback training in developing significant resistance to seizure induced by convulsive chemical substance (MMH). Since the study was not intended to test the effect of neurofeedback training on seizure mitigation in the first place, the influence of experimenters' expectation is impossible. In addition, the ability of participants to anticipate seizure resistance can also be ruled out because the study was conducted with animals. Therefore, efficacy of neurofeedback training is not subjected to any expectancy effect from participant-experimenter interaction in biasing results (Hammond, 2011). Equally important, recent findings also support the notion that beneficial effects of neurofeedback training cannot fully be explained by placebo effect (Gevensleben, Holl, Albrecht, Vogel, Schlamp, Kratz, Studer, Rothenberger, Moll, & Heinrich, 2009; Monastra, Monastra & George, 2002; Vernon et al., 2003).

Due to the frequent lack of a control group in neurofeedback studies, however, other factors involved in determining effectiveness of training will be further discussed in the next section (Vernon, 2005; Gruzelier et al., 2006; Zoefel et al., 2011). To guard from the potential effect of placebo or participant-experimenter interaction, training effects can be maximized by including better controls, such as sham or placebo groups which are comparable with the target group, in future studies.

### *Lack of appropriate control condition*

As mentioned in the above section, a lack of control procedures to eliminate possible alternative explanations for the results observed in neurofeedback studies

is often a point of refutation for critics. To address this issue, a previously discussed extensive study by Egner and Gruzelier (2001, 2004a) on investigating effects of SMR and beta training represents a great example. Although results in the 2001 study demonstrated the impact of SMR training on improving attentional processing, this study did not include a comparable control group. As a result, findings in this study were weakened since psychosocial factors, such as degree of practice, might also have been involved. In the 2004 follow-up study, fortunately, supportive evidence of SMR training effect on attentional processing from the 2001 study was strengthened by involving a comparable control group. Due to other limitations that exist in the 2004 follow-up study, however, findings of this study may not be as promising as it appears. For instance, no pre- and post- measures of EEG baselines changes with respect to resulting EEG changes were obtained from neurofeedback training. Moreover, the effects of training on reducing commission errors in the 2001 study could not be replicated in the 2004 follow-up study (Vernon, 2005). Furthermore, no significant improvement on task performance following beta training despite that faster reaction time was observed in this group (Vernon, 2005).

Taken together, by involving comparability between experiment and control groups, a number of recent findings suggest that the lack of control comparison cannot fully explain the beneficial effects of neurofeedback training (Levesque et al., 2006; Drechsler et al., 2007; Zoefel et al., 2011; Enriquez-Geppert et al., 2013). As reports with respect to effect sizes for training gains and transfer of learned skill are often missing in neurofeedback research, however, it is still difficult to tap the size of training benefits and the efficacy of a training regime (Enriquez-Geppert et al., 2013). Therefore, confirmation of voluntary changes in EEG activity resulting from neurofeedback training is plausible, yet evidence of training impacts on corresponding mental and behavioural performance is ambiguous, at best. To guard from addressing lack of a control condition, an active control group examining

different EEG frequency band should be included in study protocols for training, as well as calculations of effect sizes.

### 4.2.3. External Validity

External validity refers to the extent to which the results can be generalized to other populations and settings (Cozby, 2004). Based on the fact that a single study is usually conducted with a particular sample and procedure, it is important that findings in a study hold true when research involves other populations of participants or in different settings. When generalization of inferences based on the experiment can be made, replication of results can be conducted by manipulating or measuring the variables in other ways. In neurofeedback research, experimental problems that appear to threaten the validity of this type include limited population pool, effect transferability, as well as research methodology or systematic review versus meta-analysis.

***Limited population pool***

Although one fundamental research assumption postulates that the sample pool being chosen in a study is representative to individuals in a general population, participants in a study rarely are randomly selected from the general population without potential bias. Generalization of research findings therefore is limited to a certain sample pool that is being selected.

To investigate therapeutic effects of neurofeedback training, individuals who participate in a study are often selected based on clinical features and availability. Selection of sample groups in the clinical sector is highly restricted because the research focus has mostly been directed to individuals with a particular kind of mental illness such as ADHD, epilepsy, and anxiety because of clear abnormal EEG patterns which can be more readily observed in these individuals. Research on the general population in the public sector is more complex and problematic. Although attention has been devoted in a wider range of performance enhancement such as

sports, music, arts, and mental and behavioural functioning, the most available population sample being selected often consist of college students and volunteers.

In a study examining research publications in various social psychology journals for example, studies in over 70% of the articles published between 1980 and 1985 were conducted with college students (Sears, 1986). Since most of the students being studied were freshmen at sophomore year in their late-adolescence, research findings might be skewed and reflect a predominant population group who is educated, with high cognitive skills, as well as in need for social and authority approval (Sears, 1986). Moreover, Rosenthal and Rosnow (1975) have demonstrated that volunteers who sign up for a study, versus non-volunteers who are chosen for a study, possess characteristics which are different in various ways. Furthermore, it is important to include comparisons of two or more cultures in a study since the hybrid North American population, even samples of college students, is increasingly diverse in ethnic background. Regardless of the fact that incorporating cultural differences into psychology research has emerged in recent literature (Miller, 1999), cultural consideration centering on identifying similarities and differences is still lacking in neurofeedback research.

Taken together, the problem of unrepresentative population sample is devastating and hinders the strength of a study by restricting generalization of research findings. To guard from the potential effect of a limited population pool, researchers can randomly assign participants to different conditions and compare to a control group, while taking cultural diversity in consideration.

***Effect transferability***

If a technique is effective, then it should demonstrate both immediate and long-term impacts on a function over time, and not be limited to one or two occurrence(s). In general, neurofeedback studies using pre- and post-training measures support a beneficial relationship between changes of targeted EEG frequency bands and corresponding performance enhancement during training

session. However, studies concerning the beneficial impact of EEG changes between training sessions have rarely been conducted.

To resolve this issue, Egner and Gruzelier (2004b) conducted an experiment to study changes in theta-to-alpha ratio within- and between-session. In this study, participants engaged in 5 sessions of training at the posterior midline region (PZ), 10 sessions of training at the same region (PZ), and 10 sessions of training at the frontal midline region (FZ). Despite that theta-to-alpha ratio at posterior region was increased both within- and between-session, no significant changes in alpha, theta, or theta-to-alpha ratio at frontal region was observed within- and between-session. However, higher changes of theta-to-alpha ratio at frontal region were observed in the second half of the training process. While within-session changes of theta-to-alpha ratio at posterior region were associated with more decreases in theta than in alpha, changes at frontal region were associated with more increases in theta than in alpha during the sessions. In summary, characteristics of EEG frequency are complicated in nature, presumably based on different neurogenesis. In other words, changes in a particular EEG frequency band can differ in terms of temporal, such as degree of changes, and spatial, such as brain regions, aspects. Given that characteristics of EEG in different brain regions can be highly complex, or even contrasting, traditional neurofeedback protocols restricting measures on a specific brain region may provide incomplete data by recruiting partial neuronal resources of a limited area (Loo & Makeig, 2012). To evaluate transferability effect of EEG training from within-session to between-session, therefore, a closer examination on the heterogeneous nature of EEG frequencies across various scalp sites is in urgent need.

In addition to maintaining a learned skill over time, it is also important to apply the skill in a practical way. Based on technological constraint, however, neurofeedback experiments are often conducted in a laboratory setting which allows studying the impact of EEG training under highly controlled conditions. This

restriction of conducting neurofeedback studies in an artificial setting, therefore, may further limit the application of neurofeedback technique in real-life settings (Vernon, 2005).

To guard from the potential effect of transferability, future research should directly address a number of questions awaiting exploration. For examples, is there any required condition to be met for transferring immediate to long-term impacts of a particular EEG band? Does a specific training regime contribute changes in specific neural correlate of a mental, or cognitive, function and corresponding behavioural improvement? Does interaction between neural and cognitive processes mediate transferability of an effect? Does inconsistency in training sessions or protocols influence effect transferability? Do studies conducted in different settings, such as lab versus field experiments, offer complementary or contradicting results?

***Research methodology or systematic review versus meta-analysis***

Despite that neurofeedback is a relatively young field in the scientific arena, increased interest in both clinical and public sectors has expanded research in this area. To generalize a substantial amount of growing findings, a systematic literature review is conducted to summarize, integrate, and evaluate published studies in traditional neurofeedback literature (Vernon, 2005, Thompson et al., 2008; Curran & Stokes, 2003; Huster et al., 2014; Enriquez-Geppert et al., 2013). The advantage of a systematic review rests on its ability to guide future research directions by identifying inconsistent findings and neglected areas based on existing studies (Leucht, Kissling & Davis, 2009). Due to high reliance on research selected by the writer, however, generalization of inferences derived from narrative review may be biased and susceptible to subjective judgment and preference of the reviewer.

On the other hand, meta-analysis is a comparatively new technique that consists of statistical procedures for comparing a large number of studies in an area (Leucht et al., 2009). By employing effect sizes to compare a given finding across different studies, reliability of a finding can be better achieved (Leucht et al., 2009).

To increase the strength of drawing accurate generalization from an expanding wealth of neurofeedback studies, researchers begin to adopt this technique for combining the actual results of a number of studies.

While the narrative method offers directions for future research by identifying qualitative trends in existing literature, vulnerability to reviewer bias constitutes a weakness of this approach. Although meta-analysis is helpful in determining the current stage of a particular topic and drawing comprehensive conclusions based on quantitative procedures, application of this method in neurofeedback research is still in its infancy (Lofthouse, Arnold & Hurt, 2012). As Bushman and Wells (2001) revealed, the interpretation of information and accuracy of deriving conclusion in literature reviews can be improved following brief training in meta-analysis. Literature review and meta-analysis, together, may provide valuable insights in generalizing research results and strengthen evidence of findings in a complementary manner.

### 4.2.4. Conclusion Validity

Conclusion validity refers to the degree of accuracy which statistical conclusions about the relationships among variables are reached on the basis of the data (Cozby, 2004). In other words, conclusion validity is obtained when a correct relationship exists between variables. In neurofeedback research, experimental issues that appear to threaten the validity of this type includes correlational inference.

#### *Correlational inference*

One difficult issue of deriving valid and sound conclusions from neurofeedback research relates to the problem of drawing causal inferences from correlational relationships between EEG changes in brain states and behavioural outcomes. Although a wealth of evidence in neurofeedback studies suggest that learning of self-modulating EEG activity can lead to beneficial effects on mental and

behavioural performance, research findings are often based on associations between specific changes of EEG activity and corresponding changes of mental or behavioural outcomes. In consequence, a clear picture of predictable changes or reliable correlations between outcome variables involved in neurofeedback training has yet to consistently established in both clinical and performance research sectors (Vernon, Frick & Gruzelier, 2004; Vernon, 2005). For instance, induced changes of EEG activity do not exclusively occur in the targeted frequency band (Enriquez-Geppert et al., 2013).

In addition, temporary enhancement of EEG amplitude does not necessarily transfer to the observed changes in EEG activity of the targeted frequency range outside of training (Egner & Gruzelier, 2004a). Moreover, since multiple regions of the brain are activated and communicate throughout the brain during the performance of a task, EEG activity underlying different components of the mental processes involved may spread out over the entire cortex, and hence do not entail a simple relationship (Klimesch, 1999; Doppelmayr et al., 2000; Campbell, 2011). The cooperative and interactive nature of multiple brain regions involved in respective functioning, thus have obvious implications for suggesting a high level of complexity of neural dynamics between EEG activity and mental processes. It follows that variable conclusions of neurofeedback effectiveness can be drawn from a failure to identify consistent relationship between changes in EEG signals and outcome variables. Furthermore, changes in EEG signals may also be subjected to external factors outside the immediate electrophysiological processes, such as the training protocol and psychosocial impacts, as discussed in previous sessions.

Taken together, it is possible that neurofeedback can serve as a steppingstone to maximize the strength of research evidence by advancing from making correlational to causal inferences in higher confidence. To guard from the potential effect of drawing conclusion from correlational inference, systematic investigation of training impact on producing predictable neurophysiological

outcomes is needed. Since correlational data can only provide supportive evidence at best, direct manipulation of variables is also necessary. In order to strengthen the ability to derive valid conclusion from correlational data, further investigation with respect to a direct and precise linkage from association to causality is required at the forefront.

Let's assume for the moment that such direct and precise linkages are possible. In other words, changes in mental state and processes can manifest as changes in brain and brain behaviour, and research in neurofeedback is observing and measuring what we intend it to be observing and measuring. Then, the next question is how might one go about designing and conducting a study that would explore and help determine to what extent can the mind alter brain activity such that neurofeedback can be used in a practical manner? This implicates the bandwidth problem, which we turn to now.

# Chapter 5.

# The Problem of Bandwidth

According to a radical view of embodiment, changes in subjective experience must objectively manifest in ways that reflect changes in brain, body, and behaviour, and vice versa. As previously discussed, a growing body of research on neurofeedback points to human's ability to modulate brain activity at will and voluntary changes in EEG can produce enhancing effects on mental and behavioural performances in various ways. In other words, the ability in learning how to modulate brain activities in a given brain area and in a given frequency of our own accord, is a necessary prerequisite to any determinable effect manifested. If mind is indeed embodied in matter, as embodied cognition suggests, then any changes of mind in an individual must simultaneously accompany or be accompanied by changes in one's brain and body.

Concerning educational matters with respect to the mutual relationship between mind and brain, the major questions to ask are whether conscious control of brain activity is possible at will, as well as whether volitional alterations in mental state manifest physiological changes of brain behaviour. The general question as to the extent to which one can identify a mental state according to changes in brain and brain behaviour is beyond the scope of this thesis. The goal here is to explore potentiality of how learning to use our minds can provide an impact on our brains in an equivalently deliberative and determined manner. In other words, what are the educational implications of voluntary changing EEG activity for research and practice with neurofeedback? To what extent, such as in what specific frequency ranges, brain regions and/or combinations, can the mind change brain rhythms?

How quickly and to what duration are such changes possible? What kinds of variance in these abilities are there between individuals? All these questions pertain to the very practical problem of bandwidth; in that the answers to them will determine the speed at which neurofeedback can be used for information transfer. In this chapter, an experimental methodology and design is provided as to how one might begin to address these questions.

## 5.1. ActiMatt: A New Method for Neurofeedback

A recently developed software program at the ENGRAMMETRON lab at Simon Fraser University called *ActiMatt* (Menzies, 2013) is a convenient and non-invasive tool that has been developed for research on neurofeedback. As a modified version of BioSemi ActiView (see Figure 1), a popular EEG measurement system in electrophysiology research, the design and functionality of ActiMatt serves as a sophisticated and flexible tool for educational neuroscience research. Working together as a unified system, these components have been designed for collecting, displaying, and recording changes in EEG signals. One special feature of ActiMatt is the software's functionality with components to receive bio-electrical signals from multiple sensors such as heart rate, respiration, galvanic skin response (GSR), body temperature, electrooculogram (EOG), electromyogram (EMG) and EEG (see Figure 2).

**Figure 1. ActiMatt as a modified version of BioSemi ActiView**

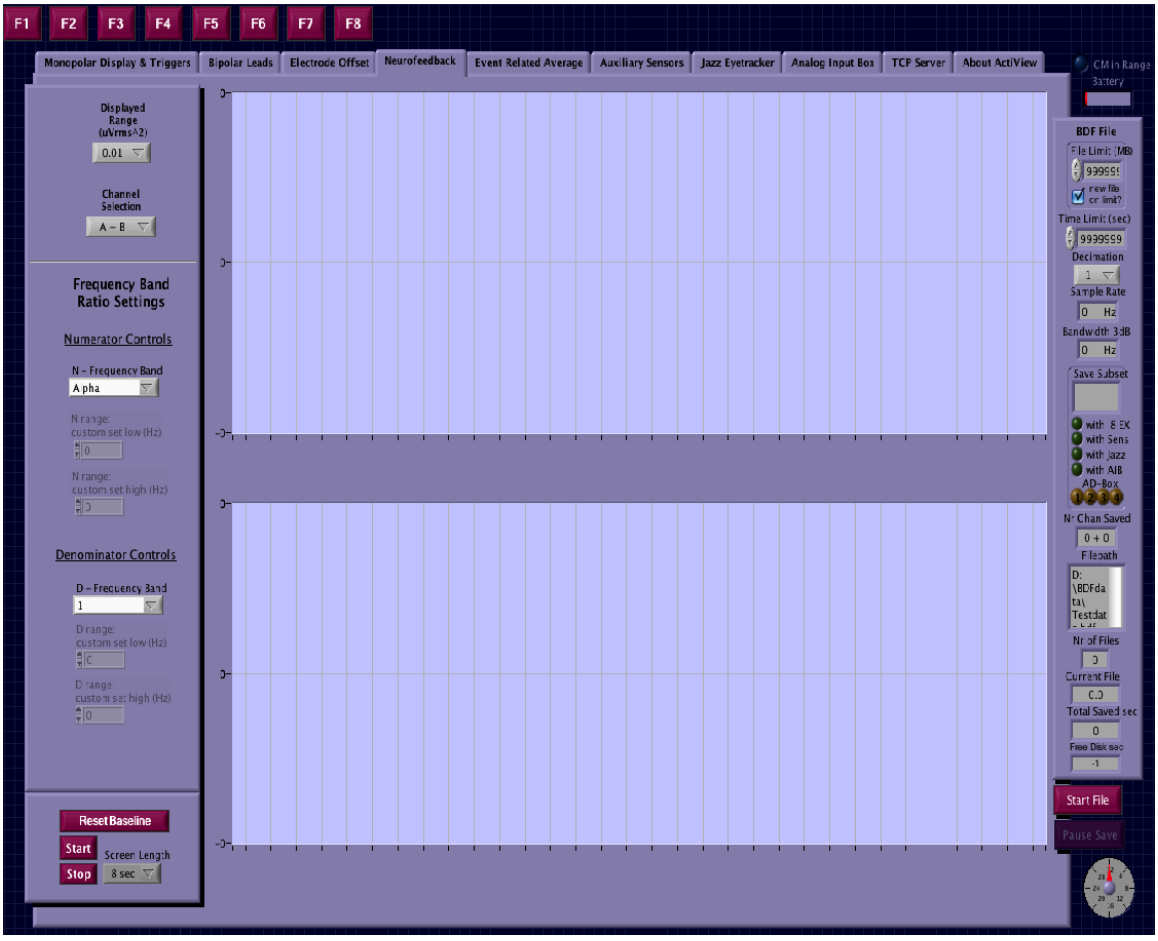
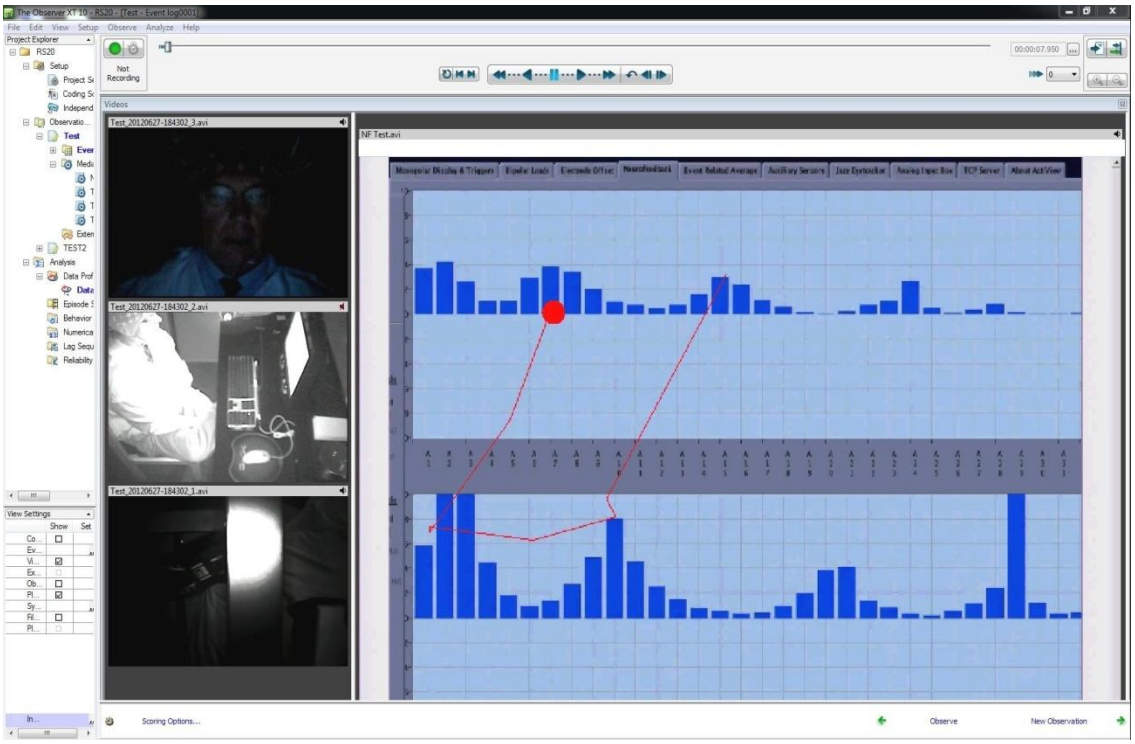


**Figure 2. ActiMatt's multi-functionality in action: to receive bioelectrical signals from multiple sensors**



In comparison to collecting information based on a single electrode with most neurofeedback research tools, this new software offers increased resolution and flexibility to relay concurrent EEG data from as few as 1 to as many as 256 electrode channels. Another advantage of detecting all brainwave activity present in the range of 1-50 Hz, EEG activities in the most commonly studied frequency range are captured. In addition, the use of a user-friendly platform providing graphical programming interface provides different options for users to display real-time visualization of bio-signals as desired (see Figure 3).

**Figure 3. ActiMatt: neurofeedback tab panel (all EEG channels)**


These options include direct representations of a specific frequency band's power, an inverted representation of the band's power, or the ratio of power in any two-frequency bands (see Figure 4, 5, and 6). Also, the software is capable of measuring localized brain activity and provides instant feedback to corresponding brain areas of interest (see Figure 7).

**Figure 4. ActiMatt: neurofeedback bar panel (a specific EEG band)**

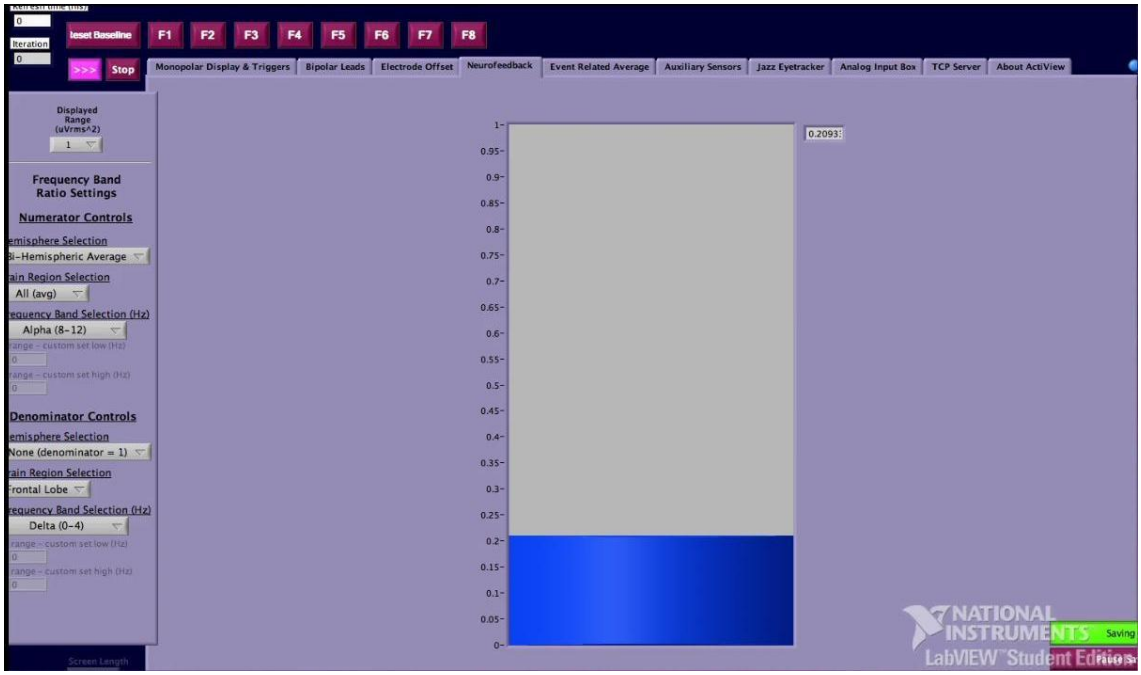



**Figure 5. ActiMatt: detail of user controls for neurofeedback (alpha)**

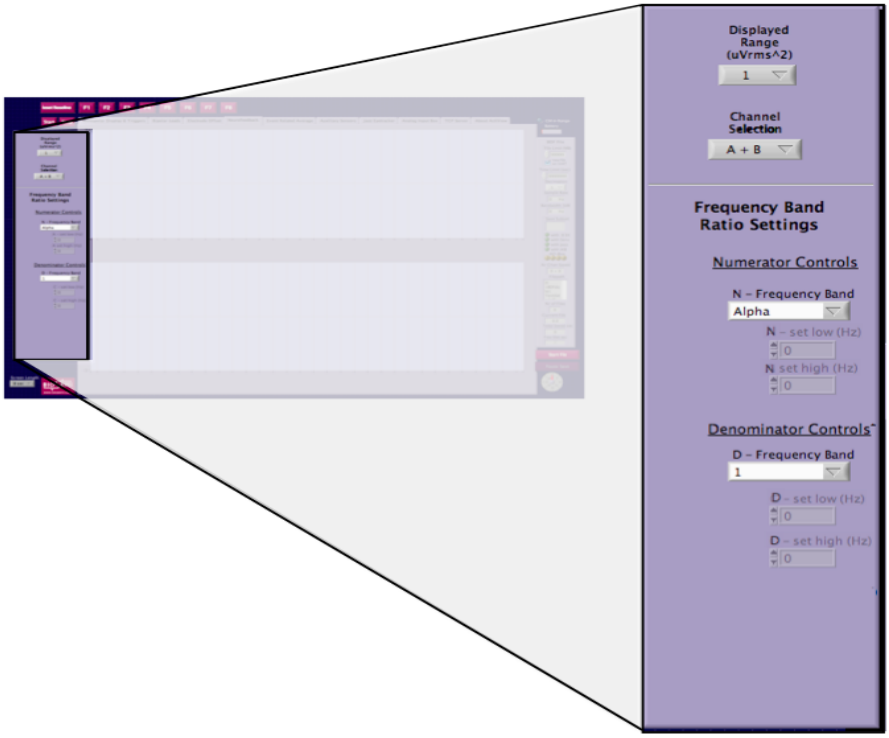


**Figure 6. ActiMatt: detail of user controls for neurofeedback (alpha-to-theta)**

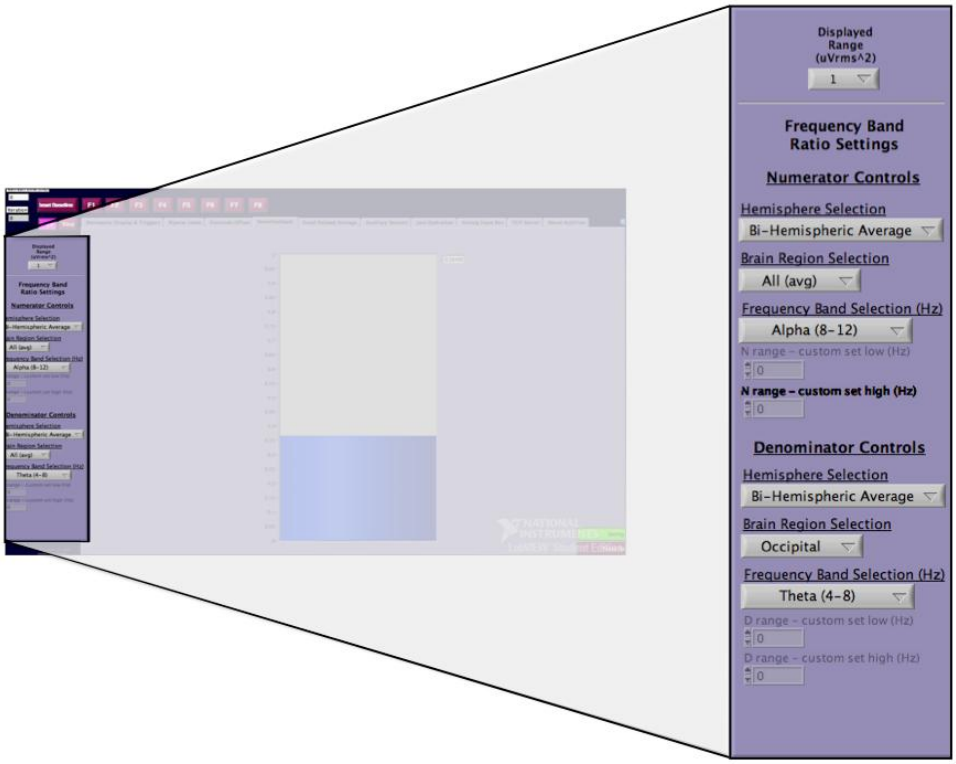
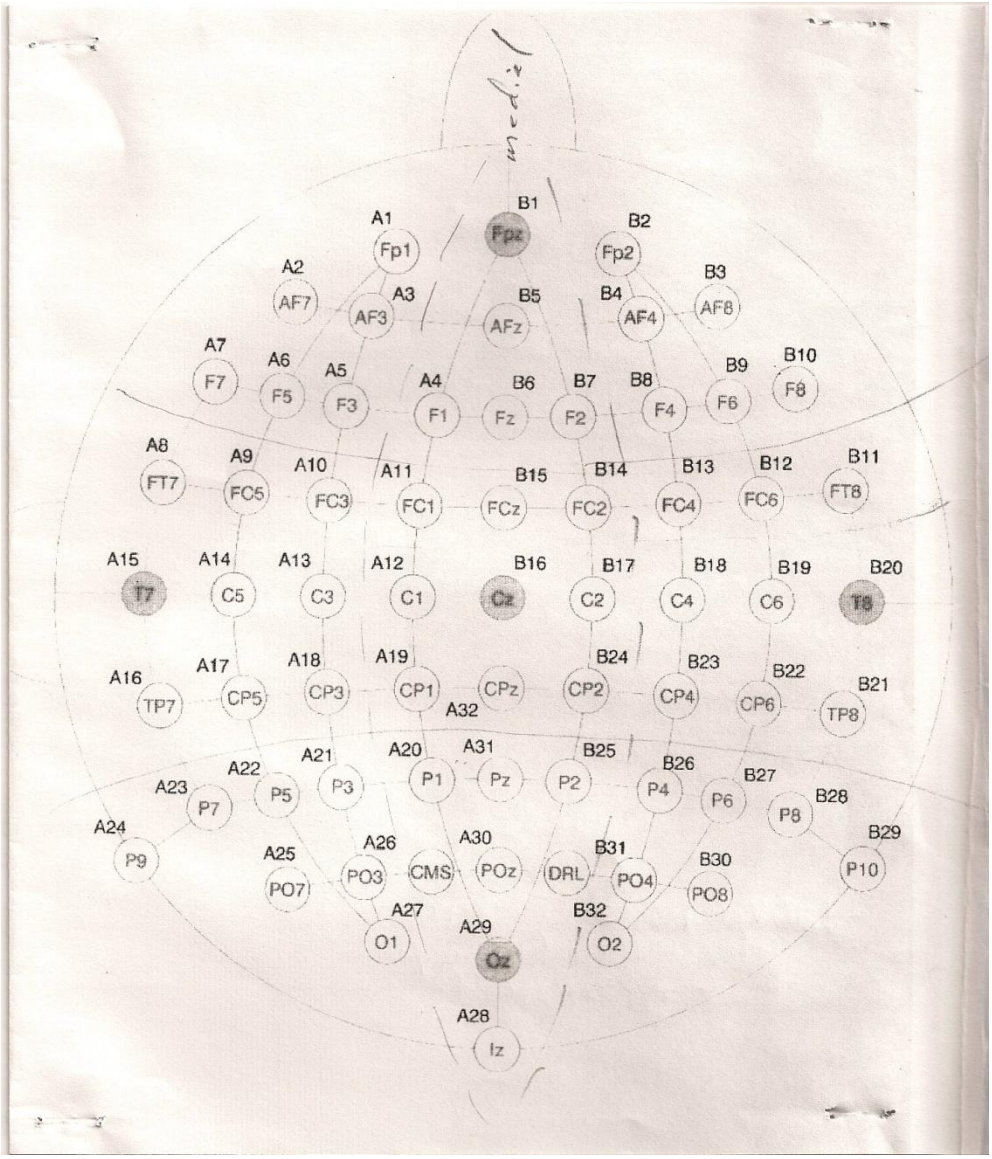


**Figure 7. ActiMatt: localized brain activity scalp locations**




By providing choices for users to define a specific brain region and suitable frequency range, effects of training interactions across and between brain hemispheres and scalp locations can be explored in better scope and extent. After receiving analog electrical signals from each electrode being measured, raw signals are independently and simultaneously converted into 24-bit digital information. Converted signals then are processed for display and for collection in a saved file in

BioSemi Data Format (.BDF) compatible with various data analysis software, such as *Brain Electrical Source Analysis* (BESA) and EEGLAB.

In summary, the ActiMatt software program can be adopted as a valuable research technique for neurofeedback learning. By using a user-friendly interface that offers instant visualization of changes in EEG signals, this non-invasive tool facilitates learning in self-monitoring and self-modulating brain activity in response to immediate, concrete feedback. Also, the precision and versatility of this tool opens up an opportunity for researchers to learn more about how neurofeedback may be used to optimize study on the relationship between EEG control and mental, and behavioural, performances in a comprehensive and objective manner.

## 5.2. What Can Be Done?

One fundamental question of neurofeedback for educational purposes considers whether people can learn to change their own brain activity at will. As a comprehensive and integrative research tool for educational neuroscience research into neurofeedback, learnability of most EEG frequency bands and corresponding brain topography can be better studied using ActiMatt in scope and extent.

### 5.2.1. Refined temporal resolution of measurement

As mentioned above, the discrete-channel neurofeedback utility of this software program covers a wide range of brain wave frequencies. Most EEG band activities studied in research literature hence can be adequately detected and further investigated. With ActiMatt, the self-modulation of EEG changes over the course of training can also be monitored via visual feedback display in real-time. Learning to control a selectively distributed frequency band (e.g., alpha, theta, SMR and beta) and even of relative ratio of different frequency bands (e.g., alpha-to-theta), can be examined at the same time in a single study; the participant can learn

to intentionally increase or decrease the desired EEG frequency band during the course of each training session.

For example, in a hypothetical study, following a pre-feedback baseline measure for a 5-min period with eyes-closed, a participant can engage in single frequency band monitoring consecutively for 5-min intervals with an intention to increase the selected frequency band. Then, after a resting baseline measure for 5-min, again, with eyes-closed, the participant now switches the goal to decrease the same frequency band selected consecutively for 5-min intervals. A 5-min post-feedback baseline measure with eyes-closed can be included to compare any changes in EEG resting potentials. As learning a new skill often requires higher mental effort, a short resting period for 1 to 2 minutes between each consecutive 5-min interval may be deemed beneficial to avoid mental depletion and increase effective control. Not only that the same protocol can be implemented for all EEG bands to investigate learnability of bandwidths in a particular range (e.g., alpha, theta, beta, gamma, etc.) or relative ratio of between frequency bands (e.g., alpha-to-theta), frequency ranges can be further defined to explore a specific band in a fine-grained manner (e.g., upper-alpha versus lower-alpha, beta1 versus SMR, etc.) as well. To maximize experimental validity, participants can be randomly assigned into different training conditions in a counterbalancing order. In addition to demonstrating whether learned changes in brain activity take place in a wide range of frequencies, easiness and readiness of controlling a specific frequency band in various magnitudes can also be examined.

### 5.2.2. Refined spatial resolution of measurement

Although empirical research suggests that selectively distributed brain frequencies superimpose and act as a general oscillatory ensemble that provides integrative brain functions (Basar et al., 2001), localized dominancy of a frequency band in a particular brain region or mental state is also evident. For example, higher

alpha is typically observed in the parietal area and the posterior cerebral regions, whereas higher theta is commonly found in frontal area and hypothalamo- and hippocampal- regions (Hanslmayr et al., 2005; Kirk, 1998). While beta presents in both hemispheres and especially in the frontal regions during active states, gamma in the somatosensory cortex plays a critical role for governing global brain functioning (Demos, 2005; Ribary, 2005). Based on a close relationship between mental state and localized activity in the brain that are mutually influencing each other, the functionality of neurofeedback to provide instant per-brain region response allows monitoring changes in EEG activity relative to scalp locations.

Through the visualized display in a colour-coded scheme, the amplitude of different EEG frequency bands mapped onto the scalp can easily and readily be observed by users. While neurofeedback can optimize the learning experience, exploration of training effects or the interactions between and across cerebral hemispheres, as well as cortical sites, is available for researchers. Therefore, heterogeneous nature of EEG characteristics can be closer examined in a refined manner, and insights on potentiality and restriction of the capacity in human brain can also be gained. As evidence on supporting or refuting the existing literature is strengthened, understanding of brain activity can be deepen and guides prospective research in future.

Taken together, the neurofeedback technique can offer examination of changes in EEG activity in scope and extent. Although the neurofeedback technique offers better temporal and spatial precisions of recording EEG activity, its use is still subject to limitations such as difficulty in detecting sub-cortical electrical signals, individual variability, as well as a lack of motivation. With precise and versatile functionality, neurofeedback can be served as a sharper, flexible tool that can optimize both learning and research experiences. However, future research on optimizing training protocol is needed in order to reveal the full benefits, and to guard any potential limitation, of this technique. Nevertheless, it is now possible to

revise Demos' (2005) suggestion that was previously mentioned as to how long to train and how many cortical sites can be trained during a neurofeedback session is *no longer* more of an art than a science.

## 5.3. How It Can Be Done?

Assuming that our mind is shown to exert effects over brain and brain activity, and that the validity of observing and measuring intentional changes in brain activity is demonstrated by neurofeedback, then, the issue now concerns the practical impact, or extent of changes in brain activity the technique can bring. In other words, if the mind can only make limited changes in brain activity at slow rates of speed, corresponding changes in behaviour or brain functioning in such may be of limited value. If we can expand our mind by consciously altering brain activity in multiple ways, however, then increased rates of information exchange may be facilitated at the same time.

With recent technological advances, it is now possible to explore the question on whether we human are capable of expanding the bandwidth of brain activity under voluntary control in a hypothetical study. Assuming that humans are capable of voluntarily modulating any EEG frequency band in all brain regions, then:

1. the direction of changes, either increasing or decreasing, in a single frequency band can be compared in the same area
2. the degree of changes, both in amplitude and magnitude, in a single frequency band can be compared between different areas
3. the effect of learning or training outcomes can be expanded by comparing multiple frequency bands across, and between, brain hemispheres, and regions, as desired

For instance, if we choose to examine the ability to control alpha (α) in the left hemisphere (LH), then two different outcomes could result (i.e., $2^1=2$) (see Table 1).

**Table 1. Learning outcomes of controlling alpha in LH**

| | **LH** |
|---|---|
| **up α** | *(outcome 1)* |
| **down α** | *(outcome 2)* |

If we compare the ability to control alpha between left hemisphere (LH) and right hemisphere (RH), then four outcomes could result (i.e., $2^2=4$) (see Table 2 and 3).

**Table 2. Learning outcomes of controlling alpha in both hemispheres**

| | **LH** | **RH** |
|---|---|---|
| **up α** | *(outcome 1)* | *(outcome 3)* |
| **down α** | *(outcome 2)* | *(outcome 4)* |

**Table 3. Coding of learning outcomes of controlling alpha in both hemispheres**

| LH | RH | outcome (code) | |
|---|---|---|---|
| 1 | 1 | 3 | *(↑ α in both hemispheres)* |
| 1 | 0 | 2 | *(↑ α in the LH while ↓ α in the RH)* |
| 0 | 1 | 1 | *(↓ α in the LH while ↑ α in the RH)* |
| 0 | 0 | 0 | *(↓ α in both hemispheres)* |

*Note*. While 1 indicates positive outcome, 0 indicates negative outcome

If we now examine the ability to control alpha in three different brain areas such as frontal cortex (FC), occipital cortex (OC) and temporal cortex (TC), then eight outcomes could result (i.e., $2^3$=8) (see Table 4).

**Table 4. Learning outcomes of controlling alpha in three different brain areas**

| FC | OC | TC | outcome (code) |
|---|---|---|---|
| 1 | 1 | 1 | 7 |
| 1 | 1 | 0 | 6 |
| 1 | 0 | 1 | 5 |
| 1 | 0 | 0 | 4 |
| 0 | 1 | 1 | 3 |
| 0 | 1 | 0 | 2 |
| 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 |

*Note.* While 1 indicates positive outcome, 0 indicates negative outcome

Derived from the same logic, if we expand the ability to control the same EEG band to *n* distinct frequency ranges and brain regions, then we will have $2^n$ different possible encoded outcomes.

The implications of being able to identify different frequency range, or brain-area pairs that can be altered in a deliberate manner whereby the power or

amplitude of the given frequency range can be increased or decreased in that given brain area at will, has some potentially profound implications for expanding the bandwidth of brain-machine interfaces. For instance, as noted above, if more than one frequency range, brain-area pair can be altered up or down simultaneously, say, two such pairs, then two bits of information (any one of four instructions) could be executed in the time that only one bit of information (any one of two instructions) could be executed. Because of reset latency, at least twice as fast and with twice the information content. In the case of three such pairs, then, three bits of information (any one of up to eight instructions) could be executed. In other words, again because of reset latency, at least three times as fast with quadruple the information content. As indicated in the tables, different outcomes, or codes, relating to different frequency range, responses of brain-area pair could be assigned to distinct tasks by a brain-machine interface programmer. In this way, an individual could learn neurofeedback in an application independent manner, in a similar sense that learning to type is independent of what one then chooses to type.

Taken together, the neurofeedback application in basic experimental research can serve as a steppingstone that opens the potentiality of transferring from correlational to causal inferences on self-control of changes in EEG. Follow from the qualitative examination of changes in EEG activity and corresponding brain topography, quantitative investigation on bandwidth, or the rate of information exchange, of brain activity under voluntary control is possible. If the mind can volitionally facilitate information exchange in multiple states or areas, rather than making limited changes in brain activity at a slow rate, learning neurofeedback can bring revolutionary impacts of practical and educational values, even if the control of bandwidth can only be expanded a little.

# Chapter 6.

# Educational Implications and Opportunities

## 6.1. Educational Implications

As discussed throughout this thesis, neurofeedback can serve as an innovative learning tool for attending to one's own brain activity. By bringing beneficial impacts to both learners and researchers, great potentials for this technique can be used in diverse educationally relevant areas.

### 6.1.1. Theoretical value: bridging the mental to the physical

Although the debate on the causal relationship of influences between the brain and the body remains puzzling in human sciences for decades, neurofeedback studies promote better understanding of neurophysiology such as the heterogeneous nature of EEG characteristics, and offer valuable insights of a close, collaborative relationship between brain, mind, and functioning. In an attempt to resolve the myth of mind-body interaction, understanding what brain processes exercise direct effects on mental processes is the major focus in neuroscience. For educational purpose, it is also important to understand how mental processes can exercise direct effects on brain processes in a similar vein (Campbell, 2011). When subjective experience can be used to guide analysis and interpretation of neural event in the iterative loop of real-time neurofeedback, online information of physiological variables, in turn, allows conscious access to hidden neural process that is related to the mental activity (Bagdasaryan & Le van Quyen, 2013). Hence, neurofeedback is advantageous in deriving potentialities of both causal relationship

between subjective and neuroscientific data, or the mental and the physical, as well as neurophysiological mechanism underlying neurofeedback function (Bagdasaryan & Le van Quyen, 2013). A credit to technological advancement, human ability to change brain processes according to mental processes, thus, no longer a mystery. Concerning how the mind is related to the physical world of cause and effect, study grounded on quantum physics can also be useful in bridging the subjective self to the objective world (Campbell, 2011).

### 6.1.2. Experimental value: mixed methods research design

Although research in recent years has called for an increased emphasis on informing educational practice through advances in neuroscience, educational research is still attacked by its lack of a scientific evidence-based foundation (Campbell, 2006). As a research technique for designing, collecting, analyzing, and incorporating both quantitative and qualitative methods, neurofeedback can be a helpful tool to understand a research problem in a single study. When both quantitative and qualitative data, together, provide a better understanding of brain electrophysiology, valuable insights with respect to both potentialities and limitations of the human brain can be gained. With a possibility to adopt a mixed method research design in neurofeedback, educational neuroscience can combine both qualitative and quantitative methods of research in a more rigorous manner (Creswell, 2015). Therefore, how neurofeedback technique may be used, and be expanded, in a rigorous manner are important considerations for optimizing the learning process, as well as the training experience, on attending to one's own brain activity in future research.

### 6.1.3. Practical value: neurofeedback as brain-computer interface (BCI)

Brain-computer interface (BCI) is a neuroscience technique of using the mind as a machine that serve a similar function as neurofeedback. Through direct

communication pathways between the brain and an external device, a BCI system can be used for directing voluntary control of brain activity at assisting, augmenting, or regulating cognitive activity and sensory-motor functions (Curran & Stokes, 2003). Applying neurofeedback as an extension of BCI systems extracts user's intentions from his or her brain activities; this method enables users to gain voluntary control of their cortical oscillations through moment-to-moment information from their EEG activities (Curran & Stokes, 2003). By learning to self-regulate EEG signals, participants aim at changing their brain patterns in response to feedbacks, so that voluntary manipulation of brain activity can be used to control external devices such as computers, switches, or wheelchairs.

Designs of both BCI systems and neurofeedback training require a learned skill to control and self-regulate brain activity at will to assist subsequent mental or behavioural performances. The nature of BCI and neurofeedback can be perceived as adaptive learning tools serving higher functioning purposes. Let us consider typing as an analogy. Learning to type is also an acquired skill that requires voluntary mental control for external devices and executing behavioural tasks. When we first learn to type, we start off with stroking one single key. As our typing skill improves, we gradually learn to type out all the letters, words, sentences, paragraphs and meaningful passages in progression. By connecting each component of an acquired skill to a meaningful whole, beneficial outcomes contributing to higher functioning follow.

In a similar vein, when we first acquire the neurofeedback technique as a new skill, we may begin by learning to execute a single task or behaviour through voluntary control of a specific EEG frequency band in a particular brain region. When we begin to excel with the learned skill to change brain activities at will, our abilities to perform different tasks and behaviours in different brain regions at the same time may be feasible. For instance, if one could learn to alter five specific brain region-frequency pairs simultaneously in such a manner as to detectibly, via EEG,

increase or decrease brain activity in each as described above, then one could encode 32 ($2^5$) states and assign each permutation a number and each number a distinct meaning. In other words, responses of brain-area pair could be assigned to distinct tasks by a brain-machine interface programmer as different outcomes, or codes, are related to different frequency range.

In this proposed program of neurofeedback training, what is required is to: 1) determine which frequency range and areas of the brain are most responsive to mental instructions, 2) determine if the mind can issue commands to the brain that can alter more than one frequency range brain-area pair simultaneously, and 3) to determine if there are certain frequency range brain-area pairs that are most easily controlled mentally by most people. If all of these are possible, this approach would result in neurofeedback training in a vocational sense, much akin to teaching students to type. Once the student knows how to type, they can type whatever they wish. In a similar manner, once students learn how to control brain response, then, they will know how to control various brain-machine interface applications.

As described earlier, the amount of mental effort required is often reduced when a skill is well practiced and becomes routine. Although we usually are unaware of how our body movements take place, physical actions nonetheless are under voluntary control and require little, or even no, conscious effort. Our goal is to be able to consciously control brain activity via voluntary and automatic skill with learning and practice, thereby offering beneficial contributions to mental and behavioural performances.

## 6.2. Educational Opportunities

The neurofeedback technique can be perceived as an acquired skill, or learning process, for self-regulating the brain and the mind. Adopted from the principle of operant conditioning, neurofeedback empowers individuals to learn

using their minds with volitional control to achieve particular mental or behavioural outcomes. As modulation of neurophysiological substrate depends on the sensory information fed back to the individual, feedback signals play a crucial role in controlling physiological processes (Sulzer, Sitaram, Blefari, Kollias, Birbaumer, Stephan, Luft, & Gassert, 2013). When appropriate signals conveying information of relevant changes in brain states are constantly fed back to the learner as a circuitry, timing of the feedback signal throughout the entire feedback loop via neurofeedback can serve as an immediate, powerful reward for learning to self-regulate brain activity as soon as the desired brain state is achieved (Bagdasaryan & Le van Quyen, 2013). The ability to control over brain activity, therefore, is a general property of the brain that can be learned for different neural profiles and various clinical, or cognitive, conditions when appropriate feedback information is provided (Bagdasaryan & Le van Quyen, 2013). Since neurofeedback serves as a self-driven technique, active engagement of a learner is encouraged to maximize automatization of changing EEG activity as a new form of learning for producing ideal mental and behavioural outcomes. Successful learning of self-modulation and self-regulation of the brain in a specific mental state (e.g., to relaxing our mind and focus attention on a task) when necessary can, in turn, lead to corresponding changes of cognitive and behavioural performances in a beneficial manner.

### 6.2.1. Developmental value: adaptive learning skill for higher functioning

A good analogy for considering neurofeedback as a learned skill in humans can be derived from the relationship between human motor development and acquisition of early prehensile skills. In the first few weeks after a baby is born, the newborn relies on reflexive grasp toward the object without control of gross movement with the hands (Vasta, Younger, Adler, Miller & Ellis, 2009). By 4 months of age, the infant starts to show deliberate movement towards an object in a more consistent manner (Vasta et al., 2009). By 6 months of age, the baby starts to

gradually coordinate his/her fingers (Vasta et al., 2009). At 9 months of age, prehensile skill begins to emerge as finer control of individual fingers is established, and especially between forefinger and thumb (Vasta et al., 2009). By 12 months of age, prehensile skill is fully acquired and the baby is now capable of holding crayon adaptively to make marks on paper (Vasta et al., 2009).

By the same token, developmental stages progressing from mere reflexes toward self-producing motor skills under fine control can be conceptualized in a similar way for acquiring neurofeedback skill in humans. First, acquisition of both prehensile and neurofeedback skills requires transfer of a manipulative skill from reflexes to deliberation and fine control, in a gradual progression. Second, awareness of when and how brain messages and movements take place is often lacking, except at the very beginning of learning until automatic control of the acquired skill is accomplished. Third, both skills involve an ability to use the learned skill as an adaptive tool for higher functioning purpose. For instance, prehension can be used for eating and exploring the surrounding environment, whereas neurofeedback can be employed for optimizing cognitive abilities and behavioural performance. Last, both skills can play a significant role in other aspects in human development such as acquiring knowledge, gaining self-control, and achieving self-competence.

Although acquisition of motor skill is a key feature in human infancy and continues throughout development, this is not the case for neurofeedback. As Rabinpour and Raz (2012) suggest, neurofeedback trainings which begin early in childhood can provide greater beneficial impacts of developmental psychopathologies in the long run. Given that both the skills require a learning process which can bring beneficial impacts to human, there is great potential for learning and developing neurofeedback as an adaptive skill.

### 6.2.2. Clinical value: adapted learning program for inclusive education

As learning requires intellectual abilities which involve different psychological functions associated with different parts of the brain, it follows that the human brain and learning experiences are intimately related. Given that research on neurofeedback and its clinical utility has demonstrated a lot of promising outcomes for individuals in clinical populations, how can learners and educators benefit from such positive effects of neurofeedback in classroom learning?

Due to contemporary emphasis of Canadian policies on inclusive education, it is not surprising that students whose academic abilities, social skills, and motivation for learning can vary widely in education classrooms. While placing students with special needs in neighborhood schools, teachers often encounter students with different levels of intellectual and learning difficulties, and especially those who are diagnosed as having learning disabilities (LDs), within general education classrooms. In general, LDs refers to disruption of acquiring, organizing, retaining, understanding or using verbal, or nonverbal, information that results from impairments in intellectual processes, such as perceiving, thinking, remembering or reasoning (Woolfolk, Winne, Perry & Shapka, 2010). LDs can range in severity and scope and often co-exist with various difficulties including attentional, behavioural, and emotional disorders, or other medical conditions (Woolfolk et al., 2010). Since learning and behavioural functioning are interfered, academic achievement and life skills are also often hindered in result.

By exerting positive clinical effects in stabilizing disruptions of central and autonomic rhythmicity, learning experiences for students with special needs can be benefited from the direct impact of neurofeedback on facilitating attentional, arousal and affective regulations as desired. When cognitive or psychological processing is improved, acquisition of knowledge and academic achievement, in

turn, can be fostered. For instance, in a matched-controlled study with children with LDs, improvements on attention and performance IQ following theta-to-alpha training persisted after two years (Niv, 2013). In addition, consider ADHD as an example of students with learning difficulties, neurofeedback trainings, lasted from 30 to 45 minutes on a weekly basis, were found to be an effective supplement to special education in improving attentional and behavioural control, reading comprehension and composition, intelligence and continuous performance, as well as cooperation and school work in the class room (Orlando & Rivera, 2004; Rabinpour & Raz, 2012). Moreover, in a series of studies on children with ASD and Asperger's syndrome, 20 to 36 neurofeedback training sessions were found effective in reducing autistic symptoms and improving performance in multiple areas, including attention, language, cognitive awareness, executive functioning and physical health, compared to the control group (Darling, 2007). Furthermore, in another study incorporating neurofeedback as a part of Individual Education Plan (IEP) for children who are diagnosed with severe ASD (Level 6), academic, cognitive and behavioural performances were improved by reducing 64% of the autistic behaviour in the classroom setting after the first 28 training sessions (Darling, 2007). By allowing students to learn to regulate their own emotions and stress responses, neurofeedback can be used to support academic learning by stimulating intellectual abilities for self-motivating learners in the face of challenges, or alleviating anxiety level which interfere with attention processing (Niv, 2013; National Institutes of Child Health and Human Development, 2004). As comparable to its therapeutic effects in clinical studies, therefore, integrating neurofeedback in school settings has begun to emerge in recent scientific literature (Darling, 2007; Walther & Ellinger, 2010).

As neurofeedback researchers, we are pleased to see a growing public awareness and support of neurofeedback in relevant to academic, behavioural, and emotional interventions for children and adolescents in school and educational settings. Whether the goal of treatment is to enhance performance or mood as a

means to improve functioning and well-being, or if used to reducing medication dosage for students with special needs, neurofeedback can improve intellectual abilities, cognitive functions, or psychological processing, and fosters knowledge acquisition as well as academic achievement. Neurofeedback as an adapted program, therefore, can strengthen the connection between the brain and education by opening up an enriched environment and promotes diverse learning.

### 6.2.3. Practical value: potentiality and restriction of using human mind as a machine

As discussed in the previous section, both BCI and neurofeedback can be perceived as an adaptive learning tool supporting voluntary control and regulation of brain activity to assist higher functional purposes. With the advantage of incorporating neurofeedback as a BCI system, this technique can be expanded to offer better temporal and spatial resolutions of measuring a wide range of EEG frequencies in multiple brain areas. In addition to optimizing learning experience for learners, researchers can gather valuable information regarding underlying interactions between, and across, cerebral hemispheres, as well as cortical sites, by using the neurofeedback technique. If a particular mental or behavioural outcome following voluntary changes of a distinct EEG band in a specific brain area can be confirmed, then the use of neurofeedback can be expanded by covering other EEG frequencies in multiple areas. However, if voluntary changes of EEG fail, then restriction, or challenge, of brain state for practical application can be identified and assessed, thereby guiding future research. The insights of potentiality and restriction of the human brain that can be gained via neurofeedback is analogous to exploring the maximum weight we can lift up with our arms while noting that it is impossible to lift anything with our arms bending backward.

Therefore, the aim of neurofeedback is to identify specific brain regions and frequency ranges where the brain can respond to willful intentions of the mind to see if the brain can respond in such manners simultaneously on command. Not only

that the nature of EEG characteristics can be closer examined in a refined manner, insights with respect to both potentiality and restriction of brain state can also be gained by the virtue of neurofeedback. If potentiality of neurofeedback can be expanded in horizon and its application can be applied as a new form of learning as early as possible, then exercising neurofeedback as an adaptive skill may make way in opening a new world of educational opportunities.

# Chapter 7.

# Conclusion

This thesis began with the question as to whether it is possible that attending to one's own brain activity in various ways could open a new world of educational possibilities in the 21st century. Although there have been a multitude of factors to consider, this thesis has basically addressed this question in the affirmative, with several important qualifications and conditions. Addressing this question in the affirmative has involved engaging some very difficult issues at the very heart of philosophy, science, and engineering. The aim of this thesis, however, has not been to provide a definitive answer to this question, but rather to break it down into three interdependent fundamental problems, each of which must, in turn, be addressed in the affirmative.

Imagine that our minds really can control matter. Not in the sense of bending spoons, or levitating rocks, but by controlling the activity of our own body, such as raising an arm, or more to the point that concerns us here, by using our minds to effect the activity of our brain in equivalently deliberate determined ways. As simple and straightforward as this may sound, it presents us with our first challenge. How is it that our minds can have an effect on our brains? This is an important special case of the famous mind-body problem addressed here by adopting an embodied view of cognition and learning. This is the problem referred to herein as *the problem of causality*. The embodied view is not so much a solution to this problem as it is a philosophical framework for understanding why it is not actually a problem at all. Accordingly, the brain is part of what the mind is. For any opportunities that may exist for neurofeedback in education requires that it is possible for the mind to have

a controlling effect on brain behaviour. Hence, this becomes less of a theoretical problem and more of a practical one.

Assume that any study of the mind can be operationalized scientifically by observing and measuring brain behaviour, this problem of causality regarding neurofeedback presents us with a second fundamental challenge for neurofeedback in education. If our minds do not affect brain activity, how can neurofeedback be taken seriously? This is *the problem of validity*. As we have seen, there are many aspects to validity, but from the perspective of embodied cognition, the mind does affect brain activity. Accordingly, this problem is not so much a problem as to whether the mind can affect brain and brain behaviour, but more a problem of ensuring that we are actually measuring what we think we are measuring.

Given that it is possible for minds to have an effect on brain and brain behaviour, and that research in neurofeedback is observing and measuring what we intend it to be observing and measuring, what, then, are the limitations of neurofeedback? If the mind can only make limited changes in brain activity at slow rates of speed, such changes may thereby be of limited value. This is *the bandwidth problem*. In this thesis a viable approach to empirically addressing the bandwidth problem has been presented. Although it is beyond the scope of this thesis to actually conduct such a program of research, a conceptual framework for such an investigation has been provided. The aim of such an investigation will be to identify specific brain regions and frequency ranges where the brain can respond to deliberate willful intentions of the mind, and then to see if the brain can respond in such manners simultaneously on command.

The implications and opportunities of neurofeedback for education are contingent on addressing all three of these problems. This thesis has addressed each of these fundamental problems for research in neurofeedback and the challenges they present, in order to more readily identify and assess the possibilities for neurofeedback in education. As Campbell (2011) claimed, "[neurofeedback can]

empower learners through the volitional application of minds to consciously perceive and alter their own brain processes into states more conducive to various aspects of learning" (p. 9). Hence, neurofeedback can be conceptualized as a coaching practice on EEG to voluntarily train the brain to function at its maximum potential. As a personal training that challenges the brain to optimize its function, neurofeedback serves a similar function to the brain when we learn to exercise, enhance and maintain fitness and wellness of our electrophysiological capacities governing psycho-behavioural functioning.

Although, as we have seen, there are many applications of neurofeedback that address particular applications, or outcomes, in addressing the bandwidth problem, we have also seen that using neurofeedback to directly alter brain response as an end in itself, rather than as a means to another end, has the potential to greatly expand the applicability of neurofeedback. For instance, instead of training an individual to move a computer cursor on a computer screen either up and down, and/or left and right, and then training that same individual to move a wheel chair forward and backward, and/or left and right, the approach proposed in the previous chapter would enable one to use neurofeedback to learn to alter their own brain in specific ways, that could then be used to interface with any applications.

As has also been noted, there are many cognitive states and processes that have been found to be associated with increased levels of activity of one frequency range, or another in one brain region or another. For example, as previously mentioned, increased alpha activity in the left frontal cortex has been found to be associated with calm and relaxed mental states. In using neurofeedback as a means to deliberately alter the power, or amplitude, of different frequency range, brain-area pairs there could be of ancillary benefits as well, based on the cognitive effects of such alterations. In other words, a by-product of increasing alpha in the left frontal cortex could have implications for students afflicted with math anxiety.

Consider education as a form of learning in which cognitive abilities such as knowledge and skills can be guided and transformed through teaching, a valid and correct way of neurofeedback training can enlighten and foster the human brain for higher functioning in a similar manner. By promoting conscious awareness of our mind-body interaction in a concrete and observable manner, neurofeedback possess a great benefit of enriching our brain by strengthening electrocortical patterns while increasing mental flexibility. If attending to, and learning of, one's own brain activity in practical ways can be confirmed by valid and reliable scientific techniques, then, opportunities of neurofeedback for education can be broaden in significant value. With contemporary advancements in neuroscientific research and brain recordings, discovery of neurofeedback as a fruitful tool for attending to one's own brain activity has begun to make headway in opening a world of educational possibilities in the 21st century.

In order for any aforementioned potentialities of neurofeedback to be possible, however, there is the larger context in which neurofeedback finds itself, and that is squarely between the broad areas of education and neuroscience. As a matter of fact, teaching children in classrooms is a very different vocation than studying neuronal behaviour in brains. It is not surprising, therefore, that many educators, such as teachers, administrators, researchers, policy makers, remain prudent and sceptical regarding the role of the neurosciences in education, let alone the role of neurofeedback. However, while teaching and learning are much more closely aligned with the humanities than the sciences, many, if not most, neuroscientists are less concerned with volitional mental states than the structures and mechanisms underlying brain and brain behaviour. As a result, one might say there is a huge cultural gap between educators and neuroscientists that could present many obstacles to achieve the potential of neurofeedback in education. Hopefully, this thesis can help, in some measure, to overcome some of these challenges in the educational neuroscience field.

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