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Exploring Neurofeedback Learning Using a Neurofeedback Treatment for Central Neuropathic Pain after a Spinal Cord Injury

by

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Thesis for the degree of doctor of philosophy

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Abstract

FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

School of Engineering

Thesis for the degree of doctor of philosophy

EXPLORING NEUROFEEDBACK LEARNING USING A NEUROFEEDBACK TREATMENT FOR CENTRAL NEUROPATHIC PAIN AFTER A SPINAL CORD INJURY

By Krithika Anil

Early evidence suggests that individuals can learn voluntary modulation of their own brain activity, called neurofeedback, to relieve central neuropathic pain (CNP) after a spinal cord injury (SCI). CNP after SCI is a life-changing illness that is difficult to treat. Neurofeedback that uses electrical brain activity (electroencephalogram; EEG) is a non-invasive and non-pharmaceutical treatment, which minimises side-effects. Thus, a neurofeedback system was developed in previous work targeting EEG activity associated with CNP after SCI in order to relieve pain. However, it was unclear how individuals become successful at neurofeedback and current literature on neurofeedback learning is sparse and inconsistent. The aim of this thesis was to explore mental behaviour during neurofeedback training to understand neurofeedback learning. This was done by examining mental strategies used by participants during neurofeedback training, questionnaires of general learning factors, and autonomic responses during neurofeedback training.

Twenty-five able-bodied individuals (13 female, mean age = 30.96) and ten individuals with CNP after SCI (3 female, mean age = 51.70) completed neurofeedback training on four separate visits, where interviews were conducted after each visit. Standardised questionnaires examined the influence of general learning factors (self-efficacy, locus of control, motivation, and difficulty) on neurofeedback success. Autonomic responses (heart rate, respiration, and galvanic skin response) were examined in relation to neurofeedback success. A framework model and thematic analysis were used to examine qualitative interview data. Descriptive statistics and correlations were used to examine quantitative data.

No mental behaviour differences were found between able-bodied individuals and individuals with CNP after SCI. Perceived performance of the neurofeedback task seemed to influence participants' approach to achieving the neurofeedback task. Negative affect was somewhat associated with being unsuccessful at neurofeedback. Only self-efficacy had a moderate correlation with neurofeedback success ($r =< 0.587$, $p =< 0.020$). No autonomic responses were significantly correlated with neurofeedback success. The mental behaviour of 70% of participants were directly inspired by the user interface design. Interviews revealed five types of success goals created by participants to assess their neurofeedback performance; not all goals aligned with the researchers' success goal despite reminders of the task instructions. Furthermore, no participant could focus on more than one piece of information from the user interface at once. A third of participants reported that the interface design interfered with their neurofeedback performance. This thesis displays the complexity of behaviour involved in neurofeedback learning that future research should acknowledge, and particularly emphasises the importance of a user interface design that facilitates neurofeedback learning.

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Research Thesis: Declaration of Authorship

Print name: Krithika Anil

Title of thesis: Exploring Neurofeedback Learning Using Neurofeedback Rehabilitation for Central Neuropathic Pain after a Spinal Cord Injury

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
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6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:
    - Anil, K. et al. (2019). Neurofeedback for central neuropathic pain: understanding successful neuromodulation in able-bodied and spinal cord injury participants. Oral Presentation, European Health Psychology Society Conference 2019
    - Anil, K. et al. (2019). Neurofeedback for central neuropathic pain treatment: mental strategies used for successful neuromodulation. Oral Presentation, Congress on NeuroRehabilitation and Neural Repair 2019

Signature: Date:

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List of Abbreviations

AB	Able-bodied participants
ADHD	Attention deficit hyperactivity disorder
ALS	Amyotrophic lateral sclerosis
ASIA	American Spinal Cord Injury Association
C	CNP participants
CI	Confidence interval
CNP	Central neuropathic pain
COREQ	Consolidated criteria for reporting qualitative research
ECG	Electrocardiogram
EEG	Electroencephalogram
EMG	Electromyogram
EPR	Expected pain relief
ERD	Event-related desynchronisation
fMRI	Functional magnetic resonance imaging
GSR	Galvanic skin response
KUT	Kontrollüberzeugungen im Umgang mit Technik
LoC	Locus of control
MS	Mental strategy
PI	Point increase
RSP	Respiratory rate
SCI	Spinal cord injury
SD	Standard deviation
SE	Self-efficacy
SMR	Sensory-motor rhythm
SP	Successful participants
TA	Thematic analysis
TCD	Thalomocortical dysrhythmia

Chapter 1 Thesis Introduction

This thesis explored how individuals use a novel technology called neurofeedback; neurofeedback is a system in which individuals learn to voluntary self-regulate brain activity using an external, real-time representation of that brain activity. This is achieved by associating a specific mental behaviour to the correct changes in brain activity, and then repeating this mental behaviour to continue inducing these changes. However, neurofeedback literature provides little information on how individuals learn this self-regulation. An understanding of how individuals achieve neurofeedback success is important to the guidance given to users and the users' performance. Before discussing neurofeedback learning, the usefulness of the current neurofeedback system will first be detailed.

Neurofeedback has been used to enhance cognitive performance (e.g. working memory [1]) or as a treatment (e.g. ADHD [2]), and uses measurements of various brain activities such as blood flow (functional magnetic resonance imaging; fMRI) or electrical brain activity (electroencephalogram; EEG). The current neurofeedback system is based on EEG and aims to treat central neuropathic pain (CNP) after a spinal cord injury (SCI). CNP after SCI is pain that arises from direct damage to nerves in the spinal cord [3, 4]. CNP after SCI does not respond well to medication and patients are usually referred for further treatment, which is usually ineffective [5, 6]. A neurofeedback treatment was developed because it offered a non-pharmaceutical, non-invasive treatment option with minimum side-effects. Furthermore, the neurofeedback system can be used at home, allowing patients who have reduced mobility to use the treatment in their own time.

The neurofeedback treatment was developed by Vuckovic et al [7], who examined motor cortex activity by comparing paraplegic patients who have CNP, paraplegic patients who do not have CNP, and able-bodied individuals. They found that during motor imagery, those with CNP had increased activity in specific EEG frequencies (theta and alpha frequencies) compared to the other participants groups. A pilot study recruited seven patients with CNP after SCI and examined which specific combination of EEG frequencies would induce pain relief for CNP after SCI [8]; reducing theta and beta frequencies while increasing the alpha frequency were found to be associated with pain relief. This pilot study provided promising results showing that neurofeedback training produced pain relief of CNP after SCI. Further development of this neurofeedback treatment would involve a larger sample size, a sham trial to test for a placebo effect, and a control group.

However, an instinctive question regarding how individuals are able to achieve neurofeedback success fuelled a literature search that produced limited and inconsistent information. The lack of conclusive information on neurofeedback learning prompted an investigation into this topic using an explorative approach; a research question, instead of a hypotheses, was used as the foundation for examination: “how do individuals become successful at neurofeedback?” It is emphasised to the reader that this thesis examined the neurofeedback learning process and not the effectiveness of this technology. The explorative approach combined qualitative and quantitative examinations, where participants (able-bodied individuals and individuals with CNP after SCI) were interviewed about how they attempted neurofeedback and asked to complete questionnaires measuring psychological variables (locus of control, self-efficacy, neurofeedback difficulty, and motivation). Autonomic responses (heart rate, breathing rate, and galvanic skin response) were also measured to understand if neurofeedback learning related to changes in physiology beyond those directly related to EEG. Intensity and quality of pain felt by participants with CNP after SCI were also measured to understand if having pain influenced behaviour towards neurofeedback learning. This explorative approach provided key contributions to the research area by displaying the depth of behavioural complexity influencing neurofeedback learning not previously acknowledged by the majority of current neurofeedback literature. Incorporating this behavioural complexity in future research may resolve the current inconsistent information on neurofeedback learning.

This thesis first provides a background on two core elements of the research: CNP after SCI and neurofeedback. This is followed by a literature review on the main research topic of neurofeedback learning. A methodology chapter briefly discusses the underlying philosophical assumptions of the chosen research paradigms and method; this precedes the methods chapter. The complexity of the data set prompted the organisation of results into three chapters presenting qualitative findings, a mix of qualitative and quantitative findings, and unexpected findings regarding the neurofeedback interface design (chapters 6, 7, and 8 respectively). Thus, the analysis plan is not written in the methods chapter, but split across the three results chapters. The thesis concludes with a general discussion and suggests directions for future research.

Chapter 2 Background to Central Neuropathic Pain and Neurofeedback

This chapter provides background information on the core topics of this thesis. This includes the basic mechanisms of CNP after a SCI and EEG-based neurofeedback. This chapter also presents the neurofeedback system examined in this thesis and how it may reduce CNP after a SCI. The final section of this chapter outlines the main aim of this thesis to provide a foundation for the literature review on neurofeedback learning in the next chapter.

2.1 Basic Mechanisms of CNP after SCI

Pain is defined as "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" [9], and can be divided into nociceptive pain and neuropathic pain[1]. Nociceptive pain is caused by actual or potential damage to non-neural tissue, such as a bruise or burn, and is the most common type of pain that individuals experience. Neuropathic pain is defined as "pain arising as a direct consequence of a lesion or disease affecting the somatosensory system" [10], and its estimated prevalence in the general population is between 6.9% and 10% [11]. Neuropathic pain is a complex pain system in which the current poor understanding of physiological and psychological mechanisms makes treatment challenging. Furthermore, the mechanisms of CNP change depending on its cause. While there are many causes of CNP, this thesis will focus on CNP after SCI. The main areas affected by CNP after SCI are the brain and the spinal cord, presented below.

2.1.1 Basic Structure of the Brain and Spinal Cord

The brain consists of the cerebrum, the cerebellum, and the brain stem (Figure 2.1). The cerebrum is the largest brain structure consisting of the left and right hemispheres, which can be divided into four areas: frontal lobe, parietal lobe, temporal lobe, and occipital lobe (Figure 2.1). Within these

[1] A third category of pain has been recently introduced by the International Association for the Study of Pain called nociplastic pain [1], defined as "pain that arises from altered nociception despite no clear evidence of actual or threatened tissue damage causing the activation of peripheral nociceptors or evidence for disease or lesion of the somatosensory system causing the pain". This pain was not included in the main text to avoid distraction from the focus on neuropathic pain.

lobes, different functional areas exist, such as the motor area, sensory area, visual area, auditory area, and others. The neurofeedback system examined in this thesis monitors the brain activity produced by the motor and sensory areas (this monitoring is described in a later section). The motor area, or the motor cortex (within the frontal lobe), refers to brain regions that are involved in the planning, control, and execution of voluntary motor functions. The sensory area, or the primary somatosensory cortex (within the parietal lobe), refers to brain regions that control and process sensations of touch, such as pressure, vibration, pain, and temperature. Together, these brain regions can be referred to as the sensory-motor cortex.

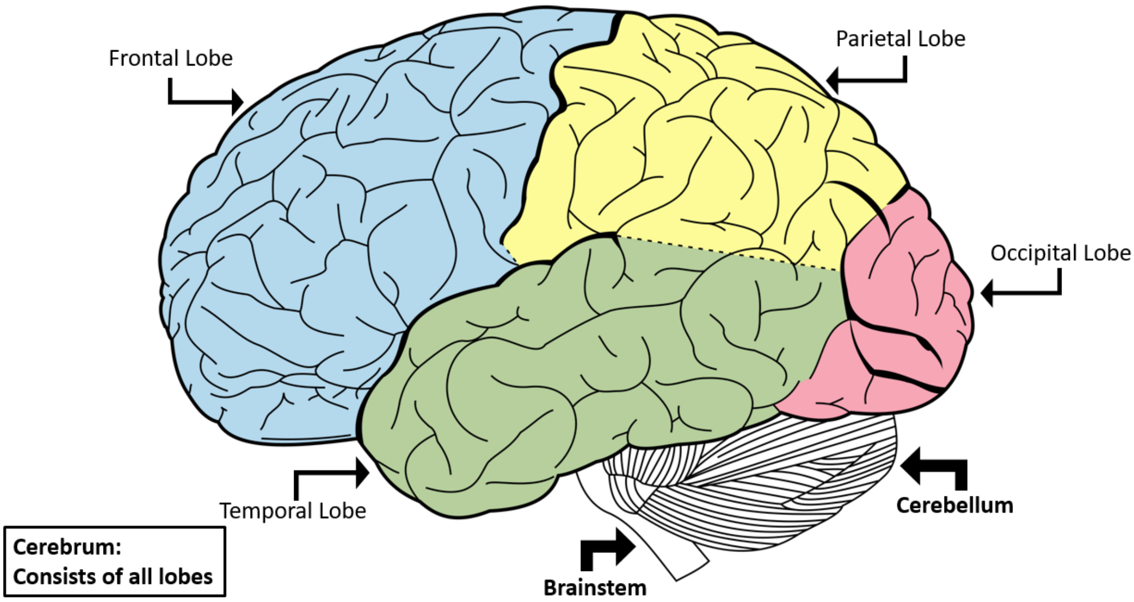


Figure 2.1 Diagram showing the basic structure of the brain [12]

The spinal cord is a long, tubular structure consisting of nervous tissue extending from the brain stem to the coccyx (Figure 2.2), and is the primary pathway for nerve signal transmission. The brain and the spinal cord together make up the central nervous system. The spinal cord is segmented into 31 sections, each containing a number of nerve pairs called dorsal and ventral roots that send information to and from the brain respectively. The segments are named according to the vertebral structure that encases each segment: eight cervical segments (C1-C8), twelve thoracic segments (T1-T12), five lumbar segments (L1-L5), five sacral segments (S1-S5; segments not depicted in Figure 2.2 but refers to the region labelled as “Os Sacrum”), and one coccygeal segment.

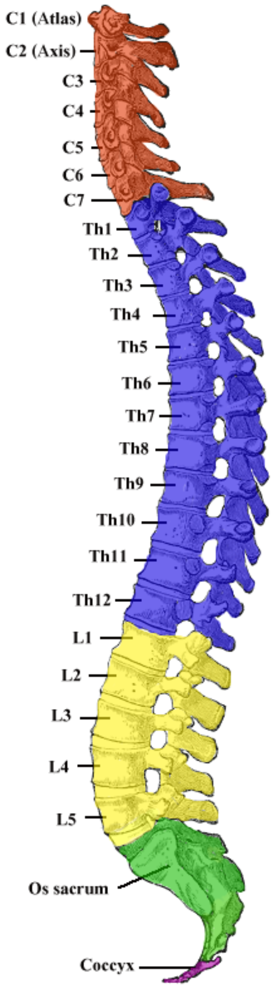


Figure 2.2 Diagram of the spine [13]

2.1.2 Pathophysiology

SCI is a life-changing injury that results in acute or chronic motor and sensory dysfunction due to interruption or destruction of nerves carrying information to the spinal cord, called deafferentation [3-5]; yearly global incidence is between 250,000 and 500,000 [6]. The level at which the injury occurs refer to the segments shown in Figure 2.2, and is defined by the International Standard for Neurological Classification of SCI [14] as "the most caudal segment of the spinal cord with normal sensory and antigravity motor function on both sides of the body". The type of injury can be divided into paraplegia (injury within the thoracic region and below that may result in paralysis of the lower limbs) or tetraplegia (injury within the cervical region that may result in the paralysis of the upper and lower limbs). SCI can be further classified based on motor and sensory function according to the American Spinal Cord Injury Association (ASIA) classification system [14]. This classification is shown in Table 2.1.

Table 2.1 ASIA classification of SCI motor and sensory function

Class	Function	Impairment
A	Complete	No motor or sensory function is preserved in the sacral segments S4-S5
B	Incomplete	Sensory but not motor function is preserved below the neurological level of injury and includes the sacral segments S4-S5
C	Incomplete	Motor function is preserved below the neurological level of injury, and more than half of key muscles have a muscle grade less than 3
D	Incomplete	Motor function is preserved below the neurological level of injury, and at least half of key muscles have a muscle grade of 3 or more
E	Normal	Motor and sensory function is normal

The CNP sensation is described as electrical, tingling, numbing, pins and needles, or temperature-related descriptors [15]. CNP after SCI is divided into three groups [16]: (1) below level neuropathic pain, (2) at-level neuropathic pain, and (3) above level neuropathic pain. This division assists in identifying the specific pathophysiology of CNP after SCI. The transmission of nerve signals are adversely affected by SCI, resulting in interruption of communication between the brain and the rest of the body. A number of physiological changes occur at the site of injury and in the brain after this interruption of communication that has been documented by experimental research. These changes include anatomical changes (e.g., decaying of higher order neurons [17, 18]), neurochemical changes (e.g., reduction of inhibitory neurotransmitters [4, 5, 19]), and inflammatory changes (e.g., elevation of pro-inflammatory agents promoting nerve sensitisation in the spinal cord [3, 5]). Neural reorganisation is also observed in the sensory-motor cortex of the brain, as SCI is a condition that affects sensory and motor abilities [20, 21]. This neural reorganisation is believed to be part of the plasticity of the brain that is induced in response to the interruption in communication of nerve signals caused by the SCI, and are associated with the development of CNP. However, it is unclear which of these changes lead to the development of CNP or whether the development of CNP induces some of these changes [5]. Brain activity changes associated with CNP after SCI can also be seen in EEG recordings. These changes will be discussed later in this chapter in relation to discussions of neurofeedback for CNP after SCI.

2.1.3 Impact of CNP after SCI on Daily Life

CNP can be a disabling symptom of SCI [22] by disrupting an individual’s ability to return to work, continue with daily routines, socialise with others, and enjoy their hobbies; thus, CNP after SCI can reduce quality of life [23-25]. There is also an increased risk of developing depression and persistent low moods [26, 27] due to frustration emerging from trying to control CNP. The extent of control an individual perceives to have over their CNP is considered a major factor that can affect long-term adjustment to pain [28] and physical ability [29]. This perceived control is discussed in terms of internal locus of control (belief that control lies mainly within one's own abilities, e.g. believing that engaging in physiotherapy will relieve pain) and external locus of control (belief that control lies mainly outside one's own abilities, e.g. believing that pain will remain the same regardless of engagement in physiotherapy) [30]. Greater levels of internal locus of control have been found to be predictive of lower pain intensity, compared to external locus of control [31]. In terms of physical ability, locus of control affects an individual's perception of how well they can do daily tasks [30]. For example, if an individual believes that they have no control over their physical ability, they may actively limit their participation in certain activities. This further reinforces the belief of external control due to their lack of participation. The external locus of control can be a negative cycle that can be thought of as a maladaptive coping behaviour. However, external control beliefs can be changed to internal locus of control through behaviour therapy that challenges negative thoughts, and education regarding medical and psychological complications [30]. Sociability can also be negatively affected by CNP after SCI; individuals with this condition have reported feeling isolated from the able-bodied population [23, 24]. Difficulty in communicating their experience of pain (as neuropathic pain is uncommon) can lead to restraint in talking about their pain and self-isolation from the able-bodied community. Furthermore, feelings of being a burden and anticipated judgement can prevent individuals with CNP after SCI from socialising [23, 24].

2.1.4 Treatments for CNP after SCI

Treatment methods for CNP after SCI can be grouped into pharmaceutical, invasive, and non-pharmaceutical and non-invasive methods that target the attitude towards pain or target the pain directly.

Pharmaceutical treatments for CNP after SCI include various types of medications, such as analgesics, opioids, tricyclic antidepressants and anticonvulsants. While medication can partially reduce pain [32], this reduction is often not sufficient [8]; 40 to 60% of individuals treated with medication show only a partial reduction in pain [33]. Furthermore, some side effects of medication (such as additional pain or sleep deprivation) have been reported to be even worse than the pain of CNP resulting in decreased adherence to medication [23]. Patients may either alter their own medication schedule or halt their regime entirely without the advice of their health professional. Hearn et al [23] reports that this is due to patients feeling as if their medication and/or health professionals are taking control of their lives because health professionals prioritise medication without acknowledging the feedback of the patient [23], causing feelings of frustration and distrust in their pharmaceutical treatment. While medication is beneficial to an extent, other methods of treatment must be considered in cases of inadequate pharmaceutical pain relief. Invasive treatments, such as dorsal horn surgery or an electrical implant to stimulate nerves, are usually employed when other options have been exhausted [34]. When invasive procedures succeed in relieving pain, patients report an improvement of quality of life, such as increased social activities and more positive emotional responses, such as acceptance, towards their pain [35]. However, invasive procedures are not guaranteed to work and pain may come back again after several years [32]. Due to the high risks of surgery (complications such as blood clotting or infections), invasive procedures are used less frequently and as a last resort.

Non-pharmacological and non-invasive treatments that target the attitude towards pain aim to alter the individual's perception and belief system surrounding pain to decrease suffering. In other words, these types of treatments focus on increasing adjustment to pain. There is a lack of research examining the effectiveness of these treatments in the population of individuals with CNP after SCI; thus, research on general chronic pain is considered here. Attitude-towards-pain targeted treatments have been shown to reduce pain intensity through increasing awareness of one's own sensations [36, 37] or through changes in perception about pain [38]. These treatments have also been shown to reduce the reliance on pain relief medication and decrease hospital readmissions [39]. However, attitude-towards-pain targeted treatments are recommended for managing pain rather than supressing pain; not everyone accepts their CNP after SCI as part of their lives and understandably insists on treatments that will reduce their pain. Thus, further treatment needs to be investigated to meet this demand.

Non-pharmacological and non-invasive treatments that target pain directly include neuromodulation methods. Neuromodulation is where nerve activity is altered through targeted stimulation, and this method can be used to relieve CNP with techniques such as repetitive transcranial magnetic stimulation (rTMS; using a magnetic field to stimulate specific cortical regions) and transcranial direct current stimulation (tDCS; using low electrical currents to stimulate specific cortical regions) [8]. rTMS and tDCS have been shown to reduce pain within 48 hours and pain reduction is maintained long-term (approximately one month) [40-43]. Neurofeedback is a neuromodulation technique that has been shown to reduce pain (discussed in further detail in the next section), and may be more beneficial to patients with CNP after SCI than other neuromodulation methods. Firstly, neurofeedback is a voluntary neuromodulation method, which means that users of neurofeedback (i.e. patients) are the ones inducing the neuromodulation. This voluntary neuromodulation is explained in detail later in this chapter; the focal point of the current discussion is that neurofeedback requires active participation by the patient in order for the treatment to work. This can be likened to behaviour-therapy, where patients must be active participants in the activities of behaviour-therapy to produce positive clinical results. Being active in the treatment addresses the psychosocial factor of perceived control: individuals may feel like they are in control over their pain when using neurofeedback. Secondly, neurofeedback has the potential to be used at home, which will allow patients to use this treatment within their own schedule. The physical disabilities that come with CNP after SCI can often restrict mobility of patients, making it difficult to schedule appointments for treatments that require the skills of professionals to be present. A voluntary, home-based treatment addresses this mobility restriction and allows patients to be in control of their treatment.

It is clear that CNP after SCI is a complex condition and has a significant, adverse impact on daily life that is further complicated by the difficulty in treating the condition. It is important to develop further treatments that provide effective relief of CNP after SCI. The next section introduces neurofeedback and the evidence for its potential role in relieving CNP after SCI.

2.2 Basic Mechanisms of EEG-Based Neurofeedback

Electrical bio-signals can be recorded from the human body from the cumulative electrical potential produced by neurons or muscles. These electrical bio-signals can be divided into categories based on the location on the human body, such as electrocardiogram (ECG; the activity of the heart), electromyogram (EMG; the activity of muscles), and electroencephalogram (EEG; the activity of the brain). These signals can be monitored to gain voluntary self-regulation of involuntary bodily functions, such as heart rate or muscle tension. This self-regulation process is called biofeedback, where individuals develop voluntary control over a real-time representation (such as a visual display on a computer screen) of specific features of their own bodily functions. Biofeedback has been used for improving health and performance associated with these bodily functions. Neurofeedback is a specific type of biofeedback using brain activity, and can be monitored through various systems such as homoencephalography (HEG), functional magnetic resonance image (fMRI), Magnetoencephalography (MEG), and EEG (Table 2.2 briefly describes how each type works).

Table 2.2 Examples of neurofeedback systems and their brief descriptions

Type of Neurofeedback	Type of Activity Being Controlled by User
HEG	Cerebral blood flow and oxygenation density
fMRI	Blood oxygen level
MEG	Magnetic fields produced by electrical neural activity
EEG	Electrical brain activity

Neurofeedback has potential to enhance cognitive performance (e.g. working memory [1]) or to treat various conditions (e.g. ADHD [2]). This thesis examines an EEG-based neurofeedback treatment, and will not discuss other neurofeedback systems nor neurofeedback to enhance performance. There is a debate within the literature on whether or not neurofeedback is an effective treatment; this depends on the condition that is being treated. Neurofeedback seems to be effective for ADHD (specifically targeting hyperactivity and inattention) as shown by randomised, controlled trials [2, 44, 45]; neurofeedback for substance addiction, on the other hand, has not been examined within a clinical trial. The issue of effectiveness is further complicated as treatment outcomes have not been shown to specifically relate to the specified threshold of brain activity changes. For example, positive outcomes for ADHD were found in the neurofeedback group compared to the control group, but only half of the neurofeedback group achieved neurofeedback success [46]. This suggests there are non-specific treatment effects that contribute to the treatment outcome, or that the threshold for change was set too high. Further research is needed to clarify the specific effectiveness of neurofeedback; however, this will not be addressed in this thesis. This thesis examines how individuals learn to achieve neurofeedback success using an EEG-based neurofeedback system that aims to reduce CNP after a SCI. Before neurofeedback learning is discussed, the properties of EEG activity and the neurofeedback protocol for CNP after SCI will be introduced.

2.2.1 EEG Activity

EEG activity is a reflection of electrical brain activity, and can be recorded by placing electrodes on the scalp. The 10-20 system (Figure 2.3) is a method of electrode positioning on the scalp for EEG procedures. The name of this method refers to the distances between adjacent electrodes, which are either 10% or 20% of the total nasion-to-inion or A1-to-A2 distance of the head. Each electrode location has a letter and a number for identification of brain region. The letters F, T, C, P and O stand for frontal, temporal, central, parietal, and occipital regions, respectively. There is no central lobe; "C" is used for identification purposes. Even numbers refer to locations on the right hemisphere and odd numbers refer to locations on the left hemisphere. "Z" refers to a location on the midline of the head.

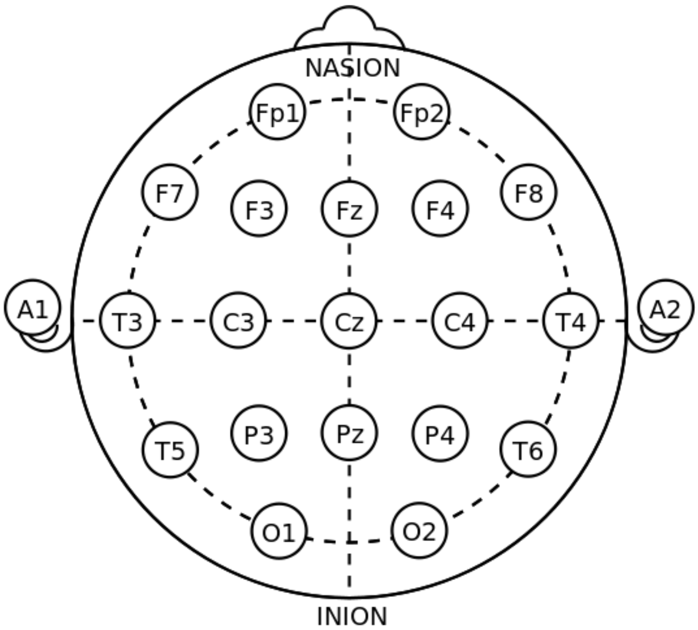


Figure 2.3 Diagram of 10-20 system for EEG electrode application [47]. Nasion and inion, and A1 and A2 are points on the head to find Cz (midpoint) from where other positions are then measured.

EEG activity appears as oscillatory motions, and these neural oscillations are considered to reflect communication within the brain related to sensory and cognitive functioning [48]. In brief, scalp EEG activity is the result of summed synchronised electrical activity of neurons at the electrode location. This electrical activity is generated by the postsynaptic potentials of cortical pyramidal neurons (named as such due to the shape of the cell body). However, EEG activity is not just the product of these pyramidal neurons; all active neurons contribute to EEG [48]. The contribution of the cortex pyramidal neurons is overpoweringly large compared to all other brain structures. This is because there are many more cortical pyramidal neurons than subcortical neurons, and the distance from subcortical neurons to scalp electrodes is larger than from cortical neurons to the scalp electrodes [48]. The electrical signals passed along a neuron vary in frequency (Table 2.3), which can reflect the task(s) an individual is performing. There are many neurons at any given location that send varying types of information; thus, EEG electrodes reflects the continuous and fluctuating electrical activity of a collection of neurons at that location. However, it is unknown what processes contribute to maintaining consistent neural oscillations, or how dominant frequencies shift from one to another [48]. Scalp EEG collects a broad area of electrical activity and does not reflect small or specific neural oscillations. Thus, scalp EEG measurements are limited, but deep brain EEG collection can be practically and ethically challenging on humans as it requires the invasive procedure of applying electrodes directly to the brain.

Table 2.3 Frequency bands of EEG activity

Band Name	**Frequency (Hz)**
Infra-low	<0.5Hz
Delta	0.5 – 3Hz
Theta	3 – 8Hz
Alpha	8 – 13Hz
Beta	13 – 30Hz
Gamma	30 – 200Hz

It is important to note that the above frequency ranges are not standardised and vary within the literature. The above frequency ranges depict the general range associated with their respective bands.

Frequency band training is the common method used in EEG-based neurofeedback and is the method used by the neurofeedback system within this thesis (described in 2.3.3); however, there are other features of EEG that can be used for neurofeedback that will be briefly considered here. Neurofeedback can use slow cortical potentials (SCP), which are voltage changes of a given EEG signal [49]. These changes are collected by comparing a timeframe of cortical activity to a baseline of the same timeframe, for example, comparing two seconds of cortical activity during a mental task to two seconds of cortical activity during rest. SCP are categorised according to the sign of comparison [49]: negative SCP are associated with decreasing the excitement threshold of neurons resulting in increased cortical activity, and positive SCP are associated with increasing the excitement threshold of neurons resulting in decreased cortical activity. Connectivity is another neurofeedback method that refers to patterned associations of a chosen EEG feature between two or more cortical regions [49]; connectivity shows which cortical regions are associated with certain behavioural events, mental tasks, or conditions. Numerous other EEG features can also be used, such as signal amplitude [50] or event-related potentials (EEG responses directly resulting from a specific stimuli) [51], that cannot be detailed here due to the limited space. Furthermore, these features can be used in combination during neurofeedback training, dependent on the protocol designed by the researchers.

It is important to note that EEG activity is a reflection of the electrical activity of the brain as a whole (although the largest contribution are from the sources closest to the electrodes). Historically, research perspectives focused on the localisation of functions to specific brain regions; some research in present times can also be seen to hold this perspective [52]. However, this is inaccurate as a single task or function may receive input from various brain structures that may not necessarily be adjacent. Thus, activity from an electrode may not necessarily reflect activity of the location-associated brain structure. A global measurement of EEG activity must be recorded to localise generation and understand the direction and strength of electrical activity [52]. Another important note is that all frequency bands are reflected in all brain regions; however, certain behaviours or physiological conditions can be related to specific brain regions, where particular changes in frequency dominance or shift are most apparent. Ultimately, EEG is a reflection of how different brain regions communicate with each other. The main brain region associated with CNP after SCI is the sensorimotor cortex, and the main frequency bands associated with CNP after SCI are the theta, alpha, and beta bands. This will be discussed in further detail in the next section.

2.3 Neurofeedback for CNP after SCI

EEG-based neurofeedback has potential to reduce pain in those with CNP after SCI (evidence discussed below). The relationship between EEG activity and general chronic pain will be introduced before focusing on CNP after SCI.

2.3.1 Neurofeedback for General Chronic Pain

There is a growing understanding that pain is the result of cortical processing of painful sensations and not a direct reflection of the pain intensity itself. Apkarian et al [53] illustrates how brain activity changes across participants depending on their perception of pain despite the same pain stimuli exposure in all participants. This has led to research investigating the relationship between chronic pain and EEG activity. Pinheiro et al [54] conducted a systematic review that found a general trend of increased power in the theta band in individuals with chronic pain during rest (i.e. periods during which individuals were awake but not actively participating in any specific physical or mental task). Animal studies using deep brain EEG show that increased power in the theta band is correlated with thalamic dysfunction, where abnormal sensory processing is observed [55]; this suggests that chronic pain may result from abnormal sensory processing. This is supported by studies demonstrating different EEG patterns in human individuals with chronic pain compared to able-bodied individuals. For example, Bjørk et al [56] found a correlation between increased theta activity and suffering from migraines. However, not all chronic pain conditions are associated with increased theta activity. de Vries et al [57] found increased power in alpha and lower beta frequency bands (7.5-13 Hz) in individuals with chronic pain from chronic pancreatitis (permanent damage of the pancreas due to inflammation); van den Broeke et al [58] found increased alpha power (7.9-11.2 Hz) in individuals with chronic pain after breast cancer treatment. Thus, EEG patterns differ between chronic pain conditions. Despite these differences, EEG patterns of chronic pain are still thought to reflect abnormal sensory processing. Neurofeedback attempts to reverse these patterns to treat chronic pain [59-63].

Neurofeedback for pain reduction has provided promising results, supporting the possibility for developing neurofeedback into a treatment. Jensen et al [59] examined the effects of neurofeedback on eighteen people with complex regional pain syndrome (a chronic pain condition with an unknown cause), where participants attempted to reinforce alpha activity. They found a significant pre- to post- decrease in pain intensity (measured by a numerical rating scale), showing short-term pain reduction effects of EEG-based neurofeedback. However, this study did not include a control group, thus it is unclear whether the pain relief was specifically due to the neurofeedback. Caro and Winter [64] compared fifteen people with fibromyalgia (a chronic pain condition with an unknown cause affecting the whole body) who received neurofeedback training that reinforced low beta (12-15 Hz) and supressed theta and high beta (22-30 Hz) with sixty-three people with fibromyalgia who only received standard medical care. They found that those who received neurofeedback training reported greater pain reduction than those who did not receive the training, further supporting the use of neurofeedback to reduce pain. However, this study did not include a sham trial to test for a placebo effect. Furthermore, the large difference in sample size between the treatment group and the control group also introduces unequal variances that likely skewed the data; this casts doubt over the validity of the findings. Neurofeedback for chronic pain has also been examined in randomised clinical trials. Kayiran et al [65] employed a rater-blinded, randomised clinical control trial with thirty-six people with fibromyalgia equally randomised into a neurofeedback treatment group (reinforcing low beta (13-15 Hz) and supressing theta activity) and a control group. They found significant pain reduction in the neurofeedback group compared to the control group. These findings are more valid that the previous studies because Kayiran et al [65] included a control group and had an equal sample size between the treatment and control groups. Furthermore, this study was randomised and blinded thus reducing selection bias. However, the sample size was low and no sham trial was included. Farahani et al [66] conducted a randomized control trial comparing neurofeedback to transcranial electrical nerve stimulation (another neuromodulation treatment similar to tDCS) and a control group to treat severe headaches; each group consisted of fifteen participants. They found that neurofeedback was the most effective in reducing pain; however, issues of small sample size and the lack of a sham trial can also be seen here. The current evidence for the use of neurofeedback as a treatment to reduce pain in chronic pain conditions is promising. However, most research in this area have limited sample sizes that make it difficult to claim conclusive evidence in favour of neurofeedback as a treatment. Studies with larger sample sizes are needed for more certain evidence in support of neurofeedback. Additionally, more randomised, controlled clinical trials are needed to establish neurofeedback as better than control. These clinical trials need to implement sham and double-blinded conditions to establish the effectiveness of neurofeedback as a treatment for pain reduction.

2.3.2 EEG Activity of CNP after SCI

CNP after SCI is a condition that interrupts both sensory and motor functions, and thus affects the sensory-motor cortex. CNP after SCI also affects other areas of the brain (such as the posterior parietal cortex, which plays a role in attention to pain); however, this thesis will focus only on the sensory-motor cortex due to its relevance to the neurofeedback protocol under examination.

Disruption of the sensory-motor cortex by CNP after SCI is supported by the abnormal EEG activity observed in this cortical region in those with CNP after SCI compared to able-bodied individuals [20, 67, 68], i.e. the thalamocortical resonance is seen to be disrupted in those with CNP after SCI. Thalamocortical resonance is the oscillatory neural activity between the thalamus and various other cortical regions in the brain, including the sensory-motor cortex. This mechanism is thought to be a system of synchronisation between different brain regions [69] and necessary for integrated sensory information processing [70]. Thalamocortical dysrhythmia (TCD) is a phenomenon where this resonance is disrupted by abnormal changes in neural activity in the thalamus. TCD produces low frequency (theta) oscillations that interrupt normal flow of information in the thalamo-cortico-thalamic network [81]. This results in disturbances of sensations, motor performance, and cognition. The evidence for TCD is based on the finding of these low frequency oscillations in various human conditions, such as tinnitus, Parkinson’s disease, and other neurological conditions [71-73], and this is also found in those with CNP after SCI at the sensory-motor cortex [7, 67, 74]. Increased activity in the theta band has been suggested to be the signature of CNP, and is found in those with

CNP after SCI and absent in those with SCI without CNP. The below shows the differences in EEG activity between those with and without CNP after SCI to illustrate the existence of a distinct EEG pattern associated with CNP.

EEG Activity due to SCI without CNP

Reduced activity in the alpha band has been recorded across all brain regions in those without CNP after SCI compared to able-bodied individuals [75, 76]. Increased power in the beta band has also been found in those with SCI compared with able-bodied individuals across all brain regions [75]. However, there were no differences between SCI and able-bodied individuals in the delta or the theta bands [75, 76].

EEG Activity due to SCI with CNP

Individuals with CNP after SCI have reduced alpha and increased theta and beta compared to individuals without CNP after SCI, which illustrates that the existence of CNP further reduces alpha after SCI; additionally, dominant alpha is shifted to lower frequencies [7, 67, 77]. Reduced alpha activity was also found in those with CNP after SCI in response to visual sensory input (produced with eyes open and eyes closed state) in the thalamocortical network compared to those without CNP after SCI [67]. Event-related desynchronisation (ERD) occurs when the amplitude of oscillatory activity decreases in response to an event (e.g. mental imagery). Individuals with CNP after SCI demonstrated increased ERD in the theta, alpha and beta bands during imagined movements[2] of painful and non-painful limbs compared to individuals with SCI without CNP [7].

The abnormal EEG activity found in those with CNP after SCI may be the outcome of the plastic nature of the brain; EEG activity can change drastically if sensory input is significantly abnormal. For example, individuals who have congenital blindness have considerably reduced alpha activity in the occipital lobe (the visual processing cortex) [78], accompanied by drastically increased alpha in the frontal lobe compared to able-bodied controls. This can be considered a compensatory process of

[2] Imagined movements (motor imagery) refer to the action of mentally stimulating a particular part of one's body, such as feet or hands, by imagining a movement of that body part. Abnormal brain activity during imagined movements has been linked to the presence of neurological conditions, and can be used in therapy to reduce painful sensations or increase mobility in these conditions. Imagined movements can also be used to enhance movement performance, and is used in a wide variety of sport training.

the brain. The same plasticity may be occurring in individuals with CNP after SCI, where the brain compensates for the abnormal neuron functioning in the sensory-motor cortex. This is further supported by the cortical reorganisation that is associated with CNP after SCI, as shown by brain imaging studies [20, 21]. This EEG pattern is the basis for the neurofeedback system examined in this thesis, and the following section details the development of a neurofeedback system for CNP after SCI and the results of pain-reduction research using this system.

2.3.3 Development of the Neurofeedback Protocol and Related Research

Previous research has shown that, first, it is possible to alter EEG with neurofeedback training, and, second, that reduction in general chronic pain is possible with EEG-based neurofeedback (section 2.3.1). Thus, it may be possible to try to reduce pain in people with CNP after SCI using neurofeedback training. Specific EEG signatures have been observed in the presence of CNP after SCI and not in the presence of SCI without CNP (section 2.3.2). However, these frequency-specific signatures need to be more precise for optimum effectiveness, such as specifying the exact relevant frequency bands, in what direction (reinforcing/supressing), and at what electrode location should be targeted. Therefore, Hassan et al [8] investigated the specific frequency bands, direction, and electrode location that was potentially most likely to reduce pain in CNP after SCI. Please note that the following mentions of Cz, P4, C3, and C4 refer to EEG electrode location on the head as defined by the 10-20 system (see Figure 2.3). Hassan et al [8] tested four neurofeedback protocols (protocols chosen based on evidence from previous research; Table 2.4) in seven patients with CNP after SCI: (1) reinforcing lower beta (12-15Hz), and supressing theta and higher beta (20-30Hz) at Cz, (2) reinforcing alpha, and supressing theta and higher beta at P4, (3) reinforced alpha, and supressed theta and higher beta at C3, (4) reinforced alpha, and supressed theta and higher beta at C4. The electrode locations from all four protocols are over the sensory-motor cortex.

Table 2.4 Summary of the four neurofeedback protocols tested by Hassan et al [10]

Protocol Number	Reinforced Bands	Supressed Bands	Electrode Location
1	Lower Beta (12-15Hz)	Theta and Higher Beta (20-30Hz)	Cz
2	Alpha	Theta and Higher Beta	P4
3	Alpha	Theta and Higher beta	C3
4	Alpha	Theta and Higher Beta	C4

Lower beta was reinforced instead of alpha in protocol 1 because previous studies have associated reduced chronic pain with increased lower beta (also known as the sensory-motor rhythm or SMR [79, 80]). Hassan et al [8] found that protocol three and four (Table 2.4) provided pain relief, which agreed with the preferred site of other neuromodulation methods such as rTMS and tDCS [101, 102]. However, patients reported greater pain relief from protocol four (C4 electrode location) compared to protocol three (C3 electrode location). It is unclear why training at C4 produced greater pain relief than C3. It may be due to the small sample size, but it could also be due to the order of protocol testing. All patients in this study participated in all four protocols, where protocol order was not reported; protocol four may have been the last protocol to have been tested. If this is the case, it may be that control of EEG became increasingly better as each protocol was tested, which could have led to participants perceiving that C4 was providing them with greater pain relief. It was also reported by Hassan et al [8] that C3 resulted in spasms during neurofeedback training; thus, participants may have preferred C4 over C3 not due to CNP-related pain relief but to avoid spasms, which also may cause pain.

The results of the above study provides the information of frequency-specific EEG activity, direction, and location needed for an EEG-based neurofeedback system for CNP after SCI. Furthermore, this study indicates that this neurofeedback protocol can reduce pain in CNP after SCI (although it may also be due to a placebo effect, discussed further in the next paragraph). However, it is important to note that the results from Hassan et al [8] should not be seen as conclusive evidence, as the study had a small sample size that did not report randomisation of protocols nor included a control group.

Neurofeedback training at C4 also seems to reduce EEG over-activity during imagined movements [68]. Increased ERD (event-related desynchronisation) is observed during imagined movements in individuals with CNP after SCI compared to individuals without CNP after SCI [7]. This reduced EEG activity was found to be similar to the activity of individuals with no CNP (able-bodied individuals and SCI patients). Hasan et al [68] found that during training with protocol four, the increased ERD usually seen during imagined movements had reduced, where the largest reduction was found in the theta band. This finding further illustrates the relationship between frequency-specific EEG activity and CNP after SCI, and supports the potential for neurofeedback as a treatment for CNP after SCI. While the findings are promising, it is too early to determine whether this neurofeedback protocol can be used as a treatment for CNP after SCI. Repeated randomised clinical trials with sham controls must be conducted to determine the effectiveness of this neurofeedback treatment.

One important question is whether or not this neurofeedback treatment is the cause of pain reduction or whether this was due to a placebo effect. Hassan et al [8] tested for placebo with two methods: (1) showing patients a pre-recorded display of EEG activity and (2) providing neurofeedback from Oz (occipital area), which is a cortical area not associated with pain. Pain reduction was not reported and cortical activity did not differ between pre-post training during either placebo tests. This suggests that neurofeedback training observations from the main study were not due to a placebo. Furthermore, the true (non-placebo condition) neurofeedback training produced widespread reduction in cortical activity during imagined movements of painful and non-painful limbs that only occurred in those who reported pain reduction [8]. This further supports the association between frequency-specific EEG activity and CNP after SCI, which also decreases the likelihood that the pain reduction was a placebo. However, this placebo testing was only in a small sample size (7) and was not blinded nor randomised. Therefore, a more robust placebo testing needs to take place during a randomised controlled clinical trial.

However, a more prominent question arises before trying to tackle the above issues: how do people learn to control their EEG activity? This question is important because neurofeedback requires active participation; unlike medication where the user waits for the medication to take effect, neurofeedback requires the user to associate mental strategies with correct changes in EEG activity, and continue those strategies to control their EEG activity. If a person cannot associate a mental strategy, then the desired clinical outcome (pain reduction) may not occur. Hassan et al [8, 68] do not specify the instructions that are given to participants in order to control their EEG activity in the correct direction. Therefore, it is unknown whether the instructions given in their study were sufficient to promote successful neurofeedback or whether participants had to learn with minimal guidance. Examining how people learn to control their EEG activity may aid in understanding the process of neurofeedback success. Understanding neurofeedback learning using this protocol for CNP after SCI is the main aim of this thesis, and the background and surrounding neurofeedback learning literature are discussed in detail in the next chapter.

Chapter 3 Neurofeedback Learning

Neurofeedback requires active participation on behalf of the user to self-regulate an external representation of brain activity; the user must employ the appropriate mental behaviour in order to achieve neurofeedback success. Physical behaviour is not used because physical movements risk introducing artefacts (interruptions) in the EEG signal that decrease the accuracy of the feedback provided to participants. In some instances, specific instructions of mental behaviour can be given to the participant, such as instructing users to imagine body movements (motor imagery) to improve neurological functioning [81]. In other instances, such as the current neurofeedback system for CNP after SCI, no specific instructions are given and the user, through trial-and-error, must identify the appropriate mental behaviour themselves. The appropriateness of the mental behaviour is whatever behaviour leads to neurofeedback success, which can be dependent on numerous factors such as the targeted brain activity (discussed in further detail throughout this chapter). Trial-and-error identification may demand a considerable amount of time and resources, and therefore not suitable for routine clinical practice. A better understanding of neurofeedback learning may aid in the development of standardised, or at least better structured, guidance that neurofeedback trainers can use, thereby reducing the resource burden of neurofeedback training. Furthermore, improved guidance may increase patients' chances at succeeding in neurofeedback and thereby increase their chances of inducing pain relief for CNP after SCI. Finally, understanding neurofeedback learning may also aid in identifying predictors of neurofeedback success.

The thesis aims to better understand neurofeedback learning using an exploratory approach due to the lack of information in current literature. This chapter details this lack of information by evaluating existing information and its gaps. The existing information was spare and inconsistent, which prompted this chapter to consider neurofeedback learning theories to better understand the knowledge foundation of neurofeedback learning. However, these learning theories did not sufficiently explain neurofeedback learning; thus, this chapter looked to factors from general learning (i.e. locus of control, self-efficacy, difficulty, and motivation), which are used by this thesis to examine neurofeedback learning. Additionally, this chapter discusses autonomic responses (heart rate, breathing rate, and galvanic sweat response) to neurofeedback learning, which are also used by this thesis to examine neurofeedback learning. The main aim and objectives of this thesis are outlined at the end of this chapter. Before reviewing the various influences of neurofeedback learning, it is important to also consider how one determines "success" at voluntary control of brain activity.

3.1 Being Successful at Neurofeedback

The term "success" refers to the achievement of a pre-defined purpose, for example, the general purpose of a running race is to identify the fastest runner, where an individual is considered successful if they are the first competitor to cross the finish line. The purpose of neurofeedback as a treatment is to produce a positive clinical outcome in the targeted condition. Thus, successful neurofeedback would be defined by correctly controlling one's brain activity to produce that positive clinical outcome (although there are cases where correctly performing neurofeedback does not lead to a positive clinical outcome, this is not the topic of this thesis and will not be discussed here). However, neurofeedback studies use a variety of success criteria [82] that are not based on the extent of control needed for a clinical outcome, but based on an arbitrary criterion to examine if brain activity was controlled in the correct direction.

One of the most common methods to assess neurofeedback success is to examine EEG changes over time; this can be done in a number of ways, such as comparing EEG features from the first neurofeedback session to the last or by comparing EEG features from one session to the next. Another common method is to choose a threshold that the user must achieve before being identified as successful, such as increasing an EEG band power by at least 10% from the first neurofeedback session to the last session. Ancoli and Kamiya [83] emphasise that baseline measures are important to consider when assessing neurofeedback learning, reasoning that learning should only be considered if a user increases or decreases the targeted EEG feature beyond their naturally produced levels. Some neurofeedback protocols combine various criteria, such as the one examined in this thesis: both a threshold and comparison to baseline are used (further detailed in section 5.5). A further "success" concept to consider is that users, with enough training, should be able to voluntarily control their brain activity without feedback. Some researchers argue [84, 85] that neurofeedback as a treatment is only of value if long-term effects can be seen outside of the training. This concept is rarely examined in current literature; however, there is limited evidence to support that users can voluntarily control their brain activity without feedback. For example, Nowlis and Wortz [86] found that four out of their six participants were able to do so, although the small sample size limits the confidence in this study's findings. It is clear to see that assessing neurofeedback learning is difficult due to the variety of methods that are used and promoted in current literature. However, the above mentioned methods only consider EEG features and do not consider behavioural concepts of learning.

Neurofeedback is a treatment that requires the active participation of users, where users must employ an appropriate mental behaviour to correctly control brain activity that may lead to a positive clinical outcome. Thus, neurofeedback can be considered a skill and not a passive task [87, 88]. As with any skill, various behavioural factors may influence the outcome of neurofeedback learning (as detailed in the rest of this chapter). An important aspect of acquiring a skill is the ability to correctly self-assess performance [89-91]. Self-assessment is a reflective process that is used to evaluate performance on a task and assists in determining the next steps to take for improvement [92]. It is considered a key process not only to sustain motivation but also supports continued learning improvements and achievements [93]. Self-assessment has been used in a wide variety of areas, such as academic education [92], project management [94], and motor-learning [93], but it has not been discussed in neurofeedback literature to the knowledge of the author. Yet, this thesis argues that self-assessment should be considered alongside EEG-related criteria to identify successful performance. As mentioned previously, neurofeedback requires active participation that relies on users to judge whether their current mental behaviour is achieving the neurofeedback goal; self-assessment would be an important part of the neurofeedback process, without which users may not be able to improve in their performance.

However, some research suggests that users can unconsciously be successful at neurofeedback, where users do not realise they are have been provided neurofeedback training. Kaplan et al [95] provided participants neurofeedback via a screen that changed colours according to different EEG frequencies. Participants were not told that the screen was linked to their brain activity and were only told to sit comfortably while looking at the screen without a specific purpose. Initially, the screen was observed to cycle through a variety of colours but eventually progressed to only showing a single colour palette (such as green or orange). This was not found in their control or sham conditions. Kaplan et al [95] argue that their results show unconscious neurofeedback learning, where participants changed the colour of the screen to a preferable colour via unconscious neurofeedback processes. However, this study did not ask participants about their colour preference and involved a small sample size of 15 participants; thus, the reliability of their conclusion needs to be confirmed in further research with a larger sample size. Similarly, Ramot et al [96] provided fMRI auditory feedback to participants who thought the audio they heard was provided at random. This study also found that participants' brain activity changed according to the auditory feedback, further suggesting that unconscious neurofeedback is possible. While these studies show evidence of unconscious neurofeedback abilities, unconscious control is not useful to implement neurofeedback as a *treatment*. As previously mentioned, neurofeedback treatments are considered to only be useful if long-term neuromodulation effects can be observed [84, 85].

However, neurofeedback learning was not observed between sessions in Ramot et al [96], suggesting that unconscious neurofeedback may not produce long-term effects (Kaplan et al [95] conducted the neurofeedback training in one sitting and could not examine between session EEG changes). Furthermore, the current neurofeedback system was designed to be portable to enable individuals with CNP to eventually conduct neurofeedback training by themselves in their own home. Without self-awareness of one’s own performance, it is possible that users may give up on neurofeedback if they perceive no improvement. Lastly, the current neurofeedback interface design (i.e. bars that turn green with correct control of EEG activity, further detailed in section 5.5) provides indications of correct control even without active participation, which is due to random EEG fluctuations. If users cannot identify when the bars become green for longer, they may not identify the required mental behaviour to achieve neurofeedback success. Therefore, this thesis has chosen to include user self-assessment as part of its success criteria, and is detailed in section in 7.1.1.

3.2 The Inefficiency Problem

Many neurofeedback studies find that some participants are not able to regulate their brain activity; these participants are referred to as “non-responders”, “non-learners” or “non- regulators” in the literature [97]. A review of eleven studies by Alkoby et al [82] found that non-regulators range from 16% to 57%. While this problem is similar to other types of treatment, e.g. medication is not effective for 100% of patients, neurofeedback requires considerable resources to implement and active effort from the user. However, most neurofeedback studies do not report the number of non-regulators in their participant sample [82], which obscures the prevalence and understanding of this inefficiency problem. Despite this barrier, current literature attempts to examine the possible neuro-physical and behavioural causes of this problem.

3.2.1 Neuro-Physical Causes

In some neurofeedback systems, the chosen neuroimaging technique may not be appropriate for a particular neurofeedback protocol [98] as it may not be sensitive enough for the targeted brain activity. For example, fMRI-based neurofeedback may have been used when EEG may provide better quality feedback as fMRI provides good spatial resolution but poorer temporal resolution. However, most research does not compare brain activity measured by different methods to determine the optimal method of neurofeedback. Research teams may be limited by their resources, or lack thereof, and use a less-than-appropriate neuroimaging technique reducing the likelihood of succeeding at that neurofeedback task. Another cause may be due to unwanted actions of the user, for example, excessive bodily movements (artefacts such as muscle or eye movements) from the user may be mistakenly recognised by the neuroimaging equipment as brain activity resulting in inaccurate feedback [99]. This can be minimised by instructing the user to be consciously aware about excessive physical movements.

More complex causes of the inefficiency problem may be due to the neurological traits of the user. For example, Wan et al [100] found that alpha amplitude during rest before alpha neurofeedback training correlated significantly with neurofeedback success, and suggested that this may be a neurological predictor of neurofeedback learning ability. Resting-state EEG can be influenced through medications (e.g. clozapine increases low-frequency EEG activity [101]) or through behaviour-change therapies (e.g. mindfulness increases alpha activity [102]); it is unclear whether these methods can be used to specifically alter resting-state EEG to promote neurofeedback success. Yet, unchangeable neurological traits may be compensated by adjusting the representation of the EEG feedback signal. One consideration is the optimal speed of the feedback, which is influenced by the pre-processing of the raw EEG activity before delivering the feedback to the user. Sherlin et al [103] states that faster feedback improves the accuracy of the feedback. However, feedback that is too fast may reduce users' ability to associate mental behaviour with changes in the feedback signal; the feedback signal may change before the user can identify the behaviour that lead to that change. Optimising the speed of the feedback may assist users in identifying appropriate mental behaviours. Adaptive neurofeedback systems may also compensate for unchangeable neurological traits. Participants recruited by Bauer et al [104] adjusted the difficulty level of the neurofeedback task by self-rating the mental effort required for that training session (e.g. reducing the threshold for EEG changes if mental effort was rated high). The adaptive neurofeedback system allowed individuals to adjust their learning curve, which resulted in improved neurofeedback performance.

Responses from the autonomic nervous system (the biological system responsible for the mostly automated regulation of internal organs such as the heart or lungs) have been associated with changes in EEG activity. For example, Heck et al [105] concluded that respiration contributes to cortical events after finding specific patterns of EEG activity following cycles of inhalation and exhalation. Examining autonomic responses, similar to neurological responses, may assist in understanding the learning process of neurofeedback. Yet, little neurofeedback research has examined autonomic nervous system markers of learning. This thesis examined autonomic responses during neurofeedback training, and justification for this examination is discussed in more detail later in this chapter (section 3.4).

Examining neuro-physical causes of the inefficiency problem aims to reduce the number of non-regulators. However, neurofeedback requires active participation on behalf of the user, heavily indicating the influence of behavioural factors. Thus, behavioural causes of the inefficiency problem must also be considered.

3.2.2 Behavioural Causes

While the literature acknowledges that behavioural factors influences neurofeedback performance [97, 106], the specific direction and extent of this influence are unclear. Kadosh and Staunton [97] found sixteen studies in a systematic review examining psychological factors as a predictor of neurofeedback performance. Attention ability was stated as an overarching psychological factor influencing neurofeedback performance. Yet, only two studies [107, 108] examined attention ability, which used measures of reaction speed to a stimuli [108] or a memory test [107]. Attention is assumed to be an influencer of neurofeedback performance, as the user is required to pay attention to the feedback of their EEG activity in order to achieve self-regulation. These two studies, however, indirectly examine attention by measuring reaction speed and memory. Despite attention ability being considered an important factor for neurofeedback, little research has examined the specific extent of attention ability on neurofeedback performance. Motivation is another important factor that was examined by six studies [108-113]. It is argued that users must be motivated for the active involvement required by neurofeedback. Yet, the specific extent of motivation is also unclear. For example, Enriquez-Geppert et al [109] found that motivation, measured using a numerical rating scale, was not an influential factor of neurofeedback performance. Yet, Nijboer et al [112] found that two dimensions of motivation ("challenge" and "mastery confidence" of the standardised Questionnaire for Current Motivation) positively associated with neurofeedback performance. This implies that certain aspects of motivation, and not motivation as a whole, influences neurofeedback performance. Finally, mood is another factor that was examined by six studies [111-116]. Similar to motivation, the specific influence of mood on neurofeedback performance is unclear. Many studies do not examine the same feature of mood; for example, Diaz et al [114] found that anxiety does not predict neurofeedback success while Nijboer et al [113] found that a general positive mood can be used as a predictor. Other studies found that various features of mood, such as empathy [111] and depression [115], also influence neurofeedback performance. The lack of consistent measures complicates interpretations of the relationship between mood and neurofeedback.

Despite the claims that behavioural factors plays a crucial role in neurofeedback success, the evidence is sparse and inconclusive. This reflects the complexity of behaviour that occurs during neurofeedback training. Most research aims to understand this complexity via quantitative measures such as standardised questionnaires. Quantitative measures, while useful, do not capture in-depth detail of the research topic. For example, although attention ability may be measured before neurofeedback training, it cannot state whether the user was attentive during the neurofeedback training itself. Although, it is unrealistic to measure such details while users attempt the task, it may be useful to measure them after they complete the task. A qualitative approach may capture this in-depth information not found by quantitative methods, thereby contributing to the understanding of neurofeedback learning. Kober et al [98] and Nan et al [117] used a qualitative approach by categorising mental strategies derived from participant-written notes of their spontaneous mental behaviours (written immediately after their training). Kober et al [98] concluded that having no strategy (strategies that could not be verbalised or described, e.g. "just concentrating") were more effective than having a strategy (i.e. strategies that could be verbalised or described, e.g. "relaxing") when regulating sensory-motor rhythm (SMR) activity (13-15 Hz over the motor cortex). This suggests that implicit learning (learning without awareness) is more important than explicit learning (learning with awareness) for neurofeedback success. However, Nan et al [117] concluded that strategies related to positive thinking were more effective when regulating alpha activity. These studies together suggest that regulating different EEG activity requires different types of mental behaviours. Thus, new mental behaviours may emerge when qualitatively examining the current neurofeedback protocol for CNP after SCI that regulates theta, alpha, and higher beta. Hardman et al [116] (a non-qualitative study) asked participants to generate negative SCP (slow cortical potentials) in either the left or right brain hemisphere, where one group of participants were asked to use emotional mental strategies and another group to use no particular strategy; they found no difference in neurofeedback performance between the two groups. This finding conflicts with the findings of Kober et al [98] and Nan et al [117], further suggesting different mental behaviours are required for different neurofeedback protocols. However, this conclusion is unreliable as only three studies, that used varying neurofeedback protocols, examined the relationship between mental behaviour and neurofeedback performance. Furthermore, the two qualitative studies asked participants to write down their mental strategies that they used during neurofeedback training. Participant-written notes delivers prompt information that also reflects individual experiences and thoughts. However, it does not allow for appropriate clarification of vague phrases risking incorrect assumptions that may be influenced by bias from the researchers. One-to-one interviews may reduce this risk, where immediate clarification and follow-up questions can be asked that may produce more in-depth data. Thus, this thesis qualitatively examined neurofeedback learning using one-to-one interviews.

Before further discussing the use of a qualitative approach, this chapter will first discuss theories of neurofeedback learning due to the spare and inconsistent evidence in the literature. Reviewing these theories may provide a better understanding of the knowledge foundation for neurofeedback learning.

3.3 Learning Theories of Neurofeedback

Learning theories are not only important to understand neurofeedback behaviour, but also to contest and verify existing related knowledge. Well-established theories minimise practices based on false or evidence-lacking assumptions that risk poor or unreliable outcomes, such as low neurofeedback success rates or inconsistent research findings. Thus, neurofeedback learning theories, and their validity, are important to consider. The main theoretical mechanism considered to underpin neurofeedback learning is operant conditioning. However, it does not satisfactorily explain the learning process of neurofeedback; thus, other neurofeedback learning theories will also be discussed.

3.3.1 Operant Conditioning

Operant conditioning is a general learning process that strengthens or weakens behaviour through rewards or penalties [118]. Behaviour that is followed by a reward (positive reinforcement) or removal of a penalty (negative reinforcement) reinforces that behaviour, while behaviour followed by a penalty (positive punishment) or removal of a reward (negative punishment) suppresses that behaviour. In the context of neurofeedback, positive reinforcements, and sometimes positive punishments, are used to encourage self-regulation of brain activity. For example, the neurofeedback system used in this thesis presents three bars (for theta, alpha, and high beta) to the user representing EEG activity. These bars change colour from red to green to indicate correct self-regulation (positive reinforcement). Although operant conditioning is generally considered by the literature to explain neurofeedback learning, there is a problem translating operant conditioning to neurofeedback in humans. Positive reinforcement is only applicable if the user accepts the successful self-regulation of brain activity as a reward. Studies showing animals who are successful at neurofeedback [119, 120] can be said to be using operant conditioning as the reward is food, a pleasant stimulus that is desired by the animal who learns neurofeedback in order to acquire that stimulus. It is unlikely that users, both animal and human, accept successful neurofeedback as the reward itself. Some may argue that the reward is the clinical outcome when using neurofeedback for treatment purposes, such as providing pain relief for CNP after SCI. However, this reward is not immediate; an immediate reward provided directly after the behaviour is performed is a requirement of operant conditioning. Otherwise, behaviour is simply reinforced and not conditioned.

Reinforcement of behaviour without conditioning indicates that the behaviour is performed to achieve a goal. For example, an injured individual may decide to engage in physiotherapy to regain mobility. Although the reward of mobility is not immediate, and may be delayed for several weeks, the individual engages in physiotherapy to achieve that eventual goal of mobility. Koralek et al [119] also suggests that behaviour required for successful neurofeedback is goal-orientated and not conditioned. They trained rodents in neurofeedback using either food or sugared water as a reward. Successful neurofeedback significantly decreased when the rodents had free access to the rewards before a neurofeedback session. While the food and sugared water was a reward for the rodents, the reward's desirability was subject to change. They concluded that neurofeedback ability was acquired intentionally in order to achieve a goal. In the context of participating in a research study, participants may be motivated to achieve the goal provided by the researcher (i.e. to be successful at the neurofeedback task) as they made the decision to volunteer for the study. However, users may not become successful at neurofeedback if they decide that the goal is not worth achieving. If a participant decided the task was, for example, too much effort or too difficult, their desire to achieve the goal would reduce and may result in neurofeedback failure. This heavily implies that behaviour during neurofeedback is dictated by the user and not conditioned as applicable to operant conditioning. External reinforcements may assist in encouraging the user to actively practice achieving neurofeedback, such as praise from the researcher or the eventual reward of a clinical outcome. However, the decision to engage in appropriate behaviour during neurofeedback lies mainly with the user. Furthermore, assessing the validity of using operant conditioning to explain neurofeedback learning is currently not viable as the behavioural factors of neurofeedback learning in the literature are not derived from mechanisms of operant conditioning [82]. Connecting these factors to the underlying theory is important to validate the use of operant conditioning to explain the learning process of neurofeedback.

There are several other theories that attempt to explain neurofeedback learning (though not as prominent in the literature as operant conditioning); however, similar to operant conditioning, these theories have yet to be validated in research. Nevertheless, it is important to consider alternative perspectives that may assist in revealing the underlying mechanisms of neurofeedback learning.

3.3.2 Dual-process Theory

Dual-process theory put forward by Wood et al [121] suggests that two overarching types of processes contribute to neurofeedback learning: automated processes and controlled processes. Automatic processes encompasses unconscious processes that are effortless; for example, driving can become automatic: when one drives a daily route and arrives at the destination without recollection of the actual drive. Controlled processes encompass conscious processes that demand active attention; for example, individuals are consciously supervising their actions when learning how to drive. In the context of neurofeedback, automatic processes are driven by the quality of brain activity feedback and involves involuntary cognitive mechanisms that react to this feedback. This thesis acknowledges the vague description of this automatic neurofeedback process. The immediate questions that may arise are “what specifically are these cognitive mechanisms” or “in what way does the quality of the feedback influence this automatic process”; however, the answers to these questions are unclear due to the lack of research investigating this theory. Controlled processes for neurofeedback are driven by access to information specific to the neurofeedback task (such as guidance from the researcher) and refer to verbalised self-instructions that supervise the performance on the neurofeedback task. The dual-process theory states that neurofeedback learning is dictated by a “local control network” that consists of automatic and controlled processes that assist in neurofeedback performance. An optimal local control network is achieved when irrelevant information (such as unsuitable instructions) is subdued from automatic and controlled processes, which results in an engaged and undistracted state ideal for successful neurofeedback. However, some research evidence opposes the existence of this local control network. Successful participants in Kober et al [98] could not verbalise their mental behaviour during neurofeedback (only implicit learning took place) indicating that they could not use self-instructions to influence their neurofeedback performance. This suggests that controlled processes did not exist in these individuals. Yet, it could also be argued that these individuals did not have a level of awareness of their mental behaviour to be able to verbalise it. This relates to the research field of metacognition, the examination of awareness and understanding of one's own thought processes [122], which states that not everyone has the same ability to think about their thinking. For example, an individual may not have particular strategies for learning and may simply accept whether or not they know something. Thus, the dual-process theory may need to be re-developed to allow for different levels of metacognition.

3.3.3 Global Workspace Theory

The Global Workspace Theory put forward by Ros et al [123] suggests that neurofeedback is only possible if the feedback signal is distributed globally in the brain, which is triggered by conscious stimuli. In other words, conscious reception of the feedback signal (paying attention to the signal) triggers activity in the entire brain so that each cortical region contributes to the self-regulation of brain activity. Within this global workspace, a sequence of neural events take place: (1) neural activity inherently varies in an unconditioned manner, (2) on random occasions, this unconditioned neural activity will coincidently meet the threshold of activity required by the neurofeedback protocol that is represented as "correct" control on the feedback system (the reward), (3) upon presentation of this reward, the brain may "memorise" that specific neural state by releasing a reward-based neurochemical (e.g. dopamine), (4) this is the starting point for the user to actively reproduce that neural state, where multiple reproductions are necessary to strengthen the neural state to produce effective and successful neurofeedback performance. The brain as a whole attempts to find the required neural state and develop the ability to voluntarily induce this neural state. This theory stems from research declaring that conscious reception of stimuli (e.g. noticing a change in visual stimuli) induces global connectivity of the brain compared to unconscious reception of stimuli (e.g. not noticing a change in visual stimuli; this is called change blindness). However, this theory assumes that only conscious reception is needed to improve neurofeedback and ignores other behavioural factors, such as the desire to gain the neurofeedback ability. As mentioned previously, the inefficiency problem is influenced by a variety of behavioural factors that goes beyond conscious reception of the feedback signal.

There are several other theories, such as motor learning theory [124] and awareness theory [125], that this thesis cannot detail due to limited space. However, it should be noted that other neurofeedback learning theories that have been developed but do not satisfactorily explain neurofeedback learning nor have been validated in research. Yet, each theory brings valuable information to the field by allowing researchers to identify knowledge gaps not recognised by the theory.

3.3.4 Conclusion

Operant conditioning is generally accepted as the main perspective on neurofeedback learning. However, behaviour during neurofeedback seems to be reinforced without conditioning the behaviour. This is because the “reward” is not the feedback signal itself but rather the goal of the neurofeedback task, which could be the clinical outcome or to simply be successful at neurofeedback. The reward is not immediate suggesting that operant conditioning is not the underlying learning mechanism of neurofeedback. Furthermore, the reward must be accepted as a reward by the user, otherwise the user may not engage in actively identifying the required mental behaviour for neurofeedback success. Other theories have been developed to better clarify neurofeedback learning, but also falls short of satisfactorily explaining the learning process.

Overall, there is inconsistent evidence of the underpinning neurofeedback learning mechanisms in the literature. This suggests that research should retreat to exploratory investigations (i.e. without hypotheses and minimum assumptions of neurofeedback learning) to provide a better understanding of neurofeedback learning that may generate evidence-based hypotheses for future research. Before discussing an exploratory investigation into neurofeedback learning, the next section reviews the literature on general learning factors (i.e. behavioural elements contributing to general learning), which may provide insight into the learning process of neurofeedback not found within neurofeedback learning literature. This review also informs the design of this thesis’s exploratory study.

3.4 General Learning Factors

There is inconsistent behavioural evidence to identify an appropriate general learning theory to translate to neurofeedback learning. General learning factors, instead of theories, provides the flexibility to explore how these factors influence neurofeedback learning.

3.4.1 Locus of Control

A prominent general learning factor is locus of control (LoC) [126, 127], which is the degree to which individuals perceive their control over life events. LoC can be divided into internal LoC and external LoC. Individuals with a strong internal LoC perceive life event outcomes are primarily due to their own actions and abilities (e.g. a student attributing success in an exam to their knowledge resulting in greater studying efforts to improve their knowledge for further success). Individuals with a strong external LoC perceive life event outcomes are primarily due to external forces such as fate or other people (e.g. a student attributing success in an exam to the lecturer setting easy questions resulting in maintained or reduced studying efforts). LoC may influence neurofeedback learning because neurofeedback requires active participation by the user, where identification of mental behaviour resulting in neurofeedback success relies on the user. Thus, users' belief in control over general life events may influence their perception and effort of their neurofeedback performance. LoC has been examined in previous neurofeedback studies. Kikkert [110] found that internal LoC (using Rotter's LoC scale [128]) correlated with improved neurofeedback performance (reinforcing beta). However, Burde and Blankertz [129] did not find a relationship between internal or external LoC (using Krampen's LoC scale [130]) and neurofeedback performance (using event-related potentials). These conflicting results may be due to differences in neurofeedback protocol or due to the use of different LoC scales. Alongside internal and external LoC, technology-related LoC was also analysed by Burde and Blankertz [129]. Technology-related LoC, measured by the KUT questionnaire (Kontrollüberzeugungen im Umgang mit Technik; [131, 132]), assesses LoC when using technical devices. The KUT questionnaire is the only standardised questionnaire that measures technology-related LoC and is only available in German. The author of this thesis does not speak German; however, German researchers have translated two items from the KUT questionnaire to showcase the type of items presented in this questionnaire: "*I feel helpless when dealing with technical devices and prefer to keep away from them*" and "*I enjoy very much solving technical problems*". Burde and Blankertz [129] found that technology-related LoC increased with better performance. An opposing result was found by Witte et al [133] also using the KUT questionnaire, where technology-related LoC decreased with better neurofeedback performance (SMR regulation). Again, the conflicting results may be due to the different neurofeedback protocols; however, it is difficult to infer a precise explanation without knowing the content of the KUT questionnaire due to the language barrier. Although technology-related LoC seems to influence neurofeedback performance (yet the direction of influence is unclear), this thesis does not examine this feature of LoC because the KUT questionnaire seems to be the only standardised questionnaire for technology-related LoC to the author's knowledge.

3.4.2 Self-Efficacy

Self-efficacy (SE), another prominent general learning factor [134, 135], is an individual's belief in their own ability to succeed in a task. SE may be refer to one's perceived competence of the task, e.g. an individual with high SE in painting will feel confident in painting complex imagery. SE may also refer to one's confidence to learn that competence, e.g. the same individual may also feel confident in successfully learning new painting techniques. Similar to LoC, SE may influence neurofeedback learning as the user must actively participate and identify an appropriate mental behaviour resulting in neurofeedback success. SE is generally associated with LoC, where high SE usually correlates with internal LoC [136] and low SE usually correlates with external LoC [137]. However, SE and LoC do not always have the same level of association with a given factor. For example, De las Cuevas et al [138] found that LoC, and not SE, was associated with medication adherence in patients with depression. Another example found by Kim et al [139] shows that SE, and not LoC, contributed to promoting beneficial health behaviours. Thus, LoC and SE must both be examined to understand each of their relationships with neurofeedback learning. However, to the author's knowledge, SE has not yet been examined as a predictor of neurofeedback performance. Previous studies only refer to SE in terms of cognitive outcome that suggest neurofeedback may increase SE [140, 141]. For example, Linden [142] discusses how neurofeedback may have a positive effect on SE in individuals with depression by teaching these individuals regulation of emotional states. Other studies only speculate that SE may influence neurofeedback performance as these studies did not measure SE. Bauer et al [104] states that asking participants about their perceived mental effort during neurofeedback training increases their sense of SE that may improve neurofeedback performance; however, they do not justify this statement. Neumann and Birbaumer [143] speculate that SE may be important for maintenance of motivation to continue active participation in neurofeedback training. SE is contemplated to be a potential influencer of neurofeedback performance despite a lack of evidence from the literature.

3.4.3 Difficulty

Neurofeedback is considered a difficult task to achieve [82, 144]. This is illustrated by a quote paraphrased from a participant of the first study examining neurofeedback [144]: "*One subject wryly remarked after his first session that I [the study's researcher] had succeeded in inventing a most diabolical device; it presented a task that seemed easy to perform, but instead it was designed to cause the person to fail if he tried to succeed, and to succeed only if he did not try to succeed*". Although the aim of the neurofeedback task seems simple, the counter-intuitiveness of this particular task presented a difficult path to success. Some neurofeedback studies acknowledge this difficulty by allowing participants to choose a difficulty level (by adjusting the threshold for changes in EEG activity) at the beginning of the neurofeedback training [145, 146], although they do not use difficulty level as a factor in their analysis. Difficulty of a task is a factor that influences general learning [147-149]; thus, it is likely that difficulty of the neurofeedback task influences neurofeedback performance. Yet, current studies do not examine the relationship between task difficulty and neurofeedback performance. However, Bauer et al [104] shows that adapting difficulty of the neurofeedback task according to self-reported mental effort improves neurofeedback performance. For example, if a user tells the neurofeedback software that mental effort was high for a session of neurofeedback training, the software will reduce the difficulty level during the next training session. Thus, the difficulty-level of neurofeedback is considered to influence neurofeedback performance, although its direct influence has not yet been examined.

3.4.4 Motivation

The final general learning factor presented by this thesis is motivation (reasoning for choosing only four factors is discussed at the end of this section), which is an important driver behind behaviour required to accomplish any task [150-152]. The motivation studies briefly mentioned in section 3.1.2 indicates that certain aspects of motivation, and not general motivation, influenced neurofeedback performance. Yet, this inference is questioned upon further examination. Two studies measure general motivation using a numerical rating scale, where Kikkert [110] found that motivation positively influences neurofeedback performance while the Enriquez-Geppert et al [109] did not find any influence of motivation. This contrast may be due to sample and analysis differences, as the former study had ten participants per neurofeedback condition and conducted inference statistics while the latter study had sixteen participants per neurofeedback condition and conducted descriptive statistics. The Enriquez-Geppert et al's [109] findings have more validity than the Kikkerts's [110] findings because of their larger sample size; yet, further research is needed for general motivation because no inference statistics were conducted by Enriquez-Geppert et al [109].

Three studies [108, 112, 113] used the Questionnaire for Current Motivation [153], which measures four dimensions of motivation: mastery of confidence, fear of incompetence, interest in the task, and challenge of the task. Nijboer et al [113] found that mastery of confidence was associated with improved neurofeedback performance and fear of incompetence was associated with poor neurofeedback performance; however, they do not report descriptive statistics that may show the extent of the association (i.e. the mean difference in motivation scores when comparing neurofeedback performance). These results were confirmed by Nijboer et al [112] in a later study; however, this was only found in three of their six participants. Furthermore, different aspects of motivation was found to be important for each of these three participants: participant E's neurofeedback performance increased with increased mastery in confidence, participant F's performance increased with reduced fear of incompetence, and participant A's performance increased with increased challenge. To further complicate these results, Hammer et al [108] did not find an association of any dimensions from the Questionnaire for Current Motivation and neurofeedback performance. However, they only report significant results and therefore do not report motivation results; they only review the non-significant motivation results in their discussion. This makes it difficult to further examine their analysis of motivation. Yet, some confidence is provided by Hammer et al [108] as they examined eighty participants while Nijboer et al [112, 113] had less that twenty; the considerably larger sample size indicates that the dimensions of the Questionnaire for Current Motivation do not influence neurofeedback performance.

Finally, Kleih et al [154] split participants into motivated and unmotivated groups based on scores of a motivation questionnaire that the researchers developed. However, the study does not provide a reference to the questionnaire's developmental procedure nor does the questionnaire appear to be validated prior to this study. The study addresses this issue by comparing and finding a significant difference in general motivation between the groups using a numerical rating scale; however, the differences in mean and standard deviation between the groups were minor. Thus, the quality of motivation measured by the researcher-developed questionnaire in this study is arguable, which casts doubt on the study's findings. Overall, the evidence of motivation's influence on neurofeedback learning is inconsistent. Yet, motivation is an important general learning factor that drives behaviour and should be considered when investigating neurofeedback learning.

The other behavioural factors mentioned in 3.1.2, attention and mood, will not be examined by this thesis. There were two reasons for this decision; firstly, the research design of this thesis resulted in a considerable length of the study procedure (approximately two hours, please see the General Methods chapter for details). An ethical study with human participants must ensure the length of the study procedure is reasonable. This restricts the number of factors that can be examined in this thesis. Secondly, motivation was chosen over attention and mood because early literature reviews led the author to postulate that motivation would be more important. Motivation can dictate attention level on a task [155] (e.g. motivation to achieve a reward can increase attention on accomplishing a task leading to the reward). Motivation can allow individuals to accomplish a task despite mood [156] (e.g. a student is motivated to complete an assignment regardless if they are stressed or in a positive mood). Thus, motivation was chosen to be examined by this thesis.

3.4.5 Conclusion

LoC, SE, difficulty-level, and motivation are general learning factors that can be applied to neurofeedback learning. However, there is either inconsistent (for LoC and motivation) or no (for SE and difficulty-level) evidence from current literature that investigates the extent of these factors' influence on neurofeedback performance. Examining these factors in an exploratory study may provide clarity on their relationship with neurofeedback performance. The next section discusses the concept of success within neurofeedback.

Although this thesis focuses on behavioural influences of neurofeedback learning, autonomic responses may have a relationship as well. An exploratory research design allows for the flexibility to consider a variety of factors for examination of neurofeedback learning, such as the inclusion of both interviews and physiology measurements. Previously mentioned in section 3.1.1, autonomic markers of learning may assist in understanding the neurofeedback learning process and is discussed in the next section.

3.5 Autonomic Responses and Neurofeedback Learning

As mentioned in section 3.1.1, studies have examined EEG activity markers (not specifically related to EEG activity of the protocol) of neurofeedback learning that may be used as neurological predictors of success [100]. Non-EEG physiology, such as responses from the autonomic nervous system, may also be used as such markers of learning because of their association with EEG activity during various cognitive tasks. For example, Kramer [157] found that increase alpha activity in the left temporal lobe and increase skin conductance was a positive predictor of performance during a virtual visuo-spatial, motor-response task. Magosso et al [158] found that increased heart rate variability and decreased alpha activity over the fronto-central and the parietal-occipital cortical regions reflected the level of attention engaged by participants during various cognitive tasks (visual, computational, and motor). These studies show that that autonomic activity and EEG activity are indirectly associated by their reflection of the same cognitive task. Examining the relationship between EEG changes resulting from neurofeedback and changes in autonomic activity may provide insight into the autonomic markers of neurofeedback learning.

However, autonomic activity has rarely been examined as markers of learning in neurofeedback literature. Altan et al [159] found that galvanic skin response increase and heart rate decreased after neurofeedback training; they used a method called Othmer neurofeedback, however, their explanation of this neurofeedback protocol is unclear. The neurofeedback protocol required regulation of low frequency EEG activity for forty minutes, yet they also state that they showed the first forty minutes of the movie "The Shawshank Redemption" during neurofeedback training. It is unclear how participants were instructed to regulate their EEG activity while watching this movie. Cherapkina [160] examined heart rate during neurofeedback in sport professionals; however, the research article is only available in Russian. Using an online translation tool, this study seems to state that alpha activity regulation results in increased power of low-frequency heart rate variability. This translation should be taken with caution as it was not verified by a proficient Russian speaker with knowledge of the research field.

The existence of a relationship between EEG activity and autonomic responses may result in some suggesting that providing biofeedback of autonomic responses in place of neurofeedback may produce similar clinical outcomes. Autonomic biofeedback is potentially easier than neurofeedback, for example controlling respiration is an easier task than EEG activity regulation. Thus, biofeedback of autonomic responses may be used instead of neurofeedback for treatment. However, it is doubtful that biofeedback of autonomic responses can replace neurofeedback. Neurofeedback protocols involve regulation of specific patterns of brain activity from specific cortical regions; it is unlikely that changes in the autonomic nervous system will induce this level of specificity. A more feasible scenario is monitoring the autonomic nervous system during neurofeedback training to assist users in identifying mental behaviours resulting in neurofeedback success. As stated in section 3.1.2, mood is an influencer of neurofeedback performance; it could also be part of the mental behaviour itself to improve neurofeedback performance: Nan et al [117] found that positive thinking improved regulation of alpha activity. Mood has also been associated with response of the autonomic nervous system. For example, Kop et al [161] found that a positive mood increased low frequency heart rate variability and a negative mood decreased both low and high frequency heart rate variability. Busch et al [162] showed that deep and slow breathing reduced negative feelings of tension, anger, and depression. Villarejo et al [163] successfully used galvanic skin response to predict individuals' stress level. However, evidence for mood as an influencer of neurofeedback performance is inconsistent. It is possible that mood is not directly associated with neurofeedback performance. As previously mentioned, Kober et al [98] found that having no mental strategy (not being able to verbalise your thought process) is optimal for SMR regulation and suggests an implicit mechanism is responsible for neurofeedback success. Thus, autonomic responses may correlate with this implicit mechanism instead of mood because the autonomic nervous system is largely an unconscious process. Nevertheless, it is possible that monitoring autonomic responses may be a useful indicator of neurofeedback success. Monitoring autonomic responses has been found useful in other areas: Wachholtz et al [164] related autonomic responses to pain in individuals with opioid addictions that they used to create a biofeedback system as part of a therapy for opioid addiction. Autonomic responses were self-monitored by patients who used this information to ensure they were correctly employing psychological strategies that controlled their opioid cravings [165]. Similar to this therapy, neurofeedback users could monitor autonomic responses to ensure they are employing appropriate mental behaviours to improve neurofeedback performance.

Other studies have combined neurofeedback with autonomic biofeedback to induce clinical outcomes. White et al [166] found that regulation of theta, beta, and SMR activity combined with regulation of heart rate variability and blood pressure reduced symptoms of anxiety and depression. Stokes et al [167] found that regulation of alpha and low beta combined with regulation of blood flow reduced frequency of migraines during a six-month period. However, these studies state that the autonomic responses were contributing to the clinical outcome and not just an indicator of neurofeedback success. For example, White et al [166] states that anxiety reduces heart rate variability, suggesting that increasing heart rate variability would contribute to reducing anxiety symptoms. Autonomic biofeedback may also contribute to relieving CNP after SCI. Individuals with CNP after SCI have lower heart rate variability compared to able-bodied individuals and individuals with only SCI [168]. A further study showed that reduction of CNP after SCI using electrical stimulation resulted in an increase in heart rate variability [169], confirming the connection between heart rate variability and CNP after SCI. It is possible that providing biofeedback of autonomic responses alongside neurofeedback may further contribute to relief of CNP after SCI. However, this is only possible if there is a relationship between autonomic responses and changes in EEG activity in individuals with CNP after SCI, which current research has not yet investigated to the author's knowledge. Nevertheless, autonomic responses acting only as an indicator of neurofeedback success may be of benefit to neurofeedback users. Thus, this thesis will examine the relationship between neurofeedback performance and autonomic responses.

3.6 Summary and Conclusion

This chapter reviewed current knowledge on the learning process of neurofeedback. Across neurofeedback studies, there is a problem of some users failing to regulate the targeted EEG activity that can range up to 57% of the study participants. Research has attempted to explain unsuccessful neurofeedback with neuro-physical causes such as excessive physical movements interfering with feedback, and behavioural causes such as motivation of the user to accomplish the neurofeedback task. Behavioural causes were further reviewed as this thesis explores neurofeedback learning from a behavioural perspective. However, evidence for behavioural factors influencing neurofeedback performance was inconsistent, which may be due to differences in neurofeedback protocols or adoption of inappropriate mental behaviours. Furthermore, valuable neurofeedback learning information may not have been captured due to the limitations of quantitative methods, suggesting that a qualitative approach may provide more in-depth information on neurofeedback learning.

Examination of neurofeedback learning theories revealed that these theories did not satisfactorily explain neurofeedback learning. Thus, an exploratory approach may provide clearer information with minimum assumptions and generate evidence-based directions for future research. The equivocal evidence on behavioural factors and explanations by neurofeedback learning theories compelled the author to consider factors from the general learning literature (LoC, SE, difficulty, and motivation). The last feature of the exploration of neurofeedback learning is autonomic responses. The relationship between EEG activity and autonomic responses suggest that specific autonomic response in heart rate, respiration, and galvanic skin response may be associated with neurofeedback performance. This relationship could be used to assist users in becoming successful at neurofeedback and has potential to contribute to relief of CNP after SCI.

3.6.1 Study aim and objectives

The main research aim is to better understand neurofeedback learning with minimum assumptions through an exploratory approach. The research objectives are to answer the following questions:

1) What mental behaviour(s) do participants use to succeed at neurofeedback?
2) What is the relationship between general learning factors (i.e. LoC, SE, difficulty, and motivation) and neurofeedback performance?
3) Do autonomic responses (i.e. heart rate, respiration, and galvanic skin response) directly relate to neurofeedback performance?

Chapter 4 Methodology

The previous chapters presented gaps within the neurofeedback learning literature. The inconsistent evidence lead the author to conclude that neurofeedback learning should be examined from an explorative perspective. This chapter outlines the methodology, that is, the underlying philosophical assumptions for the research approach used by this thesis. The methodology is important to consider to ensure the chosen research methods (detailed in the next chapter) are appropriate for the study.

4.1 Philosophical Stance

Before discussing assumptions of the chosen research approach, it is first important to understand the philosophical stance of the author that resulted in choosing these methods. This sections outlines this philosophical stance, and how this influenced the adoption of the chosen research approach.

Ontology and epistemology are two main concepts used to understand the assumptions of a methodology [170]. Ontology is the study of "being", that is, the nature of reality and what is possible to know about this reality. It is concerned with the question of whether reality exists independently from human beings or if reality only exists in the context of a human's perception. Epistemology is the study of knowledge and how one discovers knowledge. It is concerned with the question of whether knowledge is viewed as objective (where the researcher takes on an observer role and cannot influence knowledge) or if knowledge is viewed as subjective (where the researcher takes on an influencer role and their interaction with reality changes knowledge). Combining ontology and epistemology provides a spectrum of perspectives that influences the approach to research. One end of the spectrum is a realist ontology with an objectivist epistemology [171]; this perspective views reality as independent from human beings and assumes that, with appropriate methods, knowledge is "real" and is discovered. The other end of the spectrum is a relativist ontology with a constructivist epistemology [172]; this perspective considers reality to change depending on its interaction with human beings, and that knowledge is constructed rather than discovered.

The author of this thesis holds the ontological view that reality exists independent of human beings but that this reality is shaped by the subjective perspective of each human being. The epistemological view of the author considers knowledge to be real but recognises that the understanding of knowledge is subjective. This is further described in terms of "fact" and "truth" as this is how the author conceptualises their own stance. A fact, to the author, is an objective piece of knowledge or information; for example, it is a fact than an individual who needs a wheelchair and is still able to continue normally with their life will have reduced mobility. Truth, to the author, is the understanding of reality that may change from person to person; for example, one may perceive that the individual in a wheelchair is unhealthy due to their reduced mobility, yet that individual may perceive themselves as being healthy because they are still able to work and enjoy their hobbies despite their reduced mobility. Here, the reduced mobility is a fact and the understanding of health is a truth. In the context of neurofeedback, this perspective recognises that changes in EEG activity is a measurable fact but the understanding of these changes may differ between users resulting in different outcomes of neurofeedback learning. The researcher interacting with neurofeedback users may also alter learning outcomes. The author sought to understand neurofeedback learning with minimum interference and assumptions; thus, an explorative approach was chosen.

4.2 The Explorative Approach

An exploratory approach to research is used when a question or problem is not clearly defined [173]; neurofeedback learning is not clearly defined as previously established. An explorative approach builds a foundation for evidence-based research directions and is suited to open-ended research questions (such as the objectives of this thesis). However, explorative approaches, and other observational research, are held in lower regard than experimental or deductive research [174]. Before discussing the explorative approach, this criticism will be briefly addressed.

A major criticism of explorative research is that it cannot lead researchers to conclusive evidence and is therefore not a useful research method [174]. The role of explorative research is to lay a foundation for future research by identifying patterns, not to confirm mechanisms or processes. Deductive research without this foundation risks inconsistent evidence (as seen within neurofeedback learning literature) or wasted resources examining biased hypotheses. The following is an example of the latter risk; it is an extreme example yet illustrates the dangers of lacking knowledge of underlying assumptions. Vercellini et al [175] claimed that attractiveness of a woman may predict symptoms relating to rectovaginal endometriosis (a painful condition where cancerous tissue forms outside of the uterus). However, Young et al [176] qualitatively explored perspectives of clinicians on women with rectovaginal endometriosis and found that clinicians hold biased views that may dangerously influence the treatment decisions (e.g. basing clinical decisions of symptom severity on personal opinions of the patient). Thus, the conclusion of Vercellini et al [175] is likely due to a biased view in paying more attention to the symptoms of attractive patients than unattractive patients. Understanding the “why” of a phenomenon can be just as important as understanding the “how”.

However, this thesis does not ignore the limitations of an exploratory approach. Limitations, as for any approach, must be considered to realise the extent of conclusions that can be made. As previously stated, an exploratory approach is used to identify patterns but cannot be used to confirm mechanisms. Thus, conclusions from this thesis must be made with caution when generalising findings to current evidence of neurofeedback learning. Another limitation is that exploratory approaches risk un-replicable results; exploration allows for the flexibility in research methods that prioritise opportunities to purse and explore emergent findings in-depth. This is especially true for qualitative methods. For example, an unstructured interview (interviews with no predetermined questions) for one study may ask different questions compared to the same method in a different study. This may result in different findings and conclusions. Thus, the thesis must also be cautious when generalising findings to the wider population.

Yet, an exploratory approach is suitable for examining neurofeedback learning not only due to the inconsistency of current evidence but it also provides an opportunity of examination with minimum assumptions made by the researcher. Previous behavioural investigations of neurofeedback learning have not been theory-driven. It is possible that researchers’ assumptions of neurofeedback learning influenced the results of these investigations; although, this cannot be verified as these studies did not specify the guidance they may or may not have given participants. To minimise assumptions of the author, no guidance was given to participants regarding the neurofeedback task. An explorative approach also allows for the flexibility to include multiple research methods to answer the research question. Thus, this thesis used qualitative and quantitative methods to provide a broader scope of neurofeedback learning.

4.3 Combining Qualitative and Quantitative Methods

Integrating qualitative and quantitative methods is referred to as a mixed methods approach, where the disadvantages of one method can be compensated by the advantages of the other [177]. This results in a more complete interpretation of a phenomenon compared to separate uses of qualitative and quantitative methods. Before discussing this integration, qualitative and quantitative methods will be discussed separately.

Qualitative methods are well suited to an explorative approach as it attempts to understand the "why" of a phenomenon [178]. It collects information that generally cannot be expressed in numerical form, such as interview data. Qualitative methods provide in-depth insight into an individual's experience of an event, and how this experience may shape their future interactions with the event. It allows for examination of complex features of human behaviour to offer meaning to a phenomenon. In the context of neurofeedback learning, a qualitative method can reveal the self-reported mental behaviours used during neurofeedback training as well as the self-reported motivation behind these behaviours. Qualitative methods usually use small sample sizes (e.g. fifteen participants) that raise generalisability issues of the results [177]; any qualitative findings may be a result of that specific group of participants and may differ when another group of participants are recruited. Furthermore, a decisive conclusion cannot be made from qualitative findings [177]; a pattern discovered by a qualitative method does not equate to confirmatory evidence of a process. These limitations can be balanced by the use of quantitative methods.

Quantitative methods gather numerical data and attempts to answer the "what" or the "how" of a phenomenon [178]. Behaviour research uses quantitative methods to examine empirical variables with statistical testing using systematic and standardised measurements. Within neurofeedback learning, quantitative methods can reveal the variables that result in successful or unsuccessful neurofeedback performance. It is easier to generalise quantitative findings to a population as a larger sample size (potentially hundreds or thousands of participants) is possible. Quantitative methods also provide a numerical understanding of a relationship's strength between variables, which is validated by statistical analysis; this allows researchers to understand the underlying processes explaining the occurrence of a phenomenon. These advantages of quantitative methods address the above limitations of qualitative methods. However, quantitative methods neglect how behavioural relationships or processes are initially developed or maintained [177], where a different social and environmental context may result in a different process. Furthermore, quantitative measurements of behavioural variables are limited to specific responses restricted to the language of the researchers [177] that may or may not accurately reflect participants' subjective experiences resulting in superficial findings. These limitations can be addressed with the use of qualitative methods.

Thus, neither qualitative nor quantitative methods should be elevated above the other. Each method complements each other and enables the exploration of complex behavioural phenomena. When qualitative and quantitative methods are used in the same study, this is known as mixed methods research. It is important to note that this mixed methods approach is not ideal for all types of research [177]; certain research questions are effectively answered using solely qualitative or quantitative methods. For example, a mixed methods approach would not be appropriate if the research question is only interested in the prevalence of a particular health condition. Before detailing the specifics of the mixed methods used in this thesis, the controversies regarding this approach will be briefly discussed.

The controversies surrounding mixed methods stem from the perspective that qualitative and quantitative methods are derived from opposing philosophical stances [179, 180]. Qualitative methods are seen to derive from an interpretive or relativist understanding that considers multiple realities to exist at once and are subjected to each individual's perspectives. Quantitative methods are seen to derive from a positivist or realist understanding that considers the world to have one "true" reality and its processes can be predicted with appropriate methods. These two perspectives have produced two different paths to research that is reflected in the scientific languages used by each method [180]. For example, the phrase "research has shown…" can mean an (assumption of) accurate reflection of reality to quantitative researchers while qualitative researchers may understand the phrase as one of the interpretations of constructed knowledge [181]. These two perspectives have resulted in some researchers assuming that qualitative and quantitative methods oppose each other; however, as mentioned previously, these methods complement each other and can instead be thought of as "two sides of the same coin". Yet, the approach to using mixed methods can be divided into two further philosophical stances: pragmatism and interpretivism [182].

Pragmatism views knowledge as fluid and not neatly divisible according to pure quantitative perspectives and instead views both quantitative and qualitative approaches as a requirement to understand the "true" nature of reality [183]. Pragmatism accepts the existence of multiple realities, yet states that these realities can be grouped together to derive a wider process that more accurately reflects reality. Interpretivism, however, argues that qualitative and quantitative methods are both products of social and cultural influences, and can therefore only reflect the reality of that specific context [184]. Depending on the philosophical stance, the consumption and interpretation of knowledge have practical implementations. A pragmatist assumes that knowledge will not change as long as appropriate research methods were used while an interpretivist expects knowledge to change between contexts no matter the research methods used. The author of this thesis leans towards the pragmatist perspective yet acknowledges the influence of context as argued by interpretivism. The implications for this thesis is that specific behavioural findings may change with context (e.g. recruiting a different population) yet may contribute to overall knowledge of neurofeedback learning through the understanding of general behavioural processes.

A further consideration is the purpose for using mixed methods. Sale et al [180] state that mixed methods can be used for either cross-validation, where data from different sources (e.g. interviews and questionnaires) are combined to gain a more complete understanding of a phenomena, or for complimentary purposes, where one type of data (e.g. surveys) is used to confirm the results from another type of data (e.g. focus-groups). While both these purposes are useful for different research questions, each purpose has an underlying assumption that must be considered [180]. Cross-validation purposes views qualitative and quantitative data as dependent on each other, where a researcher cannot gain the full "story" without both methods. Complimentary purposes views qualitative and quantitative data as independent of each other, where one method simply adds nuance to the findings of the other method. This thesis used mixed methods for cross-validation, where each method used only provides part of the behavioural process behind neurofeedback learning.

4.4 Summary

The author views reality as independent from human beings, however, the conceptualisation of reality and understanding of knowledge differs between individual perspectives of each human being. The explorative, mixed methods approach was chosen as it allowed flexibility to assess the open research questions of this thesis, where the author assumes a pragmatic-leaning stance and uses mixed methods for the purposes of cross-validation. The specific methods and their justification are detailed in the next chapter.

Chapter 5 General Method

This chapter outlines the methods used in this thesis, which includes the study design, participant recruitment, ethical considerations, materials used (i.e. equipment and questionnaires), and the study procedure. The chosen explorative, mixed method approach resulted in a large and complex data set; results from this data set were split into three chapters for easier comprehension of the findings. The analysis plan is not detailed in this chapter; instead, each results chapter details the analysis plan relevant to that chapter. A checklist to uphold reporting standards for neurofeedback studies [185] can be found in Appendix A.

5.1 Study Design

This study used a mixed method design that examined results within and between participants. Qualitative data were gathered from one-on-one, semi-structured interviews; quantitative data were gathered from questionnaires and physiological data (EEG, electrocardiogram (ECG; measures heart rate), respiratory rate (RSP), and galvanic skin response (GSR)). Questionnaires included measures of SE, LoC, pain intensity, pain quality, motivation, and task load. Questionnaires details are described in the materials section of this chapter.

5.2 Participants

Twenty-seven able-bodied participants and twelve participants with CNP after SCI (referred to as CNP participants from now on) were recruited for this study, totalling thirty-nine participants. Two able-bodied participants and two CNP participants were removed from the analysis due to disturbances in EEG data, where the remaining thirty-five participants consisted of twenty-five able-bodied participants (13 female; mean age = 30.96, SD = 11.19, range = 19-65) and ten CNP participants (3 female; mean age = 51.70, SD = 10.55, range = 35-68). Six able-bodied participants reported having a non-pain-related condition (hay fever, mild haemophilia A, hyperhidrosis, asthma, and polycystic ovary syndrome). Three CNP participants had a non-neuropathic pain condition (two CNP participants had chronic back pain and one had chronic shoulder pain), and one CNP participant had a non-pain-related condition (diabetes). See Table 5.1 below for details of CNP after SCI for each CNP participant.

Table 5.1 CNP participants' demographics

ID	Years Since Injury	Years Since Pain	Pain Level	ASIA Injury Level	Completeness
P1B	2.5	2.5	Below-level	T12	Complete
P3B	4	4	Both at and below-level	C4	Incomplete
P4B	36	36	Below-level	L1	Incomplete
P5B	48	2.3	Below-level	T6	Incomplete
P6B	13	13	Below-level	T4	Complete
P7B	11	4.5	Below-level	T8	Complete
P8B	20	20	Below-level	T4	Incomplete
P9B	4	4	Below-level	C4	Incomplete
P10B	13	10	Both at and below-level	C6	Incomplete
P12B	36	36	Below-level	T4	Incomplete

Able-bodied participants were recruited from the University of Southampton, Southampton, UK (students and staff). CNP participants were recruited from the National Spinals Cord Injuries unit at Stoke Mandeville Hospital, Aylesbury, UK. The decision to recruit both able-bodied participants and CNP participants was due to an interaction between the researcher and three individuals with CNP after SCI who had been using the neurofeedback system for several months. These individuals told the researcher about their successful mental behaviours in detail; all of which was related to an activity they loved and were doing when they had incurred their SCI. This led the researcher to believe that individuals with CNP after SCI may specifically use mental behaviours related to their SCI experience, suggesting that mental behaviours may differ between able-bodied individuals and individuals with CNP after SCI. Thus, both groups of individuals were recruited for this study. The motivations behind neurofeedback learning may also differ between participant groups because the potential pain relief from the current neurofeedback system is a possible motivational driver of behaviour for CNP participants. Furthermore, the mental behaviours used by able-bodied participants may differ from CNP participants, where the context of using a device that may relieve pain may influence the mental behaviours of CNP participants. Participants were recruited via convenience sampling; all participants were recruited in order of first to meet the study criteria (presented in Table 5.2). The limitations of convenience sampling are detailed section 9.3 of the General Discussion chapter.

Table 5.2 Participant inclusion/exclusion criteria

CNP participants	
Inclusion Criteria	*Exclusion Criteria*
Minimum 18 years old	History of brain injury
Minimum one-year post spinal cord injury	History of a neurological condition apart from CNP after SCI
Minimum six months of treatment history for CNP	
Reported pain intensity greater than or equal to five on a numerical rating scale (0 – no pain, 10 – worst pain)	
Able-bodied Participants	
Inclusion Criteria	*Exclusion Criteria*
Minimum 18 years old	History of chronic pain conditions
	History of brain injury
	History of a neurological condition

5.2.1 Recruitment Procedure

Able-bodied participants were recruited face-to-face (the researcher stationed themselves in populated areas of the university and invited passers-by) and through poster advertisements. All potential participants were given a participant information sheet (Appendix B) and multiple opportunities to ask the researcher any questions they may have had before deciding to participate in the study.

The health care team at the National Spinal Cord Injuries unit in Stoke Mandeville Hospital identified potential CNP participants via a review of medical records. The health care team sent postal letters of invitation; these included a brief summary of the study and contact details of the researcher. The health care team also invited potential participants during their clinical visits to the hospital spinal unit. Poster advertisements at the hospital were also used for recruitment. Potential participants were directed to contact the researcher to ask any questions about involvement in the study. The researcher was stationed at the hospital while collecting data from participants with CNP after SCI.

5.3 Ethical Considerations

Ethics approval was obtained from the ethics committee of the Department of Engineering and Physical Sciences, University of Southampton, UK and from the Research Ethics Committee of the Health Research Authority, UK. Written, informed consent was obtained from each participant before taking part in the study. All participants were provided with an information sheet and had the opportunity to ask any questions before giving their written, informed consent. All participants were informed that they may withdraw from the study at any time without reason. Able-bodied participants were given monetary incentive (£10 per visit, £40 in total) to participate in the study, and travel costs were covered for CNP participants. Only the able-bodied participants were given monetary incentive because it was expected that the target sample size would not be achieved otherwise (sample size calculation is given in section 7.1.3 of chapter 7 as this chapter uses statistical analysis powered by the sample size). This was not given to CNP participants because a large sample size was not needed; yet, travel costs were covered because it was expected that travel would be more difficult for CNP participants due to mobility issues. All participant information was anonymised before distributing their data to others on the research team, such as the supervisors of this thesis.

5.4 Materials

5.4.1 Equipment

Emotiv EPOC Model 1.0 (Figure 5.1): A 14 channel, portable EEG head set was used to record EEG signals and provide the neurofeedback to participants; it had a 14-bit resolution and a sampling rate of 128 samples per second. This headset can be adjusted to fit most head sizes and exerts slight pressure on the head to ensure good contact between the electrodes and the scalp. The electrodes were wetted with saline solution prior to application to ensure good contact for EEG recording. However, some heads had an odd shape that did not allow for good electrode contact; a band (below) was used to solve this issue.

The exact location of C4 on the scalp was difficult to determine when using the Emotiv headset. Higher quality EEG headsets usually come with a cap that assist in determining precise electrode location according to the 10-20 system. No such cap or similar equipment was provided with the Emotiv headset. The band used for tightening the headset was marked in centimetre increments and used to determine the location of C4 by manually measuring the head according to the 10-20 system. Risk of inaccuracy was reduced by practicing this method on a 3D polystyrene head and on volunteers (friends and colleagues) who did not participate in the study; reference to the literature and guidance from expert EEG researchers were used alongside this practice.

Figure 5.1 Display of the Emotiv EPOC Model 1.0

Band: A band was used in cases where the Emotiv headset did not fit appropriately on the head. This was fitted tightly over the headset to hold down electrodes for stability and proper scalp contact.

Saline Solution: Saline solution was used Emotiv headset’s electrodes for electrode connectivity.

Laptop: A computer laptop with Windows 10, connected to the Emotive headset via Bluetooth, displayed the visualised EEG activity of the user as well as the connectivity of the Emotiv headset.

Biopac MP100: This physiological signal acquisition system measured RSP, GSR, and ECG. A belt fit around the thorax/abdomen connected to the Biopac MP100 collected RSP by measuring the circumference of the abdomen (sampling frequency of 250). Electrodes, also connected to the

Biopac MP100, were applied to fingers for collection of GSR (sampling frequency of 250), and to wrists and ankles for collection of ECG (sampling frequency of 500). Figure 5.2 shows the set-up of the Emotiv headset and the Biopac MP100 on an individual.

Electrolyte Gel: An electrolyte gel was applied to electrodes of the Biopac MP100 for electrode connectivity.

Alcohol Wipes: Alcohol wipes were used to clean the participants' skin before applying the electrodes of the Biopac MP100.

Medical Tape: Medical tape was used to ensure the Biopac MP100 electrodes were stable.

Figure 5.2 Set-up of Emotiv headset and the Biopac MP100

Picture taken of participant with consent to be used in reports of the neurofeedback study
a = Emotiv headset
b = Laptop connected to Emotiv headset via Bluetooth
c = Biopac MP100
d = Saline solution for Emotiv headset electrode connectivity
e = Electrolyte gel for Biopac MP100 electrode connectivity

5.4.2 Standardised Questionnaires

All questionnaires are validated and were provided in a booklet to participants; blank questionnaires can be viewed in Appendix C.

Douleur Neuropathique 4 (DN4; [186]): The DN4 is a 4-item, validated screening tool that is used to identify the likelihood that an individual is experiencing neuropathic pain developed from any condition [187]. This tool was used as an additional measure alongside confirmation from medical records to ensure that CNP participants have neuropathic pain. The administration of the DN4 requires training, which was provided by a qualified healthcare professional from the National Spinals Cord Injuries unit at Stoke Mandeville Hospital (the recruitment site for CNP participants). It was emphasised to CNP participants that this tool was only to confirm their neuropathic pain for scientific quality purposes and not for diagnosis or treatment purposes.

General Self-Efficacy Scale [188]: A 10-item standardised questionnaire that is a self-report of general SE. This questionnaire was chosen because it measured a broad concept of SE that can be applied to a variety of situations, such as examining test-related anxiety [189] and behaviour change in cancer patients [190]. This flexibility was suitable for the exploration approach of this thesis. The General Self-Efficacy Scale is reliable and used in recent, primary research [190-192].

General Locus of Control Scale (For healthy participants only, [193]): A 24-item standardised questionnaire that is a self-report of LoC. This questionnaire had three dimensions: (1) internal LoC, (2) perception of powerful others, and (3) perception of fate. Numbers 2 and 3 are types of external LoC. Similar to the General Self-Efficacy Scale, the General Locus of Control Scale was chosen for its broad and flexible use; for example, it has been used in assessing psychoeducation in patients with bipolar disorder [194] and job satisfaction in university settings [195]. This questionnaire is reliable and used in recent, primary research [193, 194, 196]. Another LoC questionnaire was used for CNP participants and its justification is described below.

Multidimensional Health Locus Of Control Scale (For CNP participants only, [197]): An 18-item standardised questionnaire that is a self-report of health LoC, that is, belief of control over events specifically related to health and not general events. There are three versions of this questionnaire: version A and B assessed LoC of general health while version C assessesed LoC of a specific health-related condition. Version C can be adjusted to refer to the specific condition of the research topic, which is CNP after SCI in this case. Version C was used in this thesis, which consisted of four dimensions: (1) internal LoC, (2) perception of powerful others, (3) perception of doctors, and (4) perception of fate. Numbers 2 to 4 are types of external LoC. This Multidimensional Health Locus of Control Scale version C was chosen over the above general LoC scale for CNP participants because the neurofeedback system was designed to treat CNP after SCI. As mentioned previously in section 2.1.3, perceived control of pain is associated with pain intensity and physical disability; an individual with CNP after SCI who perceives that they have no control over their pain may limit their participation in certain activities [30]. Since the neurofeedback system is associated with pain relief, pain-related LoC may transfer to control over EEG activity. Thus, pain-related LoC was chosen to be examined. This was not done for other learning factors because no appropriate questionnaire existed. The author acknowledges the discrepancy in LoC measures between the participant groups and addressed this during the limitations section of Chapter 7. The Multidimensional Health Locus of Control Scale was derived from the General Locus of Control scale; the scores of these two scales can be compared through visual inspection using plots to understand whether both scales result in similar trends. The Multidimensional Health Locus of Control Scale is reliable and used in recent, primary research [197-199].

NASA Task Load Index [200]: Difficulty of a task can be assessed by examining the demands of that task, that is, task load. The NASA Task Load Index is a standardised questionnaire measuring task load, and is split into two parts. The first part consists of a 6-item questionnaire that is a self-report measure of task load. The second part measured the importance of the previous 6 items to the participant using a ranking system. Scores of both parts are calculated together to produce a single score for task load. This questionnaire is reliable and used in recent, primary research [201, 202].

McGill Pain Questionnaire – Short Form 2 [203]: A 24-item standardised questionnaire that is a self-report of pain quality. Pain scores can be grouped in to the following four categories: continuous, intermittent, affective, and neuropathic. This questionnaire is reliable and used in recent, primary research [204, 205].

5.4.3 Numerical Ratings Scales

Numerical rating scales were on an 11-point scale of 0 to 10 where 0 indicates lowest point of the factor and 10 indicates highest point of the factor. All numerical rating scales were provided in a booklet to participants; blank scales forms can be viewed in the Appendix C.

Pain intensity: This item reports the intensity of the overall pain the participant experienced at the time of completing the questionnaire. This scale has been used in previous pain research to measure overall pain intensity [206, 207].

Motivation: This item reports the motivation each participant has to take part in the neurofeedback task. A numerical rating scale was used for motivation rather than a standardised questionnaire to minimise procedure length for participants with the aim of optimising participation adherence to the study. However, this scale has been used to measure motivation in previous neurofeedback learning studies [109, 110].

5.5 Neurofeedback Protocol

The neurofeedback protocol described here follows the protocol developed by Hassan et al [8]. EEG activity feedback was given to participants from above the primary motor cortex (C4). EEG activity was presented to participants in the form of three bars on a monitor (Figure 5.3 and Figure 5.4). Each bar (from left to right) represented the following EEG frequency bands: theta, alpha, and higher beta. The middle bar (alpha) was wider than the other bars because participants previously reported that this bar was the easiest to control [8]. The neurofeedback protocol was designed to encourage the user to reinforce alpha power, and supress theta and higher beta powers (discussed in section 2.3.3). The training threshold was set to 110% of the average power in the alpha band during baseline (rest), and to 90% of the average power in the theta and higher beta bands during baseline. Therefore, users must increase their alpha power by 10% of their baseline and decrease their theta and higher beta powers by 10% of their baseline to surpass the thresholds. The bars became green when this threshold was surpassed; otherwise the bars remained red. Figure 5.3 shows an example of the different colours within each bar. The side bars became green when the height of the bars were low, representing suppression of theta and high beta, and the middle bar became green when the height of the bar was high, representing reinforcement of alpha. EEG feedback was given at a sampling rate of 128Hz in real time by calculating relative power (power during neurofeedback training compared to power during baseline; exact calculation for relative power is described in section 7.1.1) over a 0.5s long moving average window.

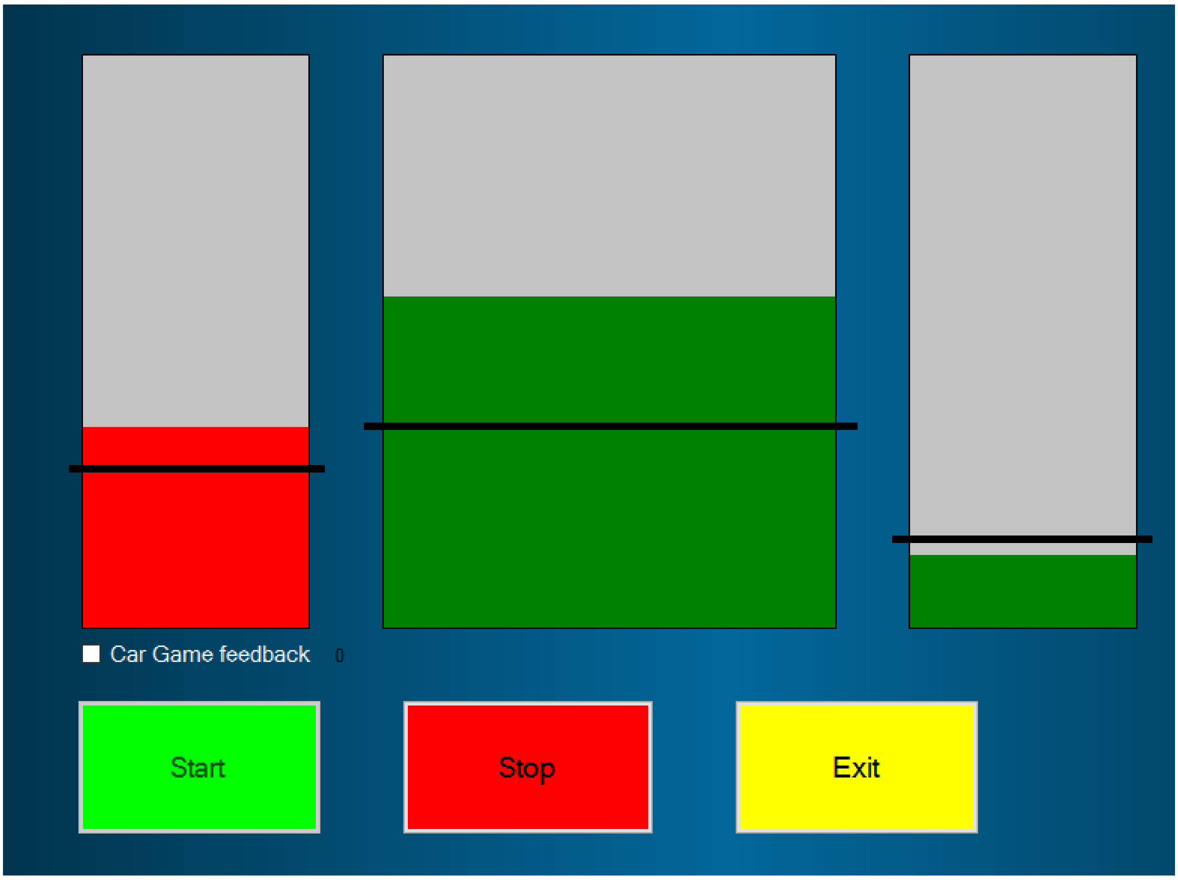


Figure 5.3 Representation of EEG activity

The black lines represent the threshold that must be surpassed for the bars to become green. The side bars, representing theta and high beta, became green when the bar was lower than the black line. The middle bar, representing alpha, became green when the bar was higher than the black line.

A single neurofeedback session consisted of six training runs (attempting to control the bars on the screen), where each run lasted five minutes. Resting EEG baseline (eyes open) was measured for two minutes before the start of the six neurofeedback training runs (Figure 5.4). The instruction given to users was “use whichever mental strategy you prefer to make the bars green”; the users had to identify successful mental behaviours to make the bars green through trial-and-error. No other instructions or guidance were given to participants. In addition to the colour-changing feedback, an “end score” was provided to participants after each run. The end score displayed how many times (i.e. how many samples) the middle bar (alpha) became green during that run. Individuals were told to keep as still as possible during the training, and that they may take a break between runs if they wished to do so. Total time taken for a single session was approximately 35 minutes, depending on the number and length of breaks taken by the participants. This training was repeated on four separate visits no more than a week apart.

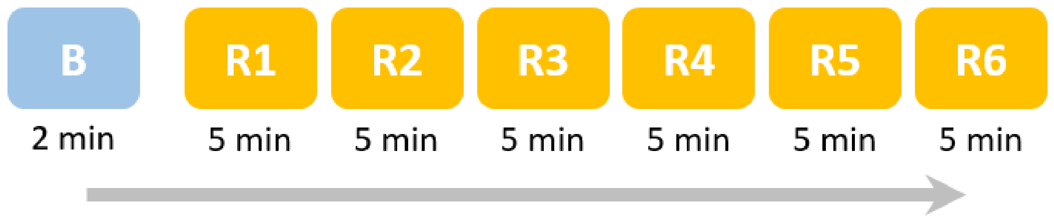


Figure 5.4 Flow diagram of neurofeedback training in a single visit
B = Baseline before the neurofeedback training
R1… R6 = First neurofeedback training run… sixth neurofeedback training run

5.6 Interview Schedule

The interview schedule was developed with reference to the literature and consultation from experts in qualitative research. This interview was semi-structured and lasted approximately 15 minutes. The following questions were asked:

To gain information on what mental strategies were used

1. Can you please describe to me, for each neurofeedback training run, what you did to try to make the bars green?
2. Did you try anything else?

To understand the quality of mental strategy used

3. Can you tell me more about [insert strategy used]?
4. Can you tell me why you used [insert strategy used]?
5. How did you feel when you tried [insert strategy used]?
6. How did you know that [insert strategy used] was working?
7. How did you know that [insert strategy used] was not working?
8. How distracted were you when you used [insert strategy used]?
9. How did you deal with the distraction?

Question 1 was asked first. Questions 2 to 11 were asked for each strategy that participants mentioned. Follow-up questions were asked to gain more details of the mentioned mental strategy (e.g. if a participant said they tried to relax, the researcher asked in what way did they try to relax to clarify if the relaxation was mental or physical). Some interviews deviated from the above schedule as some participants provided the answers before the questions were asked. CNP participants were asked "can you describe your current pain?" and "how does it compare to the pain you felt before the neurofeedback training?" to assess changes in pain experience before and after the neurofeedback training. Follow-up questions were asked to gain more details of their pain experience (e.g. if a participant reported pain reduction, the researcher asked what quality of pain was reduced to clarify whether overall pain was reduced or only a specific sensation, such as numbing pain).

5.7 Procedure

Once participants agreed to join the study, they were asked to sign a consent form (Appendix D) If participants could not sign the consent form themselves, their trusted other was permitted to sign on their behalf (this was only expected to occur for CNP participants who may have mobility issues). Their trusted other was given all information that was provided to the participant. The following is a step-by-step procedure (concise flowchart shown in Figure 5.5) after signing the consent form:

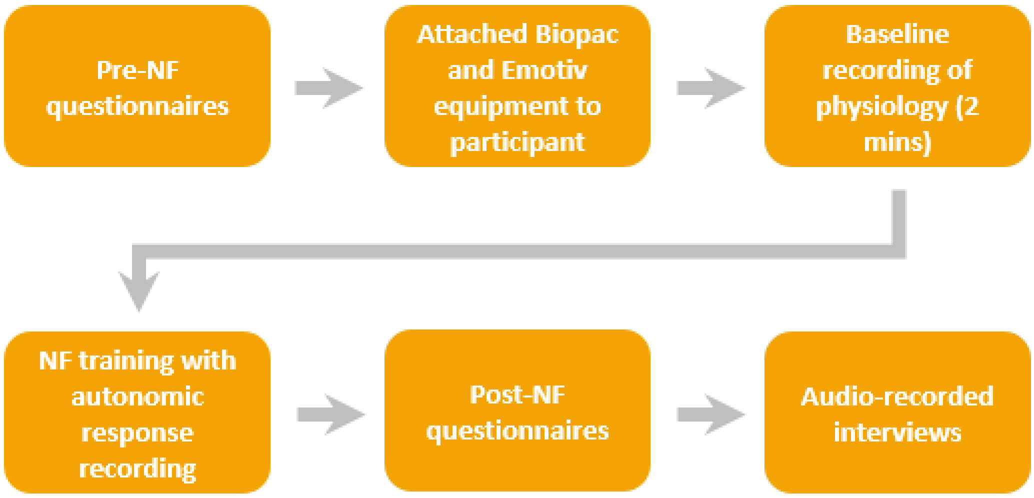


Figure 5.5 Flowchart showing procedure overview

1. Participants were asked to complete a questionnaire that measured SE, LoC, motivation, pain intensity, and pain quality (only CNP participants were asked about pain).
2. The researcher applied the GSR and ECG electrodes, and the chest belt on the participant.
3. Participants were asked to wear the Emotiv EEG head set that was connected to a tablet in front of them via Bluetooth, after which the room lights were turned off to reduce noise in the physiology data.

4. Participants were asked to sit as still as possible while their baseline EEG activity was recorded for two minutes with eyes open. Physiological data from the Biopac unit started to collect data, and did so continuously throughout the neurofeedback training visit. To distinguish between segments of the neurofeedback session, an ECG wrist electrode was tapped three times to indicate the start of the baseline and each training run. An end tap was not needed as the exact length of segments were known (2 minutes for baseline and 5 minutes per run).
5. Participants were instructed about how their EEG will be represented on the laptop (i.e. in the form of three coloured bars and how they moved), and were instructed to "use whichever mental strategy you prefer to make the bars green”.
6. Once the neurofeedback training had ended, all equipment were taken off participants, and a tissue was given to participants to wipe any electrode gel that remained on their body.
7. Participants were asked to complete another questionnaire that included the same measures as step 1 and the addition of one other measure: perceived task load of neurofeedback training.
8. Participants were interviewed about the mental behaviour they used to turn the bars green, which was recorded on an audio device. Before the interview began, participants were told that the interview will be recorded.

The above procedure took approximately 2 hours, inclusive of any breaks that participants wished to take. The procedure was conducted on four separate visits no more than a week apart, thus participants completed neurofeedback training four times.

Chapter 6 Findings Part I: Qualitative Exploration of Mental Behaviour during Neurofeedback

This chapter focused solely on the qualitative findings of mental behaviour reported by participants during neurofeedback training. The next chapter examines the relationship between mental behaviour identified in this chapter and neurofeedback performance.

6.1 Analysis Plan

An explorative approach allowed interviews to be analysed with qualitative and quantitative methods (described further below). The qualitative analysis will first be described, followed by the quantitative analysis.

6.1.1 Qualitative Analysis of Interview Data

Interview data were analysed using thematic analysis (TA), a qualitative analysis that focuses on interpreting patterned meaning across a dataset [208]. Words or phrases are assigned labels that describe the overall meaning of that word or phrase; these labels are called codes. After coding the dataset, the codes are organised into overarching themes that represent the content of that dataset. These themes are interpreted for patterned meaning[3]. Before specifying the TA used in this thesis, an overview of TA will first be introduced.

TA is an umbrella term for a variety of different approaches that can be divided into the following, as described by Braun et al [208]: coding reliability TA, reflexive TA, and codebook TA. Coding reliability TA collects and analyses data through the use of multiple coders working independently to ensure inter-coder reliability. After independent coding and theme development, a codebook is developed that only includes codes and themes that are agreed upon by all coders. Data are then

[3] It is important to note that themes could also be a summary of what participants said in relation to a topic [187]. Themes are usually based around the questions that were asked, e.g. "risks of a treatment" could derive from responses to a question that asked "can you tell me about the risks of this treatment". This type of theme usually reflects superficial meaning and may include contradictory content within a theme, e.g. a theme may include both risks and benefits of a certain treatment.

re-analysed using the final codebook. Reflexive TA aims to provide a coherent interpretation of the data that acknowledges and actively uses the subjective views held by the coder. For example, reflexive TA can be used to address racial discrimination where the coder is from the discriminated population. This is in contrast to coding reliability TA that attempts to minimise subjective interpretations with the use of multiple coders. Although coding reliability claims to minimise subjective views, it is not always achieved. For example, coding reliability TA may still be highly subjective if all coders hold similar views or have similar backgrounds. Codebook TA adopts the coding process of coding reliability, where codes and themes are organised into a codebook. However, codebook TA does not emphasise reliability compared to coding reliability TA and instead acknowledges the subjective views of the coder similar to reflexive TA. Thus, codebook TA can be said to lie between coding reliability TA and reflexive TA by combining the systematic approach and subjective acknowledgement of these respective TA methods.

This thesis used codebook TA; only one coder analysed the data (validated by an independent researcher, detailed at the end of this section), where a selection of interviews were used to developed an initial framework (codebook) that was applied to the rest of the interviews. The specific qualitative process follows the stages of Gale et al [209], and is described below.

Stage one involved careful, verbatim transcription of all interviews. Pauses, erms, ahs, and other speech fillers were not transcribed as they did not contribute to the research aim. Transcriptions were anonymised by removing all identifiable and personal information, such as names and places. However, some interviews were outsourced to a professional transcriber due to the number of interviews (35 total participants with four interviews per participant, totalling 140 interviews) and limited time to complete the thesis. Interviews from twenty able-bodied participants (80 interviews) were outsourced; no interviews from CNP participants were outsourced due to ethical restrictions.

Stage two involved familiarising oneself with the entire interview data. Repeatedly listening to the audio and repeatedly reading transcriptions were part of the familiarisation process, where first impressions and interpretations of the dataset were noted. This is an important stage to gain a deeper understanding of the meaning behind the statements from the interviewees.

Stage three involved selecting interviews to create the initial framework. Transcripts from all CNP participants and 6 randomly chosen able-bodied participants were selected for this stage. All interviews for CNP participants were analysed as this neurofeedback protocol was designed for individuals with CNP after SCI. Interviews of only six able-bodied participants were randomly selected as saturation of data (i.e. no new data could be extracted) was expected to occur after analysis of eighteen sets of interview data (12 CNP participants and 6 able-bodied participants; [210, 211]). Transcripts of able-bodied participants were randomly selected by using a random number generator (in Microsoft Excel) that provided a number between 1 and 25 (25 total able-bodied participants were recruited). This stage is not described by Gale et al [209], but was done to ensure minimum bias when selecting the initial interviews for analysis.

Stage four involved analysing the selected interviews from stage 3 line-by-line. Coding was inductive, that is, any relevant words or phrases were coded from as many different interpretations as possible by the coder. Deductive coding is where codes have been pre-established based on a literature review or experience. This study had no hypotheses and approached the study aim with open research questions, and thus used inductive coding instead of deductive coding. Coding was done over several iterations until no new code emerged. Coding was first conducted on paper and then transferred to a qualitative analysis software called Nvivo (version 12) by the company QSR International. It is emphasised for those not familiar with Nvivo that this software does not conduct the analysis for the researcher. It is a virtual tool that allows for easier classification and arrangement of the data that assists analysis. The remaining analysis was conducted using this software.

Stage five involved organising the codes from stage four into overarching themes. Codes were categorised based on common traits (e.g. codes that referred to visually remembering a past event), which are then appropriately labelled (e.g. such as “visual memory”); these are the themes. Themes were also constructed based on the codes’ relationship to EEG activity; for example, motor imagery is seen as a distinct mental activity that changes EEG activity in a specific way (further detailed in the results section). This was done over several iterations until no code was left without a theme. The resulting themes created the initial framework that was used in the next stage. The categorisation of codes into themes are shown in the results section of this chapter.

Stage six involved analysing the remaining interviews with the initial framework. Themes from the framework were used to code the relevant passages of the remaining interviews. Any new themes found during this stage were added to the framework, and all previously coded transcripts were re-analysed with the updated framework.

Stage seven, the final stage, involved interpreting the final framework. Although this stage is described as a separate stage, it was an on-going process that started from the first stage. Notes of first impressions were written down throughout these stages that described any interpretation made at the time. All interpretations were discussed with supervisors and colleagues, and were also compared to changes in EEG activity using current literature. It is acknowledged that interpretation can go on forever, but was halted once the interpretation sufficiently explained neurofeedback learning events reported by participants. The indication of sufficient explanation was based on discussions with supervisors and colleagues, and reading of the literature [212].

To reduce researcher bias of the interview analysis, an independent qualitative researcher re-coded interviews from six randomly selected participants (total of eighteen interviews) using the developed framework. This approach is in line with current qualitative research standards and suggested by Ritchie and Lewis [213]. The independent researcher's codes were checked against those of the initial coder (the author of this thesis) and any disagreements were discussed. All original themes were agreed upon, no new themes were included in the framework. The qualitative analysis was reported using the COREQ (consolidated criteria for reporting qualitative research) form of reporting qualitative research [214] (Appendix E) which provides further transparency of collection and analysis of the interview data.

6.1.2 Quantitative Analysis of Interview Data

Descriptive statistics were used to examine the frequency of each theme identified from the interview data. As the interview questions aimed to understand what participants were doing during the neurofeedback training, themes were assigned to their respective run of each neurofeedback training visit; this was done for all participants. This allowed exploration of patterns between themes, frequency of themes, and perception of success. After discussions with a qualified statistician, no statistical analysis took place given the inductive nature of these findings.

6.2 Results

Interview analysis yielded a vast amount of data that included mental strategies (mental action conducted by the participant) and affect (a psychological term referring to any experience of feeling or emotion). A third category of mental behaviour was also identified (the interface design's influence on mental behaviour), which is discussed in chapter 8. To maintain anonymity, participants are identified with a combination of numbers and letters, where A represents an able-bodied participant (e.g. 2A) and B represents a CNP participant (e.g. 5B). All quotations are italicised; phrases within square brackets are not part of the original quote but added to provide context.

Not all participants completed all four neurofeedback training visits; some participants dropped out after one visit due to not perceiving success at neurofeedback (two able bodied participants and four CNP participants) or non-study related events (e.g. unavailable transport to study site; four CNP participants). The sample size and dropout rates are shown in Table 6.1, which shows that considerably more CNP participants (7) dropped out compared to able-bodied participants (3). This is because the cost of study participation was greater for CNP participants than able-bodied participants (e.g. preparing to attend a study session can take several hours for CNP participants due to mobility issues and waiting for patient transport). Most CNP participants travelled for more than an hour for study participation, where these participants set aside the whole day for this study. Thus, CNP participants were more likely to incomplete all visits than able-bodied participants.

Table 6.1 Sample size and dropout rates for each visit

Participant Group	**V1**	**V2**	**V3**	**V4**
Able-Bodied	n = 25 DO = 0	n = 23 DO = 2	n = 22 DO = 1	n = 22 DO = 0
CNP	n = 10 DO = 0	n = 8 DO = 2	n = 5 DO = 3	n = 3 DO = 2
Total	n = 35 DO = 0	n = 31 DO = 4	n = 27 DO = 4	n = 25 DO = 2

n = Sample size
DO = Dropout; number of participants who dropped out

6.2.1 Side Effects of Neurofeedback Training

During neurofeedback training, the following side effects were observed: mild headaches (reported by ten able-bodied participants and six CNP participants), mildly irritated eyes (reported by eight able-bodied participants and three CNP participants), and flashing lights when closing eyes after returning home on the day of the training (reported by one CNP participant). Headaches and irritated eyes were reported by participants to be caused by intense concentration in a dark room during the neurofeedback training. This was alleviated by resting for several minutes between neurofeedback training runs. The cause of the flashing lights were not known; however, the participant reported that it only happened on days of the neurofeedback training, which occurred alongside headaches. The flashing lights did not persist beyond the day of the neurofeedback training. It was emphasised to this participant that they may withdraw from the study if they wished and to contact the chief investigator (the author of this thesis) if the flashing lights persisted or became worse. All side-effects were reported to the NHS ethics committee. Side-effects were not observed nor reported by participants to influence neurofeedback performance.

6.2.2 Mental Strategies

The categorisation of codes into mental strategies are summarised in Table 6.2. Thirteen mental strategies were identified from the interview data (detailed in Table 6.3): (1) Actual Movement, (2) Auditory, (3) Breathing, (4) Clearing Mind, (5) Imagination, (6) Imagined Movement, (7) Memory, (8) Moral Values, (9), Non-Specific Focus, (10) Numerical Task, (11) Pain Memory, (12) Planning, and (13) Resolving Stress. No clear differences in frequency of mental strategy were found between able-bodied participants and CNP participants (Table 6.3).

Table 6.2 Categorisation of initial codes into themes regarding mental strategies

Initial Codes	Themes	Grouping Description
• Actually moving body part (not just in mind)	Actual Movement	These mental strategies were focused on their physical body, and not imagery within the mind, where participants initiated actual movement
• Chanting green • Chanting up/down • Chanting happy • Ordering bars to become green • Imagining a sound from nature • Memory of a pleasant sound • Reciting poem/prose • Recalling a song • Spelling out words	Auditory	Sounds derived from imagination or memory, or sounds that participants spoke/sang in their head
• Focusing on breathing • Controlling breathing	Breathing	Participants focused on their breathing by either noticing their breathing or trying to control it
• Emptying mind of thoughts • Not thinking of anything	Clear Mind	Participants were trying to clear their mind if thoughts
• Imagining calm scene • Imagining green object • Imagining green scene • Doing something to the bars	Imagination	Imagery that the participant has not personally experienced, where the mental strategies were derived from watching someone else (e.g. a person on TV) or a description they have come across (e.g. from a book)
• Sexual memory • Sports memory • Imagining physical movements • Imagining doing a sport • Imagining a physical sensation	Imagined Movement	Strategies that involved imagery of moving a body part in a specific way, either from imagination or memory
• Memory of a loved-one • Memory of a pleasant sensation • Videogame memory • Memory of driving a familiar route • Memory of a shopping route • Memory with green	Memory	Mental strategies that involved imagery derived from memory, not from imagination
• Thinking about a good decision	Moral Values	Participants reported that their decision/trait reflected a moral value important to them

• Thinking about an important personal trait		
• "Just concentrating"	Non-Specific Focus	Participants only reported concentrating on the neurofeedback task without further descriptions of using imagery or other thoughts
• Counting • Maths multiplication tables • Listing prime numbers • Counting number of times bar went green	Numerical Task	Mental strategies involving a simple numerical task
• Painful sensation	Pain Memory	Memory of painful sensation
• Planning out a meal • Planning out coursework prep • Planning future event with family	Planning	Participants were thinking of the things they needed to do in order to complete a future task
• Resolving personal stress	Resolving Stress	Participant reported finding possible solutions to their current personal issues that were causing them stress

Table 6.3. A description of the mental strategies identified from the interview analysis and the number of participants that used each mental strategy; ordered from most used to least used

Mental Strategy	Description	n (*AB, **C)
Imagination	Imagery or scenarios that the participants have not personally experienced	25 (19, 6)
Auditory	Sounds derived from imagination or memory, or sounds that participants spoke/sang in their head	23 (15, 8)
Non-Specific Focus	Focus on the neurofeedback task with no verbalisation about thoughts or imagery	22 (13, 9)
Memory	Imagery or events derived from memory	18 (15, 3)
Imagined Movement	Strategies that involved imagery of moving a body part in a specific way, either from imagination or memory	17 (14, 3)
Breathing	Participants focused on their breathing by either noticing their breathing or trying to control it	13 (10, 3)
Clear Mind	Clearing the mind from any thoughts to have an empty mind	12 (10, 2)
Numerical Task	Mental strategies involving a simple numerical task	8 (5, 3)
Actual Movement	These mental strategies were focused on their physical body, and not imagery within the mind, where participants initiated actual movement	6 (6, 0)
Planning	Mentally preparing for a future event	6 (6, 0)
Moral Values	Thinking about a moral value that was important to oneself	2 (2, 0)
Pain Memory	Recalling physical pain from a past event	1 (1, 0)
Resolving Stress	Considering possible solutions to current stressful events in one's life	1 (0, 1)

n = Sample size
*AB = Able-bodied participants
**C = CNP participants

Participants did not report a clear reason for trying most mental strategies: six stated they had "*no idea why*" (18A), while the others thought the strategy may elicit the required response to control the bars ("*I just thought it would work*" – 14A). Probing did not facilitate further understanding about why the strategy might generate the required response, emphasising the trial-and-error nature of this neurofeedback training. Relatively clearer reasons were only provided by participants for two mental strategies: Pain Memory and Resolving Stress; reasons for these strategies are detailed below.

Actual Movement

Actual movement, as opposed to imagined movement, has been strongly associated to specific EEG activity that is thought to be sourced in the basal ganglia (deep brain structure) and is reflected within the sensory-motor cortex [215, 216]. The mu rhythm (made up of alpha and lower beta frequencies) decreases in amplitude just before movement, and increases again after movement [217, 218].

Six participants (6 able-bodied, 0 CNP participants) used a physical strategy instead of a mental strategy, that is, participants focused on their actual physical body and not any imagery or thoughts within the mind.

"*[I] shifted my eyes to one direction and then the other*" – 22A

"*… I did a big yawn and everything slowed down… so I concentrated on [yawning]*" – 25A

Auditory

Auditory mental activities (i.e. mental activities with no imagery, such as imagined speech) has been shown to elicit specific EEG patterns [219] related to alpha [220] and theta [221].

Twenty-three participants (15 able-bodied, 8 CNP participants) used a mental strategy only involving auditory activities, such as chanting a phrase or remembering a song, without the use of any imagery.

"*[I was thinking] be green, yes, you want to be green*" – 7A

"*I was just singing some Hindi songs [in my head]*" – 10B

Breathing

Each part of respiration cycle has been associated with specific EEG patterns [222], and slow and controlled breathing has been associated with increased alpha power [223]. Although Breathing can be considered a physical strategy, Breathing was identified as a separate category from Actual Movement as these strategies are associated with different EEG patterns.

Thirteen participants (10 able-bodied, 3 CNP participants) focused on their breathing or slowed down their breathing without the use of other mental strategies, such as imagery or auditory activities.

"*I did absolutely nothing except focus on my breath*" – 16A

"*I tried lowering my breathing to see if it would help*" – 8B

Clear Mind

Although clearing one's mind can be thought of as a relaxation technique; previous studies show that attempting to stop thoughts is a demanding mental task [224, 225] that can result in increased pre-frontal beta power [225].

Twelve participants (10 able-bodied, 2 CNP participants) tried to empty their mind from any thoughts.

"*As soon as something came to my head, I dismissed it completely*" – 16A

"*I tried to… incorporate a bit of mindfulness and… stay more focused on [the screen] and stop my mind wandering*" – 12B

Participants used various methods to achieve this: trying to reduce their thoughts one by one to eventually clear their minds, focusing on a dark space on the screen to block out any thoughts, and dismissing any thoughts that may appear in their mind.

Imagination

Mental tasks involving imagery generally decrease alpha power [226, 227]. Two identified mental strategies involving imagery were imagination and memory. Imagination was separately categorised from memory as imagination has been shown to result in different EEG patterns compared to memory [228]. For example, Ewerdwalbesloh et al [229] showed that objects that were created (i.e. imagined) correlated with increased theta power compared to those which were memorized (i.e. from memory).

Twenty-five participants (19 able-bodied, 6 CNP participants) used strategies that they have not personally experienced, and created imagery and scenarios derived from observing another person (e.g. event on TV) or through other knowledge (e.g. scenery described in a book). Participants imagined various imagery and scenarios, such as pleasant landscapes or partaking in an imagined social event.

"*I was driving with a friend with nice scenery… but it's not like actual scenery, it's my own imagination so I didn't know where this was*" – 22A

"*I [imagined] a leaf, growing on an oak tree… the little leaf forming the little bud, bursting [from] the tree, going through its whole cycle and then into autumn and the leaf falling off the tree*" – 3B

Imagined Movement

Imagined Movement (also known as motor imagery) produces similar EEG patterns as Actual Movement, such as decreased mu [230]; yet, these patterns are less pronounced in motor imagery as individuals can have trouble maintaining the imagery [231].

Seventeen participants (14 able-bodied, 3 CNP participants) imagined moving a particular body part or their whole body in various scenarios, such as imagining foot movements or partaking in a sport.

"*It was just me sort of dancing on the stage for a bit*" – 16A

"*I [imagined] wiggling my toes or [stretching] the toes*" – 8A

Memory

As previously mentioned, Memory was identified as a separate category from Imagination due to differences in EEG patterns.

Eighteen participants (15 able-bodied, 3 CNP participants) used imagery or thoughts of happy, pleasant events from their past. They recalled positive memories about their loved ones, events or situations, and sensory stimuli such as physical sensation and sound.

"*I [was thinking] about other things like positive, happy things, like my family*" – 18A

"*I completely concentrated on my puppy… and how much I love playing with him*" – 1A

Moral Values

Moral decision-making literature shows that mental activities involving morals produce specific EEG patterns [232]. For example, Orekhovaa et al [233] show that children who choose the moral option (i.e. giving cookies to the "good" puppets and not the "bad puppets") have increased alpha power in the pre-frontal cortex compared to children who do not choose the moral option.

Two participants (both able-bodied) thought about moral values that were important to them, and how these values made them feel positive and confident.

"*I would be… thinking of some things I do at work, you know, being in charge or something… [where] people rely on you*" – 17A

"*I was thinking about decisions and I have been thinking a lot about the tennis [match] and I was thinking that I was really pleased to have stuck to the rules of the contest*" – 25A

Non-Specific Focus

Non-Specific Focus, i.e. concentration, has been shown by previous research to decrease alpha and theta, and increase beta during mental concentration compared to rest that do not involve other activities such as numerical tasks or logic deductions [234, 235].

Twenty-two participants (13 able-bodied, 9 CNP participants) reported just focusing or concentrating on the neurofeedback task; they could not verbalise further what they were doing in their minds despite probing. This theme was initially labelled 'Concentration'; however, this label implied that other participants were not concentrating on the task, which was untrue. It was changed to 'Non-Specific Focus' to highlight that this mental strategy could not be verbalised beyond reports of "just" concentration.

"*I know I concentrated on it, but I couldn't say what I was thinking*" – 1A

"*I wasn't so much telling myself to make it go green as in just making it green in the same way as you can lift your arm, you don't need to think about it*" – 7A

"*I just concentrated as hard as I could*" – 4B

Numerical Task

Engaging in a numerical task has been shown to increase theta and decrease alpha power compared to rest [236], which is thought to be reflective of fact retrieval from long-term memory [237].

Eight participants (5 able-bodied, 3 CNP participants) engaged in simple numerical tasks that could be repeated indefinitely to occupy the entirety of the five-minute neurofeedback run.

"… *I did times tables, so I was literally just going through the times tables*" – 11A

"… *I count to a hundred and I count backwards*" – 1B

Pain Memory

There is little research examining the EEG activity of imagining or remembering pain when one is not in pain at that moment. However, experiencing pain has been shown to evoke distinct EEG patterns (as mentioned in Chapter 2). Furthermore, research shows that imagining painful events of others supresses the mu rhythm compared to imagining non-painful events of others [238, 239].

One participant (able-bodied) used a memory of a painful sensation. They reasoned that this memory may improve neurofeedback performance as the neurofeedback system was designed to aid individuals with pain.

"*I was thinking about what the test is for, and it's for people with pain, so I thought maybe If I think about… having pain… in different parts [of] my body*" – 2A

Planning

Planning is a cognitive task requiring mental demand similar to Numerical Task; however, planning tasks uses higher cognitive functions, such as decision-making and organisation, and higher mental workload demands that separates it as a mental task from simple numerical tasks [240]. During such planning tasks, alpha power decreases and theta power increases compared to rest [241, 242].

Six participants (all able-bodied) mentally organised future tasks.

"*I think I was thinking of my essay and what I was going to do, thinking about the different things I need to [do], different materials I can use, and where I'm going to do it*" – 11A

"*I think [I was thinking] about being in the kitchen cooking… we're just about to start an extension so I've got a kitchen designed, so it's thinking about being in the new kitchen*" – 23A

Resolving Stress

Resolving one's stress is not a particular task that is examined in the current literature; however, it can be considered a method to become calm or relaxed. Both alpha and theta have been shown to increase during relaxation tasks compared to rest [243, 244].

One CNP participant actively found solutions to their personal stresses to accomplish the neurofeedback task.

"*I was actually beginning to see a way through some of the issues that I was thinking about and finding a solution to a couple of the things*" – 3B

The participant reasoned that resolving their personal stresses allowed them to improve their focus on the neurofeedback task.

"*The thoughts were slowly getting resolved… then I was able to focus more and get more success out of focusing on the bars*" – 3B

6.2.3 Affect Induced During Neurofeedback Training

The focal point of many descriptions of mental strategies were the emotions felt during the mental strategies, thus affect was also examined. The categorisation of codes into these affects are summarised in Table 6.4. Six affects were identified from the interview data (Table 6.5): (1) Discontent, (2) Excited, (3) Happy, (4) Mentally Tired, (5) Neutral, and (6) Relaxed. No clear differences in frequency was found between able-bodied participants and CNP participants. All affects were shared by able-bodied and CNP participants.

Table 6.4 Categorisation of initial codes into themes regarding affects

Initial Codes	Themes	Grouping Description
• Bored • Disappointed • Frustrated • Uselessness • Self-blame	*Discontent*	Participants were unsatisfied with their neurofeedback performance resulting in various negative feelings
• Excited	*Excited*	Some mental strategies or the novelty of the neurofeedback induced feelings of excitement
• Happy • Pleasant • Positive	*Happy*	Positive mental strategies or satisfactory neurofeedback performance produced feelings of happiness
• Mentally tiring • Mentally straining • Sleepy	*Mentally Tired*	Participants reported becoming mentally tired after intense concentrating or concentrating for too long on the neurofeedback task
• Neutral • Not positive or negative	*Neutral*	Participants described feeling “neutral”, nothing in particular, either due to a neutral mental strategy or due to not caring about accomplishing the neurofeedback task
• Relaxed • Calm • At ease	*Relaxed*	Calming mental strategies induced feelings of relaxation or ease

Table 6.5 A description of the affects identified from the interview analysis and the number of participants that used each affect; ordered from most used to least used

Affect	**n (*AB, **C)**
Discontent	30 (22, 8)
Neutral	28 (23, 5)
Relaxed	24 (18, 6)
Mentally Tired	22 (17, 5)
Happy	18 (14, 4)
Excited	4 (3, 1)

n = Sample size
*AB = Able-bodied participants
**C = CNP participants

Discontent

Thirty participants (22 able-bodied, 8 CNP participants) felt dissatisfied with the neurofeedback task at various time points during the study. Perceptions of poor performance provoked feelings of frustration or anger towards the difficulty of the task. Others felt disappointed or useless, and blamed their lack of ability for their perceived failings at the task.

"*I just felt completely useless because I just couldn't do [the neurofeedback task] at all*" – 1B

Some participants reported becoming bored or lost interest in the task when perceived performance was not satisfactory after repeated attempts to succeed.

"*It was a bit irritating because I didn't see any changes [in the bars]… then I thought I don't care [about the task]*" – 13A

Excited

Four participants (3 able-bodied, 1 CNP participants) reported feeling excited or using exciting mental strategies during the neurofeedback task. One of these participants felt excited because they were using a novel piece of technology.

"*I was imagining myself doing things which I can't do in real life, like skating up and down ramps [or] weave in and out of cars, exciting stuff like that*" – 9A

"*I suppose excited… because [the neurofeedback] is kind of like a novelty*" – 6B

Happy

Eighteen participants (14 able-bodied, 4 CNP participants) reported feeling pleasant or happy during the neurofeedback, either induced by the positive mental strategies or because their perceived performance was satisfactory.

"*It's a happy memory in the sense that I really liked playing the game [from my childhood]*" – 4A

"*It's a positive image because I got a really nice photograph of [place] and I just kept on looking at that photograph*" – 1B

Mentally Tired

Twenty-two participants (17 able-bodied, 5 CNP participants) were mentally tired after straining to concentrate on the neurofeedback task or because they were generally tired that day. Participants reported physical symptoms alongside the mental tiredness, such as watery eyes, headache, and feeling tense.

"*I'm much more tired, it's harder to kind of stay in that zone*" – 6A

"*I'm so tired, and thirty minutes, that's quite a lot staring at green so much*" – 9B

Neutral

Twenty-eight participants (23 able-bodied, 5 CNP participants) reported feeling no particular emotion. The mental strategies they used did not induce any emotions, nor were they feeling anything particular towards their neurofeedback performance. Some participants who perceived their performance to be unsatisfactory felt neutral because they gave up in trying to accomplish the neurofeedback task resulting in not caring about the neurofeedback task.

"*They're just neutral, they're just things that I know that are green so no particular [emotional connection] to them*" – 1B

"*I wasn't particularly happy or particularly sad*" – 1A

Relaxed

Twenty-four participants (18 able-bodied, 6 CNP participants) felt free from stress or tension when their perceived neurofeedback performance was satisfactory or when they were using mental strategies that induced a calm state of mind.

"*Very relaxed, I felt no pressure to move the bars because the bars seemed to go towards the green side quite easily*" – 22A

"*I felt more calmer, in a calmer place, in [runs] one to four*" – 3B

6.2.4 The Association between Mental Strategies and Affect

Mental strategies were matched with affect for each neurofeedback training run to explore if mental strategies were associated with the predicted affect. There are 840 runs in total (six runs per visit, four visits per participant, thirty-five total participants). Mental Strategies were not recorded for all 840 runs due to incomplete study participation or failed recollection of mental behaviour during particular runs. Runs that included the use of multiple mental strategies or runs where participants were distracted for its entirety were removed from this analysis, which left 551 runs. Table 6.6 summarises the affect reported during each run of each identified mental strategy. The following is a list of mental strategies that one would instinctively predict to induce a specific emotion: Clear Mind inducing relaxation, Pain Memory inducing a negative emotion, and Resolving Stress inducing pleasant or calming emotions. Some of these instinctive predictions are accurate, as shown in Table 6.6: Clear Mind was mostly associated with the Relaxed affect and Resolving Stress was associated with the Happy affect. However, Table 6.6 show that these mental strategies were also associated with the less positive affects of Discontent, Mentally Tired, and Neutral. This was reportedly because of the neurofeedback task rather than the mental strategy itself.

"[*That run] was worse than normal, and then I felt a bit down from [my poor performance]*" – 10A (whilst using Clear Mind)

"*I may have just [been] bored looking at the screen*" – 25A (whilst using Memory)

Pain Memory was only associated with the Happy affect. The sole participant who used this mental strategy reported that the pain was associated with a sport that they enjoyed. The pain was an accepted part of playing that sport, thus the Pain Memory induced a positive emotion.

"*I have the mind-set that when you're training for [the sport], you go through times when you just hurt a lot… You get used to it*" – 2A

These results indicate that a mental strategy may not induce the instinctive affect one would predict, and may not be the source of all reported affects.

Table 6.6 Matching mental strategy with affect

		No. of Instances of Each Identified Affect						
		Discontent	***Excited***	***Happy***	***Mentally Tired***	***Neutral***	***Relaxed***	*Total (%)*
MS	***Clear Mind***	7	0	2	6	5	33*	53 (9.62)
	Actual Movement	0	0	0	0	3*	3*	6 (1.09)
	Imagination	20	2	13	14	24*	14	87 (15.79)
	Non-Specific Focus	32	0	0	9	37*	19	97 (17.60)
	Numerical Task	1	0	0	3	8*	2	14 (2.54)
	Breathing	1	0	0	4	11	15*	31 (5.63)
	Memory	1	4	23*	7	8	14	57 (10.34)
	Auditory	14	0	6	14	33*	5	72 (13.07)
	Moral Values	1	0	4*	3	1	2	11 (2.00)
	Pain Memory	0	0	2*	0	0	0	2 (0.36)
	Planning	2	1	4*	0	2	0	9 (1.63)
	Resolving Stress	1*	0	1*	0	0	0	2 (0.36)
	Imagined Movement	11	8	30	14	33*	14	110 (19.96)
	Total (%)	91 (16.52)	15 (2.72)	85 (15.43)	74 (13.43)	165 (29.95)	121 (21.96)	551

***The most associated affect for each mental strategy**
MS = No. of instances of each identified mental strategy

6.2.5 Perception of Neurofeedback Performance

Participants were asked about their overall perceived performance of the neurofeedback task. Their responses were categorised into three groups: those who perceived themselves to be successful (perceived successful; n = 18), those who perceived themselves to be unsuccessful (perceived unsuccessful; n = 8), and those who were unsure about their performance (unsure; n = 9). Examples quotes are provided below for each category.

Perceived Successful

"*I think [my performance] improved a lot [over the visits]… I felt like [the bars] got more controlled*" – 7A

"*Although it's extremely difficult to control [the bars], I found that in the end I could control them*" – 4B

Perceived Unsuccessful

"*I didn't think I could do anything to change [the bars], so I didn't think I have any possibility to change anything in a way and I give up trying*" – 13A

"*I could be optimistic and hope that success would increase [if I continued training] but if anything I would say that it would probably stay about the same [because] I cannot see any correlation to what I'm doing having an overall effect on the changing of the bars*" – 7B

Unsure

"*I'm not 100% sure if I can actually control the bars*" – 15A

"*I don't know… if I could see [a] comparison to other people… but just being just myself… I don't know if I'm being good or successful or really bad*" – 6B

Plots were created to examine how often participants changed their mental strategy within a visit and across all visits, which was grouped according to perceived performance (Figure 6.1).

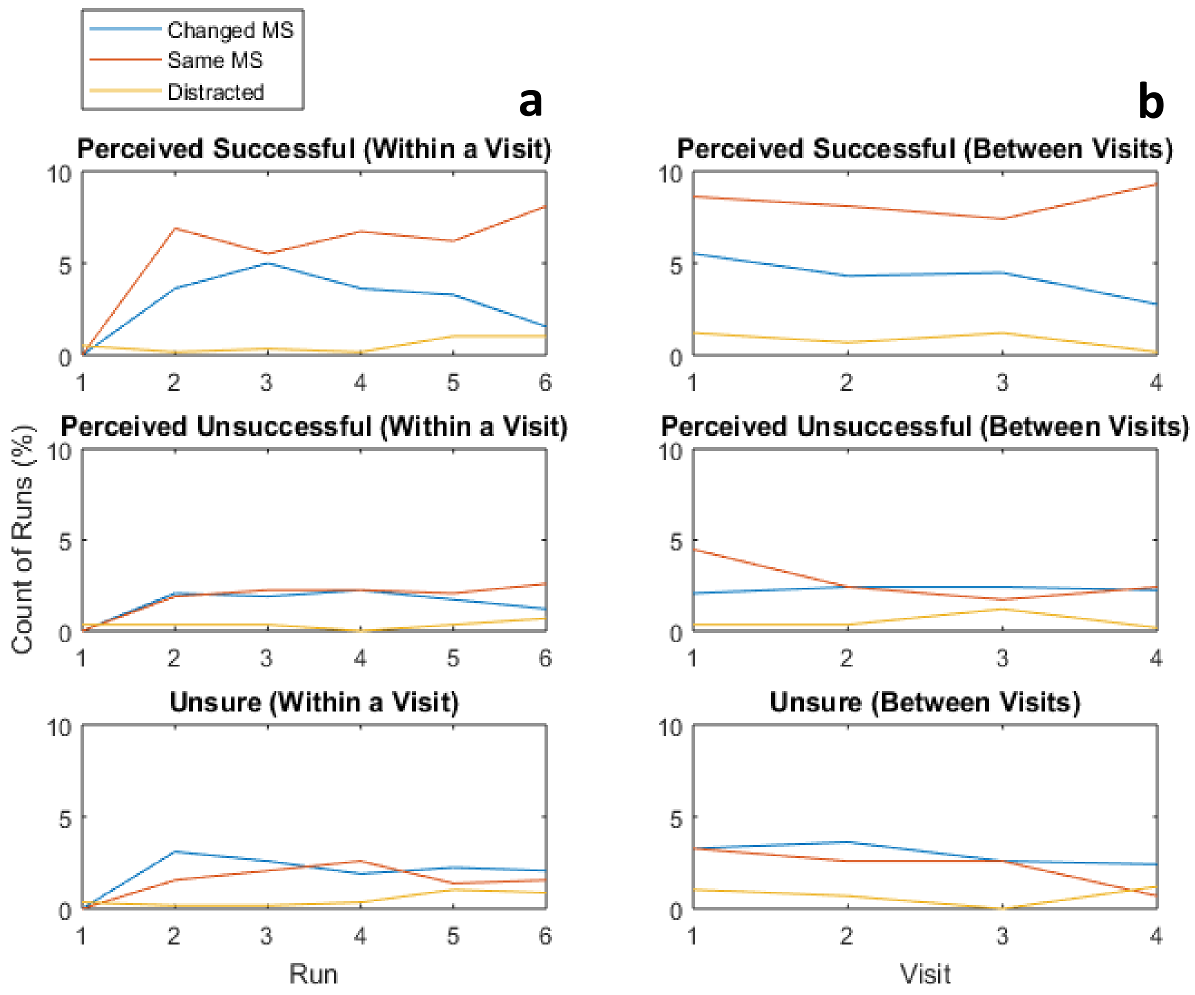


Figure 6.1 Line plots displaying patterns in changing or using the same mental strategy within a neurofeedback training visit and between visits

Percentage values (y-axis) represent the number of runs for that condition (Changed MS, Same MS, or Distracted) out of total runs (580).

Changed MS refers to the decision by the participants to change their mental strategy.

Same MS refers to the decision by the participants to continue using the same mental strategy.

Distracted refers to occasions where participants were distracted completely for that run, and did not use a mental strategy to control the bars.

Figure 6.1a shows patterns in the use and changing of mental strategies within a neurofeedback training visit. Perceived successful participants reduced instances of changing mental strategy and increased their use of the same mental strategy towards the end of the training. Perceived unsuccessful participants did not differ much in changing or using the same mental strategy. Unsure participants were inclined to change their mental strategy throughout the visit. Distractions increased from the fourth run in all groups, likely due to tiredness or boredom of the neurofeedback task. Figure 6.1b shows patterns in use and changing of mental strategies across all training visits. The pattern is similar to the within visit pattern across all perceived performance groups. However, distractions decreased in the final visit in perceived successful and perceived unsuccessful participants while unsure participants had an increase in their distractions. For perceived successful and perceived unsuccessful participants, the final visit may have encouraged them to improve their focus as they will not have another chance to attempt the neurofeedback task. The peak in distractions during the third visit may be because participants were becoming bored of the task at that point. For unsure participants, Figure 6.1b shows the opposite distraction pattern. As these participants could not tell if they were doing well at the neurofeedback task, they may have been determined to identify a satisfactory mental strategy but gave up at the final training visit. However, these explanations are speculative as the reasons for becoming distracted were not probed during the interview. Participants also suggested mental strategies that they believed were optimal for neurofeedback performance. This was categorised according to perceived performance and displayed in Table 6.7 below.

Table 6.7 Summary of suggested mental strategies reported by participants that were perceived to improve neurofeedback performance

Perception (n)	**Suggest Mental Strategy (n)**	**Reason for Suggestion**
Successful (18)	No suggestion (2)	Could not verbalise mental strategy
	No particular strategy (7)	Use any mental strategy that induces a calm, focused state of mind without being distracted
	Emptying mind (1)	It worked the best for this participant
	Positive thoughts (1)	It worked the best for this participant
	Enjoyable physical activity (2)	It worked the best for these participants
	Calm concentration (3)	It worked the best for these participants
	Calm, positive thoughts (2)	It worked the best for these participants
Unsuccessful (8)	No suggestion (5)	Believed the bars could not be controlled
	No particular strategy (1)	Focus on something simple, nothing complicated
	Concentration (1)	It worked the best for this participant
	Positive thoughts (1)	It worked the best for this participant
Unsure (9)	No suggestion (6)	No satisfactory mental strategy was found
	No particular strategy (1)	Use any mental strategy that induces an alert state of mind
	Concentration (1)	It worked the best for this participant
	Positive thoughts (1)	It worked the best for this participant

n = Sample size

Table 6.7 displays the mental strategies suggested by participants to be the most effective in improving neurofeedback performance. Ten perceived successful participants suggested specific mental strategies that consisted of calm, focused, and positive mental strategies. Seven perceived successful participants do not suggest a particular mental strategy, but state that calmly focusing (either on the bars or on a mental strategy) without being distracted improves performance ("*I think you got to be in the right frame of mind to be able to do it so not when you're tired or demotivated … [use a mental strategy] that holds your attention*" – 6A). This is in agreement with the specific mental strategies that participants' suggested. Two perceived successful participants did not suggest any mental strategies because they could not verbalise their thought process during the neurofeedback training ("*It wasn't like I thought 'I want [the bars] to get higher' I just looked at [the bars] and [the bars] did [become higher]*" – 1A).

Five perceived unsuccessful participants did not suggest a mental strategy because they believed the bars could not be controlled ("*I didn't think I could do anything to change them… and I give up trying*" – 13A). Two perceived unsuccessful participants suggested specific mental strategies of positive thoughts and uninterrupted focus. Six unsure participants did not suggest a mental strategy because they did not identify a mental strategy that improved their performance satisfactorily ("*I don't know if I'm being good or successful or really bad… so it's a bit difficult for me to say what worked*" – 6B). One unsure participant did not suggest a particular mental strategy, but stated that being alert improves performance ("*I guess being in a condition where I'm alert and well rested would potentially influence the results*" – 14A). Two unsure participants suggested specific mental strategies of positive thoughts and uninterrupted focus. Perceived unsuccessful and unsure participants who suggested a specific or general mental strategy were reported being unsuccessful or unsure because perceived performance did not meet personal standards for success ("*I felt it got easier [to control the bars over time], but… I certainly couldn't control [the bars] to be green all the time*" – 25A. Overall, a mental state, not a specific mental strategy, was suggested by participants to improve perceived neurofeedback performance: to have a calm, positive mind with uninterrupted focus.

6.3 Discussion

This chapter identified the mental behaviour (i.e. mental strategies and affects) during neurofeedback learning and a neurofeedback learning trend influenced by perceived performance. The identified mental behaviour was compared to mental behaviour identified from other research; the diversity, and the reason for this diversity, of mental behaviours is discussed. The neurofeedback learning trend is discussed in terms of decision-making, which is further detailed in chapter 9 (General Discussion). Mental behaviour will first be discussed, followed by a discussion of the neurofeedback learning trend. This chapter ends with its limitations and conclusion.

6.3.1 Mental Behaviours

Thirteen mental strategies and six affects were identified. No clear differences were found in the frequency of mental strategies or affect between able-bodied and CNP participants. As mentioned in section 5.2, the context of using a device that may relieve pain may influence the mental behaviours used by CNP participants. However, no difference in mental behaviours were found between able-bodied participants and CNP participants. The only difference found was related to attrition rates, where considerably more CNP participants dropped out of the study than able-bodied participants. As mentioned in section 6.2, CNP participants were more likely to drop out as they had a greater burden of study participation than able-bodied participants.

In most cases, participants could not verbalise a reason for the mental strategy they chose, emphasising the trial-and-error nature of this neurofeedback task. The trial-and-error nature demands spontaneous mental strategies from participants, explaining the diverse range of mental strategies across and within participants.

The diverse range can also be seen across other studies examining spontaneous mental strategies, some of which overlap with those identified in this study. Kober et al [98] examined spontaneous mental strategies during EEG-based neurofeedback training of SMR (sensory-motor rhythm) and gamma activity. They identified seven mental strategies: Breathing, Cheer (not related to emotion, but to “cheering on” the representation of brain activity), Auditory, Visual, Relax, Concentration, and No Strategy. While the underlying mental strategies and affects are similar, the approach to categorisation differs. Their Cheer theme was a subset of this study’s Auditory theme. Similarly, their Concentration and No Strategy themes are subsets of this study’s Non-Specific Focus theme. Their Visual themes is a broad categorisation; visual mental strategies can be seen in various themes identified in this study (e.g. ski jumping visualisation in Imagined Movement). The dissimilarity in code categorisation may be due to individual differences between researchers, or due to different methods of data acquisition; this study used one-to-one, semi-structured interviews providing opportunity for detailed probing while Kober et al [98] asked participants to write down their mental strategies, where probing did not occur. One-on-one interviews allowed participants to expand descriptions of their mental behaviours and permitted greater clarification of ambiguous phrases than is possible in participant-written notes. Furthermore, method differences may have also contributed to the additional mental strategies identified (e.g. Moral Values or Planning) in this study not reported by Kober et al [98] as participants were able to greater detail their mental strategies during interviews compared to participant-written notes.

Additionally, Kober et al's [98] Relax theme was identified as a mental strategy, whereas this thesis identified it as an affect. This reflects a difference in the meaning of a mental strategy between the two studies; this study separates mental action from emotion whereas this distinction is not reported by Kober et al [98]. The importance in this distinction is reflected in the current finding that a mental strategy may not induce the expected affect. Additionally, the affect may not be induced by the mental strategy but by another source, such as perception of neurofeedback performance or an unrelated event. For example, although some participants reported using Clear Mind, dissatisfaction over their perceived poor neurofeedback performance overshadowed any positive or relaxing emotion induced by this mental strategy. Distinguishing mental action from affect may also aid in understanding qualities that improve neurofeedback performance. This is supported by Kadosh and Staunton's [97] systematic review concluding that mood and emotion considerably influences neurofeedback performance. However, there is a need to specify the conditions and extent of this influence. For example, Nijboer et al [113] found that mood was associated with neurofeedback control of SMR in sixteen able-bodied individuals, but Nijboer et al [112], another study using the same mood assessment, found no such association in the small sample of six patients with amyotrophic lateral sclerosis (ALS); the influence of mood remains unclear. Thus, separating affect from mental actions may aid in understanding the behavioural mechanisms influencing neurofeedback performance.

Nan et al [117] examined training of alpha amplitude and the following spontaneous mental strategies: positive mental strategies (nature, life, entertainment, love, family, friends, and other), neutral mental strategies (calculation, work, number, game, and sports), and negative mental strategies (quarrel, anger, accident, shooting, and killing a person). Most of Nan et al's [117] mental strategies are similar to ones identified in this thesis. For example, nature and number can be seen in this thesis's Imagination and Numerical Task respectively. The main dissimilarity is that no negative mental strategies were identified in this thesis compared to Nan et al's [117] study. The different neurofeedback protocols may have contributed to this disparity; however, it is more likely due to individual differences between study samples, where participants of this study happened to avoid use of negative mental strategies. It is important to note that Nan et al's [117] mood categorisation of mental strategies was conducted post-neurofeedback training without mood assessments or confirmation from participants. Thus, this categorisation was based upon the researchers' impressions and cannot be considered an examination of mood.

The above studies show that participants use a variety of mental strategies and affects, which is further shown by this thesis. Notably, this thesis highlights the importance of examining mental strategies and affects separately, as a mental strategy may not always be the cause of the affect; this is not reported by previous neurofeedback literature. However, identifying mental behaviours alone is not enough to understand neurofeedback learning; it must be compared to neurofeedback performance, which is conducted in the next chapter. Yet, this chapter contributes to literature by displaying the range of mental behaviours that a user may use during neurofeedback learning and highlighting the separation of mental strategies and affects.

6.3.2 Neurofeedback Learning Trend

This section details the neurofeedback learning trend found by this thesis, which was influenced by perception of performance that appeared to affected participants' choice of when to change mental strategy. This trend has not been previously reported in the literature and may be useful to better understand neurofeedback learning.

Participants who perceived success were inclined to use fewer mental strategies. This can be compared to findings in motor skills literature, which state that performers learn to reduce unnecessary movements over time [245]. It may be that participants learned to reduce unnecessary mental strategies. It would be interesting to examine in future research whether this reduction is an explicit or implicit behaviour. Participants may also believe that changing mental strategies after a satisfactory one has been identified reduces the chances of succeeding at the neurofeedback task; the uncertainty in attempting new mental strategies may not be worth the risk of poor performance. This is related to a concept in decision-making literature called satisficing (a portmanteau of satisfy and suffice): exploring the available options until a satisfactory threshold is met [246, 247], and is used, for example, to investigate survey response bias [248, 249], happiness [250, 251], and consumer behaviour [252, 253]. Satisficing is used to explain behaviour in situations in which an obvious solution is unclear and is related to an individual's innate discriminatory abilities. In the context of the current neurofeedback protocol, this relates to an individual's discrimination between "more green" and "less green" of the bars. The concept of satisficing is somewhat supported by the reasons given by participants for suggesting certain mental strategies (Table 6.7); many stated that their suggested mental strategy worked the best for them, implying that the mental strategy improved their performance enough to satisfy them. Their threshold for “enough” is likely based on a subjective interpretation of “more green”; the threshold for “more green” for one participant may be higher or lower compared to another participant, perhaps dependent on their past performances. The satisficing concept is further discussed in chapter 9 in relation to findings from other chapters.

Furthermore, participants who perceived themselves as successful agreed on the general traits of a successful mental strategy (i.e. being calm and focused). While these traits may not lead to actual improved performance, it indicates that there is a somewhat explicit strategy that can be employed for neurofeedback success. However, further research is needed to understand the extent of this explicit effort. This may be done by comparing speed of neurofeedback learning between implicit and explicit learners alongside examination of changes in global EEG activity.

Participants who perceived themselves as unsuccessful or were unsure were not inclined to use fewer mental strategies compared to successful participants, suggesting they did not find a satisfactory mental strategy. Furthermore, most participants who perceived themselves unsuccessful did not suggest a successful mental strategy reportedly because they believed that the neurofeedback task was not achievable. Most participants who were unsure also did not suggest a successful mental strategy, however, this was reportedly because they did not identify a mental strategy that satisfactorily improved their neurofeedback performance, indicating they believed the task was achievable. The cause of this difference in beliefs is unknown, yet the finding suggests beliefs may influence the effort expended in accomplishing the neurofeedback task.

As previous research have not reported such a neurofeedback learning trend, to the author’s knowledge, the consequences of this trend are unknown. However, it suggests that beliefs of the neurofeedback task (i.e. its achievability) may influence engagement with the task, affecting neurofeedback learning and outcome. For example, an individual who believes the neurofeedback task is not achievable may reduce their efforts, resulting in poor performance. Thus, future research should examine the replicability of this trend and its influence on neurofeedback performance.

6.3.3 Limitations

There are several limitations of this chapter that warrants consideration. There were considerably more able-bodied participants recruited than CNP participants. Able-bodied participants are easier to recruit than CNP participants as CNP after SCI causes symptoms that reduce mobility. Thus, more able-bodied participants than CNP participants were recruited to ensure the statistical analysis (conducted in the next chapter) were powered sufficiently by the sample size. However, this also limited comparisons between the two participant groups. An equal sample between participant groups may have resulted in clearer differences in frequency of mental strategies or affect.

It should be noted that the affects were identified through verbal reports (i.e. interviews) in this study, where no pre-defined meaning was given to participants. When administrating a questionnaire measuring a latent factor, such as affect, a definition or description is provided to participants before completing the questionnaire; this is done to minimise differences in meaning between participants. Thus, there is a possibility that an affect reported by one participant may not have the same meaning as another participant. However, this study's main aim was to explore the mental behaviour during the neurofeedback task, and the identified affects would not have been revealed without this exploration. Future research primarily aiming to understand affect should include specified definitions to minimise differences in meaning behind latent factors.

Lastly, the generalisability of the findings to other neurofeedback protocols is questioned as it may be that the current identified mental behaviours were due to the current neurofeedback protocol. Mental behaviours may change with modifications of the protocol.

6.4 Summary and Conclusion

This chapter found twelve mental strategies (Clearing Mind, Display-Related, Imagination, Inducing Emotions, Moral Values, Non-Specific Focus, Pain Memory, Physical Strategy, Planning, Positive Memory, Repetitive Task, and Resolving Stress) and six affects (Discontent, Excited, Happy, Mentally Tired, Neutral, and Relaxed) reported by participants during neurofeedback training. It was found that mental strategies may not always induce the instinctive affect one would predict, for example, Pain Memory was associated with the Happy affect. A neurofeedback learning trend was found that showed those who perceived themselves to be successful tended to use the same mental strategy while those who perceived themselves to be unsuccessful or were unsure tended to change mental strategies. This trend seemed to be associated with participants' beliefs about the achievability of the neurofeedback task (i.e. whether or not it was possible to achieve the task).

This chapter not only lays the foundation for addressing the research objectives of this thesis (addressed in the next chapter), it contributes to the main research aim to better understand neurofeedback learning by highlighting the variety of mental behaviours and identifying a neurofeedback learning trend not previously reported in the neurofeedback learning literature. Furthermore, it lays the foundation for the next chapter that addresses the research objectives. The diverse range of spontaneous mental strategies and affects provides insight into the mental behaviour during an EEG-based neurofeedback training designed to relieve CNP after SCI. The revealed mental behaviours mostly concur with previous studies; however, the qualitative approach offered rich, in-depth information that lead to the identification of additional mental strategies not reported in previous literature. The in-depth qualitative approach in this chapter demonstrates a new direction for future research examining mental behaviours during neurofeedback training. The identification of diverse mental behaviours displays the complexity of the neurofeedback experience that, when examined, may explain disengagement or inability to accomplish voluntary control of brain activity.

Chapter 7 Findings Part II: The Interaction of Mental Behaviour and Autonomic Physiology with Neurofeedback Success

This chapter examined mental behaviour (identified from chapter 6), general learning factors, and autonomic physiology, and their relationship with neurofeedback success. Thus, this chapter addresses the research objectives, which are reiterated below.

1) What mental behaviour(s) do participants use to succeed at neurofeedback?
2) What is the relationship between general learning factors (i.e. LoC, SE, difficulty, and motivation) and neurofeedback performance?
3) Do autonomic responses (i.e. heart rate, respiration, and galvanic skin response) directly relate to neurofeedback performance?

The analysis plan is described before presentation of the results.

7.1 Analysis Plan

The interview data used here are the same as the data used in the previous chapter. Thus, the interview analysis plan is not repeated here. All quantitative analysis was developed with considerable contribution from a qualified statistician.

7.1.1 EEG Analysis

The raw EEG data were first de-trended by subtracting a liner regression line fitted to the data over time, i.e. the trend in the data was removed. This trend is due to artefacts (noise in the data) that cause some data distortion, such as sensor drift. De-trending allows for focus on meaningful EEG changes. The de-trended EEG data were filtered so that only relevant frequencies are shown in the signal. A Butterworth band pass filter was chosen as this filter produces a flat frequency response as possible (i.e. little to no distortion in reproducing a signal when applying a band pass filter). A Butterworth band pass filter order 5 was applied to only allow frequencies from 2Hz to 35Hz in the EEG data and attenuates all other frequency bands. The filtered signal was plotted in the time domain to show any further artefacts, such as eye blinks or body movements. Figure 7.1 shows an example of EEG activity in the time domain without an artefact; Figure 7.2 shows an example of EEG activity with an artefact. The raw data and the filtered data were manually compared to ensure that the filter did not distort artefacts, thereby hindering the researcher's ability to effectively remove them. The filter was not found to distort artefacts in any EEG data. Each artefact was were manually inspected and removed by replacing the artefact with NaN (Not-a-Number), a denotation for missing data, which was not included in the analysis. EEG data that had more than 30% of data removed was excluded from analysis.

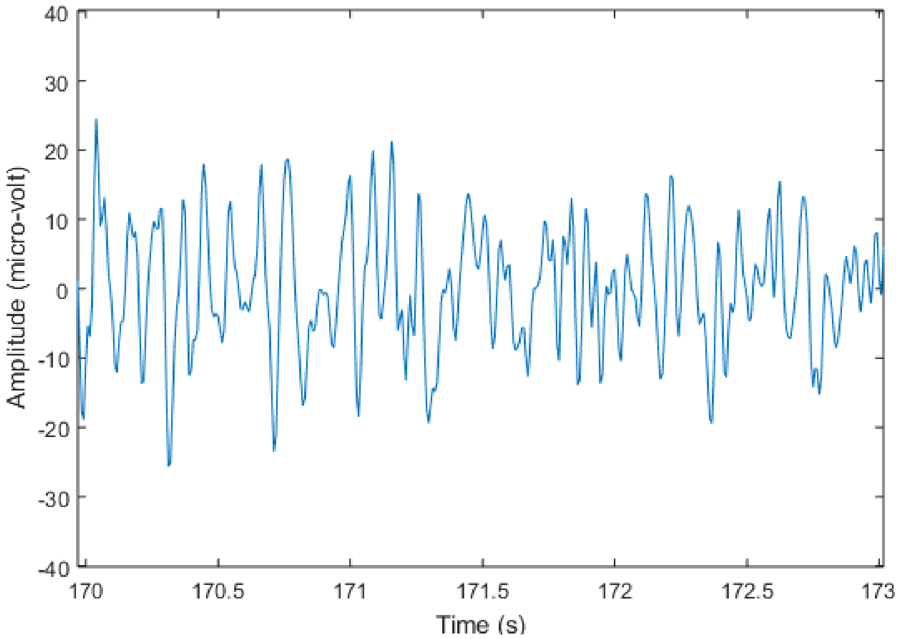


Figure 7.1 Example of EEG activity in the time domain (3 seconds)

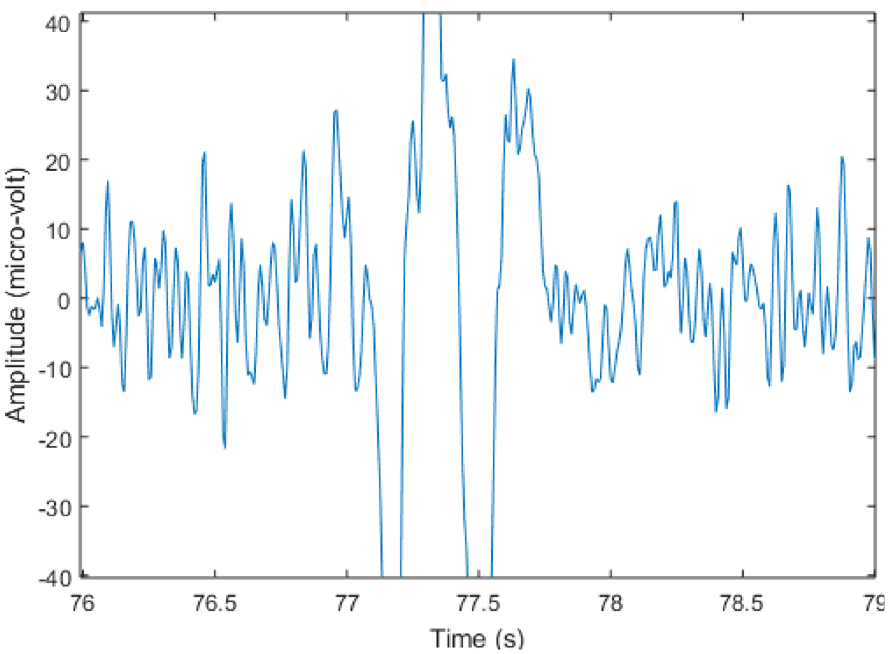


Figure 7.2 Example of EEG activity with an artefact in the time domain (3 seconds)

Relative power of the relevant frequency bands (i.e. theta, alpha, and higher beta) during neurofeedback training compared to baseline was used to analyse control of EEG activity, this will be called "change in power". To determine change in power, the following steps were taken: (1) the absolute power of the relevant frequency bands was first calculated using equation 1, which calculates the average power of the signal in a specified frequency band. (2) Relative power (the absolute power of the relevant frequency band in relation to the absolute power of all the frequency bands in that EEG recording) was calculated using equation 2; this was done for both baseline EEG data and EEG data during neurofeedback training. (3) Change in power was then calculated using equation 3.

Equation 1 Average power of a signal for a specified frequency band

$$P_{\epsilon}(f) = \frac{\sum_{i=1}^{n} x_f^2(i)}{n}$$

Where:

x_f: The filtered EEG signal in the frequency band f

n: The length of the signal (x) in samples

i = 1…n

Equation 2 Absolute power of a frequency band in relation to absolute power of all frequency bands

$$P_r(f) = \frac{P_{\epsilon}(f)}{\sum_{f=f1-f2}^{n} P_{\epsilon}(f)}$$

Where:

$P_{\epsilon}(f)$: Absolute power of specific frequency (from equation 1)

$P_{\epsilon}(f)$: Absolute power of specific frequency band; f1 and f2 are lower and higher frequencies of the selected frequency band respectively (2-35Hz, as this encompasses frequencies from theta to beta).

Equation 3 Change in power

$$P_c = \left(\left(\frac{P_{r,t}}{P_{r,b}}\right) - 1\right) \times 100$$

Where:

$P_{r,t}$: Relative power of the signal during neurofeedback training

$P_{r,b}$: Relative power of the signal during baseline

P_c: Change in power

This change in power across time (EEG curve) was used to see if participants were learning to control their EEG activity. Successful participants were identified if they met the following criteria: (1) EEG curve across time must increase (for alpha) or decrease (for theta and beta), (2) participants must be able to correctly perceive their performance at the neurofeedback task, and (3) participants must have been actively attempting to control their EEG activity. The reason for these criteria was to ensure that participants are not only correctly controlling their EEG activity, but also to ensure that participants are knowingly and actively inducing this control. No other neurofeedback studies have used the third criterion to assess neurofeedback performance to the author's knowledge; however, the general learning literature states that the ability to correctly self-assess performance is considered an important skill for any task requiring active participation [89-91]. As neurofeedback requires active participation, this criterion was used in this thesis.

To address the first criterion, individual EEG curves were visually inspected for within a visit and between visits. If the EEG curve was increasing (for alpha) or decreasing (for theta and beta), that curve was labelled as "correct". Participants were categorised as "successful" if two thirds of the within and between visit EEG curves were "correct". Participants needed to be successful in the frequency band(s) that they chose to control (identified during the interviews), as participants found it easier to focus on one or two bars instead of all three bars (see further investigation of this issue in chapter 8).

The second criterion was addressed by cross-analysing the interview and EEG data. Participants stated their perceptions of their performance (e.g. "the middle bar was the most green in the fourth run"), which were identified as either true or false. This was decided by checking if the statement matched actual success. For example, a participant states that they perceived the left bar was "greener" in R2 compared to R1. This would be identified as true if actual theta power (represented by the left bar) was lower in R2 compared to R1; the statement would be identified as false if actual theta power was higher in R2 compared to R1. The second criterion was fulfilled if participants were labelled as successful if at least two thirds of their statements were true.

The third criterion was fulfilled if participants stated they were actively trying to control the bars instead of passively observing the bars with no intention of control or were distracted from the task. If all three criteria are fulfilled, then the participant was categorised as "successful". All other participants were categorised as "unsuccessful".

7.1.2 Difference in Success Criteria Analysis

Although the thesis used the above criteria as the main identification method for success, the thesis also analysed how success rates would change when these criteria were changed. This was done to compare the thesis criteria to criteria used generally across the neurofeedback literature. Two main criteria were chosen: (1) according to the thresholds of EEG activity (in this case, it was the +/-10% change mentioned in the neurofeedback protocol, section 5.4), and (2) according to changes in EEG activity across time. These two criteria do not consider participants' mental behaviour or perception of neurofeedback performance. All three criteria were compared using a paired proportion comparison. A paired proportion comparison (Table 7.1) examines two methods sharing a common feature that influences the outcome, such as the same participant sample being used across all methods. This test produced the proportional difference between the methods and the confidence interval limits of 95%, which are expressed in percentages. The confidence interval was calculated using Newcombe's modified score [254]; this calculation will not be further detailed as it is out of the scope of this thesis. The proportional difference results provides information on which success identification method produced a higher neurofeedback success rate. More interestingly, the confidence intervals produce information on which success identification method is more likely to produce consistently similar success rates in comparison to the other methods.

Table 7.1 Calculation of paired proportion test

Count		**Condition One**	
		X *(positive outcome)*	*Y* *(negative outcome)*
Condition Two	*X* *(positive outcome)*	xx	xy
	Y *(negative outcome)*	yx	yy

n = xx + xy + yx + yy
s (positive outcome only in condition one) = yx
t (positive outcome only in condition two) = xy

Proportion 1 = s / n
Proportion 2 = t / n

Proportion difference = (t - s) / n

7.1.3 Sample Size Calculation

Sample size was calculated with significant contribution of a qualified statistician. The main statistical analysis used was a correlation (i.e. Person's R); based on sample size calculations for a correlation, 25 participants was the minimum sample size. No stronger statistical analysis was conducted due to the limited sample size. Due to the restrictions of recruiting CNP participants, the target of 25 participants was assigned to the able-bodied participant group. The sample size calculation was based on a confidence interval of 95%, the worst case statistical correlation result possible (i.e. 0), and a confidence interval width of 0.8. This confidence interval width was chosen as it was a reasonable balance between moving knowledge of the area forward and what was practically achievable at this stage of the research.

7.1.4 Questionnaire Analysis

Questionnaire scores of SE, LoC, task load, and motivation were correlated with success status of participants (i.e. whether they were successful or unsuccessful) using Person's R (normal distribution confirmed). LoC correlation was only conducted for able-bodied participants as CNP participants completed a different LoC questionnaire, where the CNP participant sample was ten. To understand if LoC had a relationship with neurofeedback success in CNP participants, the trend in the different LoC patterns were compared via visual inspection. Pain intensity and pain quality were not statistically analysed as only two CNP participants reported pain relief induced by the neurofeedback (detailed further in the results section).

7.1.5 Autonomic Physiology Analysis

Similar to the EEG analysis, raw autonomic data (ECG, RSP, and GSR) was first de-trended. The de-trended autonomic data were filtered so that only relevant frequencies are shown in the signal: a Butterworth filter (order 5) was applied to ECG, RSP, and GSR data to only allow frequencies from 0.5Hz to 30 Hz, 0.05Hz to 5Hz, and 0.01Hz to 10 Hz respectively. The filtered signals were plotted in the time domain to manually inspect and remove any further artefacts. Figures 7.3 to 7.5 show examples of ECG, RSP, and GSR respectively, with and without an artefact. The raw data and the filtered data were manually compared to ensure that the filter did not distort artefacts, thereby hindering the researcher's ability to effectively remove them. The filter was not found to distort artefacts in any autonomic data. Each artefact was replaced with NaN, a denotation for missing or tainted segment of data. EEG data that had more than 30% of data removed was excluded from analysis.

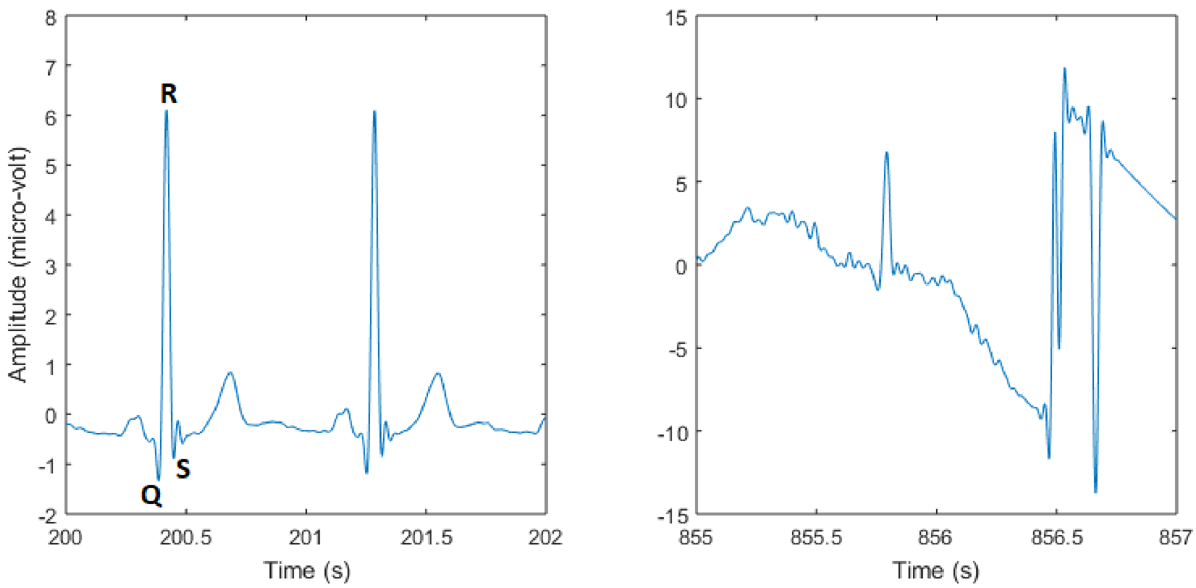


Figure 7.3 Example of ECG activity with and without an artefact in the time domain

The left figure shows ECG without an artefact, and the right shows ECG with an artefact. The left figure also displays the QRS complex, which denotes a heartbeat. Each letter corresponds to a different feature of the heartbeat.

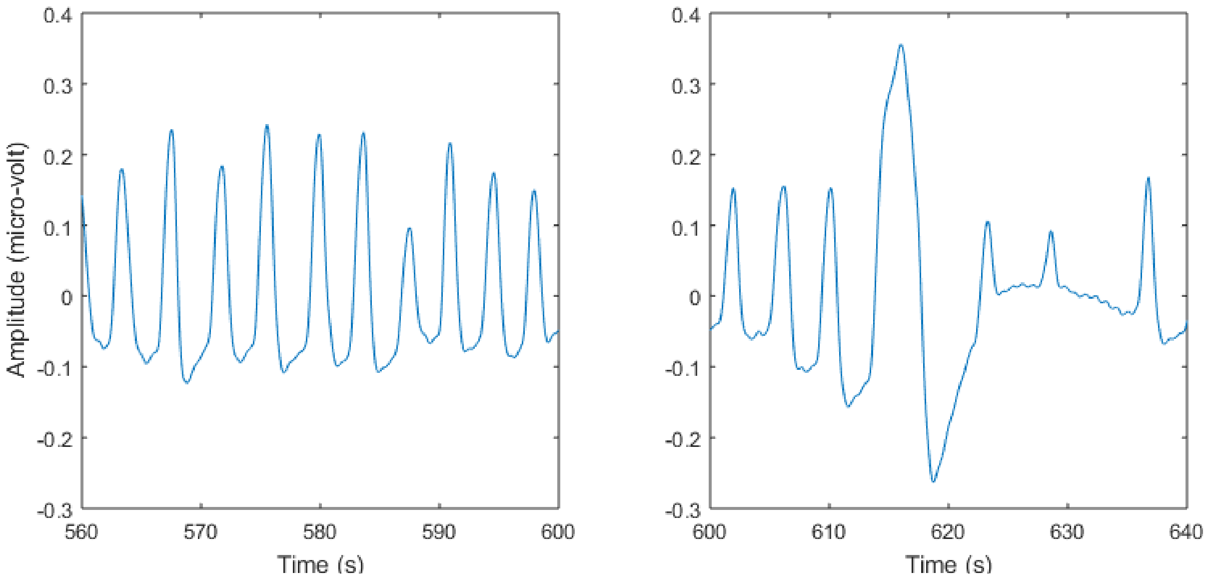


Figure 7.4 Example of RSP activity with and without an artefact in the time domain
The left figure shows RSP without an artefact, and the right shows RSP with an artefact.

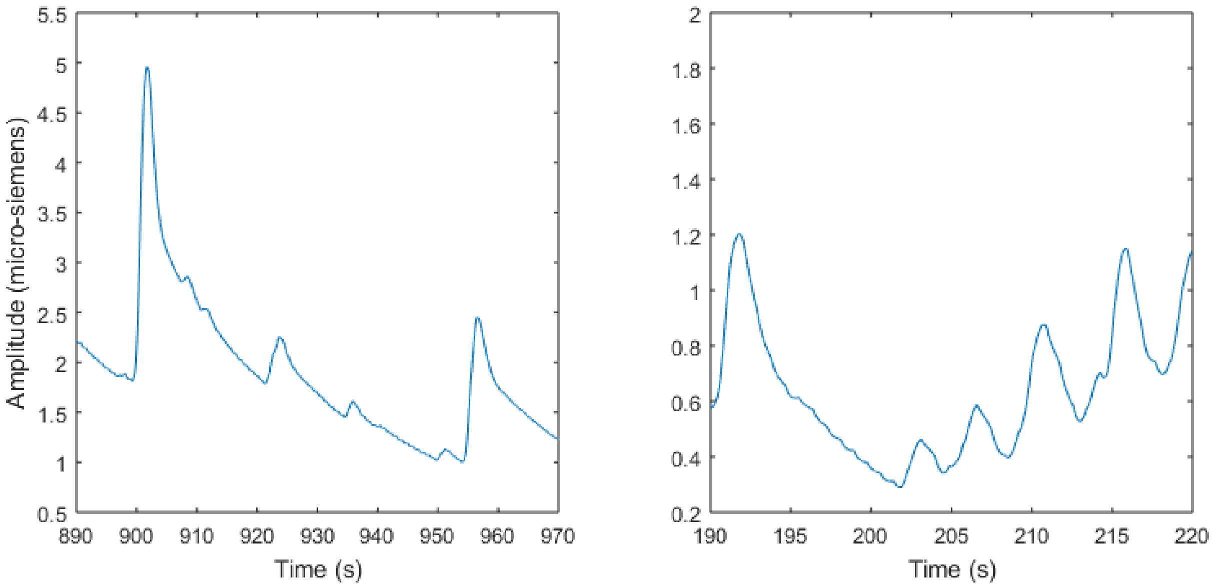


Figure 7.5 Example of GSR activity with and without an artefact in the time domain
The left figure shows GSR without an artefact, and the right shows GSR with an artefact.

Peak analysis was conducted on ECG and RSP to attain the intervals (in seconds) between the peaks of each heart beat and breathing cycle respectively. Heart rate and breathing rate were calculated using equation 4. Heart rate variability and breathing rate variability were calculated using equation 5. Similar to the EEG analysis, ECG and RSP data during neurofeedback training were compared to the data from the baseline to reveal a percentage change in ECG and RSP. These changes in the successful group were compared to the changes in the unsuccessful group using Person's R (normal distribution confirmed).

Equation 4 Calculating heart rate and breathing rate

$$R = \frac{\sum_{i=1}^{n-1}(\frac{60}{T_{i+1} - T_i})}{n-1}$$

Where:

R: Average heart rate; average breathing rate

T: Refers to the time (from the start of the recording) of the ith R wave in the ECG or the ith respiratory cycle (peak value) in the RSP signal

n: The number R-waves or respiratory peaks in the ECG/RSP signal

i = 1…n

Equation 5 Calculating heart variability and breathing rate variability

$$SD = \sqrt{\frac{\sum_{i=1}^{n-1}(R_i - R_{i+1})^2}{n-1}}$$

Where:

SD: The standard deviation as a measure of the variability of the interval between R-waves in the ECG signal or respiratory cycles in the RSP signal

R: Refers to R peak of heart beat from the QRS complex; refers to peak of a single breathing cycle

n: The length of the ECG/RSP signal

i = 1…n

Usually, GSR is analysed in the context of participants reacting to a stimuli, where features such as peak amplitude or recovery time can be examined. In the current context, the stimuli is not the neurofeedback itself but the mental strategies used during neurofeedback. However, the specific timing of the mental strategies (e.g. start of the mental strategy, the switch to another mental strategy, etc.) are not known. As GSR is a continuous measure of skin conductance, the average GSR of each neurofeedback run was used for analysis [255]: the raw GSR signal was smoothed using a moving average filter (window size of fs/2, where fs was the sampling frequency of 250) and then averaged. Similar to ECG and RSP, the data from training was compared to the data from baseline to reveal a percentage change in GSR. This change in the successful group was compared to the change in the unsuccessful group using Person's R (normal distribution confirmed). This thesis acknowledges the limitation in using the average GSR; however, autonomic analysis is not dependent on GSR alone but also includes ECG and RSP. The inclusion of multiple physiology measures may provide greater insight into the relationship between autonomic responses and neurofeedback performance.

7.2 Results

It is reiterated that not all participants completed all four neurofeedback training visits; the sample size for each visit is as follows: V1 = 35, V2 = 31, V3 = 27, and V4 = 25.

7.2.1 Comparison of Methods to Identify Neurofeedback Success

Three ways of identifying successful participants were analysed using a paired proportion comparison: (1) according to the +/-10% thresholds of EEG activity (threshold method), (2) according to correct changes (increasing alpha or decreasing theta/beta) in EEG activity across time (time change method), and (3) according to thesis criteria for success (described in section 7.1.1; thesis criteria). Table 7.2 displays the success rates according to each of these methods for identifying success. Table 7.3 shows the number of participants who were successful in all, some, or none of the methods. Table 7.4 displays the results from the paired proportion comparison.

Table 7.2 Number of participants who were successful for each success identification method

	Threshold Method	**Time Change Method**	**Thesis Criteria**
Able-bodied (% out of 25)	15 (60%)	16 (64%)	10 (40%)
CNP Participants (% out of 10)	5 (50%)	6 (60%)	5 (50%)
Total Participants (% out of 35)	20 (57%)	22 (63%)	15 (43%)

Table 7.2 shows how success rates can change depending on the method of success identification, where the thesis criteria produced the least number of successful participants. The successful participants identified using one method are not necessarily the same as the participants using other methods.

Table 7.3 Number of participants who were successful in all, some, or none of the success identification methods

Condition*	n (% out of 35)
3 Successes	11 (31%)
2 Successes	7 (20%)
1 Success	10 (29%)
0 Successes	7 (20%)

*The conditions are as follows:
Success in all methods (3 successes)
Success in two of the methods (2 successes)
Success in one of the methods (1 success)
Success in none of the methods (0 successes)
** n = No. of participants

Table 7.3 further emphasises changes in success rates according to the method used, where only a third of participants are identified as successful according to all three methods. This table shows that the same individuals who were successful in one method may not be successful in another method. Table 7.4 below shows that the time change method produced the most number of successful participants while the thesis criteria produced the least number of successful participants; this concurs with Table 7.2.

Table 7.4 Paired proportion comparison: Differences in neurofeedback success rates according to the three criteria used (expressed as a percentage out of 35)

	Thesis Criteria – Threshold Method	Thesis Criteria – Time Change Method	Threshold Method – Time Change Method
Proportion Difference	-14.30	-20.00	-5.70
CI (Lower limit)*	-33.00	-38.50	-25.20
CI (Upper limit)*	2.80	-3.80	13.10

*CI = Confidence interval (95%)

Interestingly, the confidence interval ranges of the middle column show that only the time change method is likely to consistently produce more successful participants than the thesis criteria (as both upper and lower limits are negative); the other two comparisons do not show a consistent direction. This indicates an uncertainty in the outcomes of these methods, where the thesis criteria may not always produce the least number of successful participants compared to the threshold method. Similarly, the time change method may not always produce the most number of successful participants compared to the threshold method. The uncertainty indicated by the confidence interval ranges is likely due to the small sample size, which is also why a significance test was not conducted.

Additionally, success based on the three success criteria were compared for within (Figure 7.6) and between (Figure 7.7) visits.

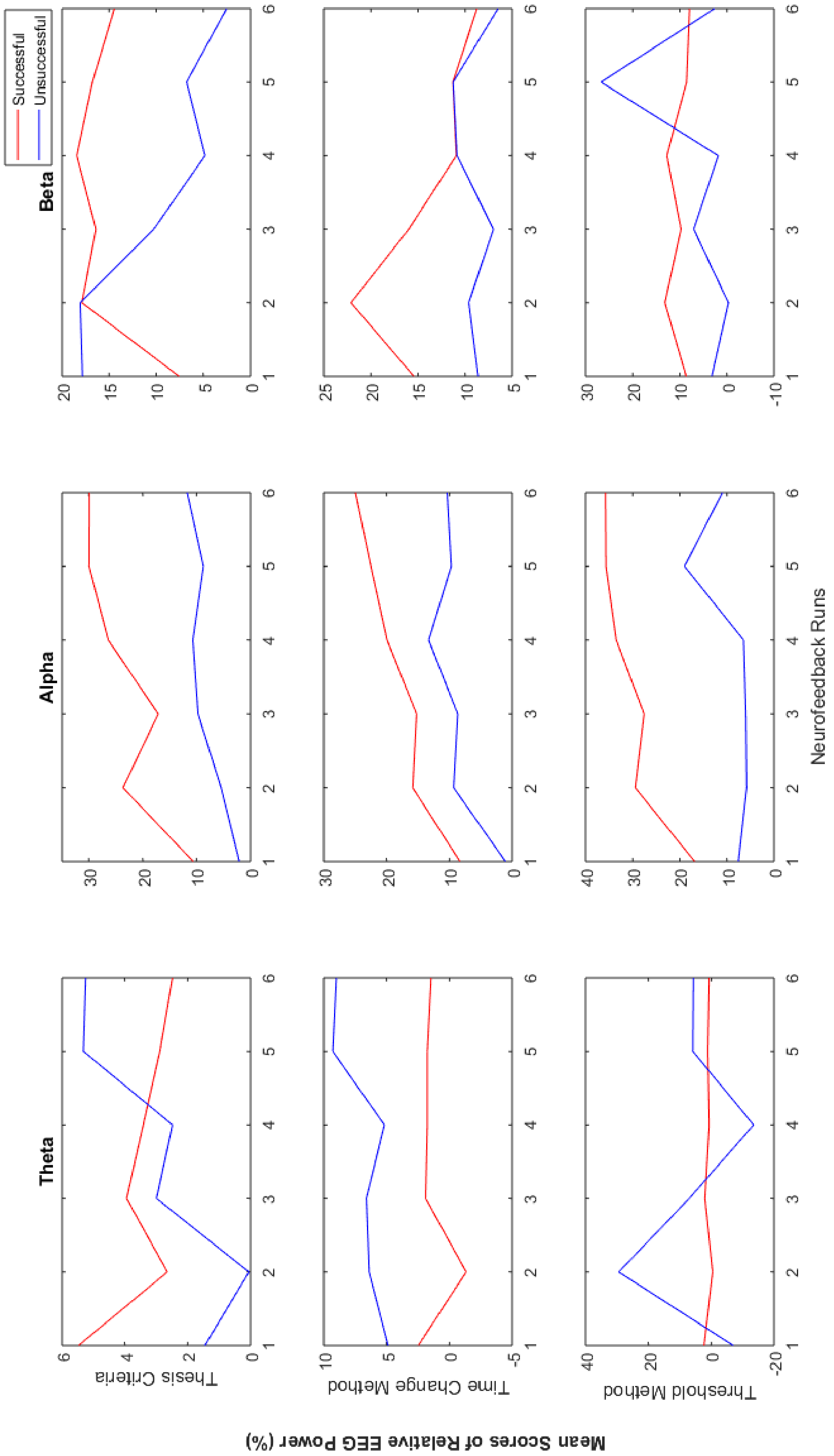


Figure 7.6 Comparison of successful and unsuccessful performances within a visit (i.e. between runs) for each frequency band (theta, alpha, and beta) and for each success criteria

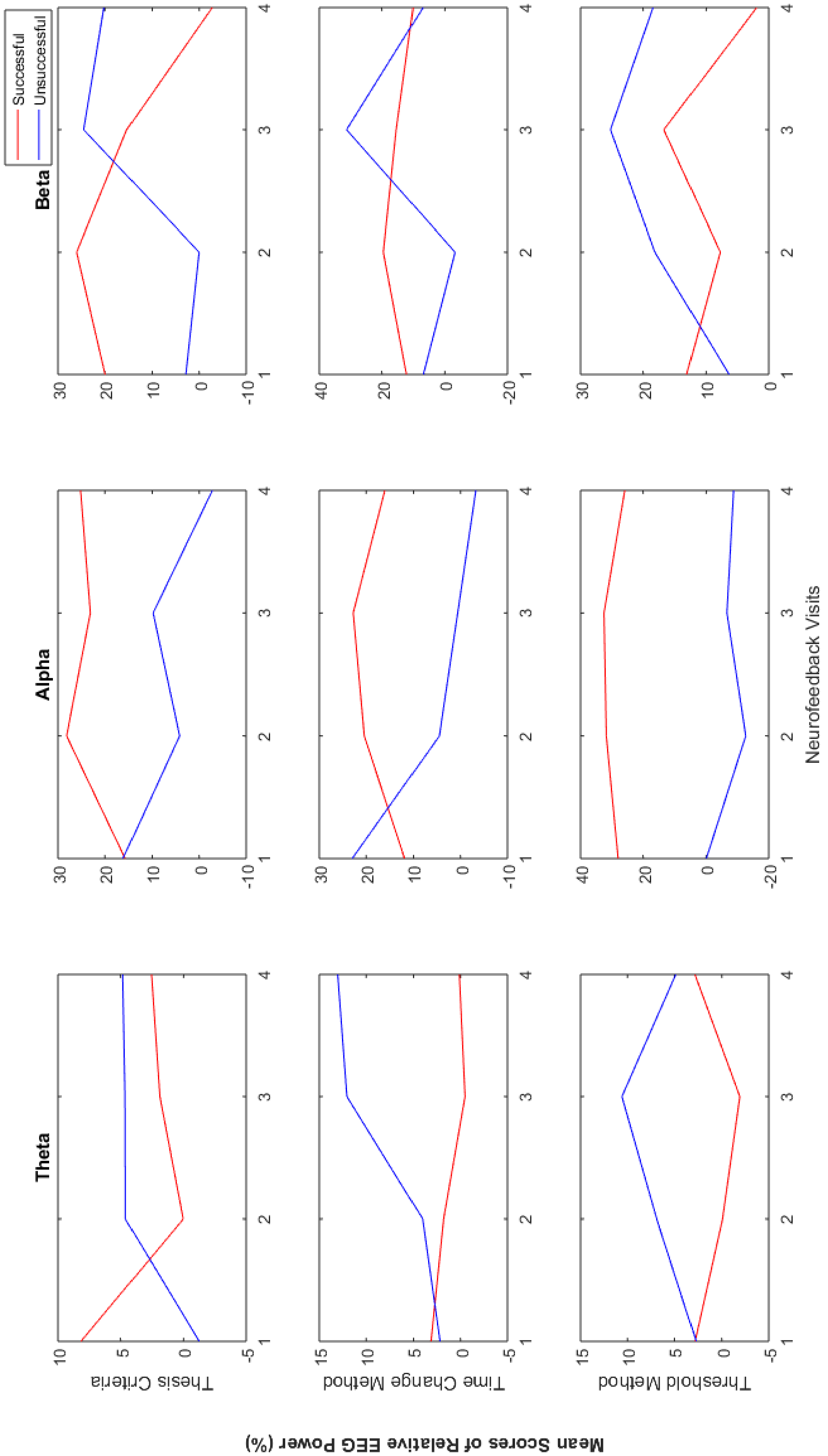


Figure 7.7 Comparison of successful and unsuccessful performances between visits for each frequency band (theta, alpha, and beta) and for each success criteria

Before discussing Figures 7.6 and 7.7, it should be noted that these figures show the *group average* performance, which hides the variation in individual performances. For example, the time-change method of Figure 7.6 shows that the unsuccessful group still increased their alpha performance within a visit. However, the individuals that made up the unsuccessful group did not consistently increase their alpha as suggested by the graph.

Figure 7.6 shows that, unsurprisingly, participants identified as successful generally had better neurofeedback performance in theta and alpha control compared to unsuccessful participants in all three success criteria. However, the opposite is true for beta. This is in line with the interview data as only 8 out of 35 participants reportedly tried to control beta (7 of which were identified as unsuccessful according to the thesis criteria). Thus, it is expected that successful participants would perform poorly at controlling beta activity. Figure 7.7 shows similar performance patterns for successful participants compared to Figure 7.6; however, between visits performance of successful participants seem to be better than their performance within a visit, particularly for beta control, indicating that successful participants were improving their overall performance with long-term training. Figure 7.7 and Figure 7.6 shows that successful participants learned to better control their EEG activity within a visit and between visits, indicating that neurofeedback learning was taking place with time. Unsuccessful participants improve their alpha within a visit (Figure 7.6); however, their performance is worse than successful participants. Unsuccessful participants also seem to perform better at beta control than successful participants. However, Figure 7.7 shows that this performance was not maintained between visits, suggesting that EEG changes within a visit for unsuccessful participants are not due to neurofeedback learning but due to another phenomena, such as perception of success. As mentioned in section 6.2.5, unsuccessful participants did not believe that the neurofeedback task was achievable. This belief may have caused unsuccessful participants to decrease their efforts to become successful at neurofeedback. Decreasing efforts may have led to decreased mental demands, which is generally associated with increased alpha and decreased beta [225, 229, 236, 240]. Thus, the decreased efforts of unsuccessful participants may have caused superficial improved performance within a visit. However, this was not systematically examined in this thesis and needs to be confirmed in future research.

Figure 7.6 also shows how the different success criteria produced different learning curves. All three success criteria produced different learning patterns for each EEG frequency, where alpha shows the most consistent patterns and beta shows the least consistent patterns. This may reflect the number of participants who attempted to control each frequency band: beta was controlled by the least number of participants (8) while alpha was controlled by the most number of participants (33).

This thesis used success criteria not used by other neurofeedback studies, it was thus important to acknowledge that neurofeedback success rates were dependent on the chosen method. The above analysis indicates that the remaining results in this chapter may have differed if another method was chosen; however, as previously stated in section 7.1.1, participants' perceived neurofeedback success plays a crucial role in the active participation of the neurofeedback task. Thus, this thesis moved forward in addressing perceived success as part of the success criteria.

According to the thesis criteria, fifteen participants were identified as successful. This is three less than the number of participants who perceived themselves to be successful (n = 18, shown in the previous chapter within section 6.2.4). While these results were not examined due to the limited time to complete the thesis, it is an interesting observation that is considered in the discussion chapter (chapter 9) within section 9.2.3.

7.2.2 Interview Analysis

Mental behaviours identified from the previous chapter were divided into mental strategies and affect. A third category of mental behaviour was also identified (relating to the relationship between the interface design and mental behaviour), which is discussed in the next chapter. Statistical analysis were not conducted on the relationship between mental behaviours and neurofeedback performance due to the varying frequency of mental behaviours (which are shown in in Table 7.6 and 7.7 of this section).

Mental Strategies

Twelve mental strategies were identified from the interview data, as detailed in the previous chapter, and summarised in Table 7.5. The prevalence of each mental strategy is also shown in Table 7.6, which is based on the use of each mental strategy per neurofeedback training run**.** Cases where participants used more than one strategy in a run have been labelled as Various Strategies, and cases where participants were distracted for most of the run (i.e. not focusing on the neurofeedback task) have been labelled as "distracted". As described in section 6.2.4, 551 runs were analysed after removal of missing or unusable runs. However, this includes also includes runs labelled as Various Strategies and Distracted; this brings the total runs to 688. There were no clear differences in the prevalence of mental strategies between the able-bodied and CNP participants.

Table 7.5. A description of the mental strategies identified from chapter 6

Mental Strategy	**Description**	**Example Quote**
Actual Movement	These mental strategies were focused on their physical body, and not imagery within the mind, where participants initiated actual movement	"[I] shifted my eyes to one direction and then the other" – 22A
Auditory	Sounds derived from imagination or memory, or sounds that participants spoke/sang in their head	"I was just singing some Hindi songs [in my head]" – 10B
Breathing	Participants focused on their breathing by either noticing their breathing or trying to control it	"*I did breathing, concentrated purely on breathing*" – 1B
Clear Mind	Clearing the mind from any thoughts to have an empty mind	"*I tried to not think of anything*" – P11A
Imagination	Imagery or scenarios that the participants have not personally experienced	"*I [imagined] a leaf, growing on an oak tree… the little leaf forming the little bud, bursting [from] the tree, going through its whole cycle and then into autumn and the leaf falling off the tree*" – 3B
Imagined Movement	Strategies that involved imagery of moving a body part in a specific way, either from imagination or memory	"I [imagined] wiggling my toes or [stretching] the toes" – 8A
Memory	Imagery or events derived from memory	"*We had a party there once, there [were] three of us sitting in the garden having a barbecue*" – 16A
Moral Values	Thinking about a moral value that was important to oneself	"*I was thinking about decisions and I have been thinking a lot about the tennis [match] and I was thinking that I was really pleased to have stuck to the rules of the contest*" – 25A
Non-Specific Focus	Focus on the neurofeedback task with no verbalisation about thoughts or imagery	"*I just concentrated as hard as I could*" – 4B
Numerical Task	Mental strategies involving a simple numerical task	"*I just ended up trying to concentrate on doing a list of prime numbers*" – 9A
Pain Memory	Recalling physical pain from a past event	"*Like trying to picture like an ache going down my – in the middle of my back*" – 2A
Planning	Mentally preparing for a future event	"*I think I was thinking of my essay and what I was going to do, thinking about the*

		different things I need to [do], different materials I can use, and where I'm going to do it" – 11A
Resolving Stress	Considering possible solutions to current stressful events in one's life	"*I was actually beginning to see a way through some of those issues, the issues that I was thinking about, and finding a solution to a couple of the things*" – 3B

Table 7.6 Frequency of each mental strategy based on runs and number of participants

Mental Strategy	**Able-Bodied**		**CNP Participants**	
	*% of times used**	*No. of P***	*% of times used**	*No. of P***
Actual Movement	1.11	6	NU[1]	NU[1]
Auditory	8.86	15	17.12	8
Breathing	5.35	10	1.37	3
Clear Mind	9.41	10	1.37	2
Imagination	14.76	19	4.79	6
Imagined Movement	18.63	14	6.16	3
Memory	10.15	15	2.05	3
Moral Values	2.03	2	NU[1]	NU[1]
Non-Specific Focus	11.62	13	23.29	9
Numerical Task	1.11	5	5.48	3
Pain Memory	0.37	1	NU[1]	NU[1]
Planning	1.66	6	NU[1]	NU[1]
Resolving Stress	NU[1]	NU[1]	1.37	1
Distracted	7.56	17	3.42	2
Various mental strategies	7.38	14	33.56	6

*% of times used out of total runs, where this column adds up to 100%
** Number of participants that used that mental strategy
[1] NU = Not Used; these mental strategies were not used by that group of participants

Table 7.7 shows the relationship between neurofeedback success and each mental strategy, where success rate percentages are based on the total number of participants who used that strategy. No mental strategy can be concluded to be better or worse for neurofeedback success as some successful strategies with a high success rate were used by a low number of participants, e.g. Pain Memory had a 100% success rate but used only by a single participant. It appears that success rates are approximately 50% in mental strategies used by a relatively high number of participants, indicating that the mental strategy may not play a crucial role in neurofeedback success. As a statistical test was not conducted, this inference must be taken with caution.

Table 7.7. The success rates of each mental strategy and the number of successful participants that used that strategy; ordered from most used to least used

Mental Strategy (MS)	**No. of SP* Using MS (Total n** Using MS)**	**Success Rate in %**
Various Strategies	9 (20)	45.00
Imagination	8 (19)	42.11
Distraction	5 (19)	26.32
Auditory	5 (18)	27.78
Imagined Movement	8 (17)	47.06
Non-Specific Focus	5 (16)	31.25
Memory	6 (14)	42.86
Clear Mind	6 (11)	54.55
Breathing	4 (10)	40.00
Actual Movement	3 (5)	60.00
Numerical Task	0 (4)	0.00
Planning	1 (4)	25.00
Moral Values	1 (2)	50.00
Pain Memory	1 (1)	100.00
Resolving Stress	1 (1)	100.00

*SP = Successful Participants
**n = No. of participants

Figures 7.8 shows “heat maps” of changes in mental strategies used by successful and unsuccessful participants, within and between visits. Mental strategies do not change much within a visit; however, there are slight changes between visits. Successful participants considerably increased their use of Imagination in V3; all other strategies remain relatively similar in use. Unsuccessful participants reduced their use of most strategies. This likely reflects the study’s dropout rate (as 6 out of 10 participants who dropped out were unsuccessful; refer to Table 6.1 for dropout rate) rather than a reflection of any cognitive trends.

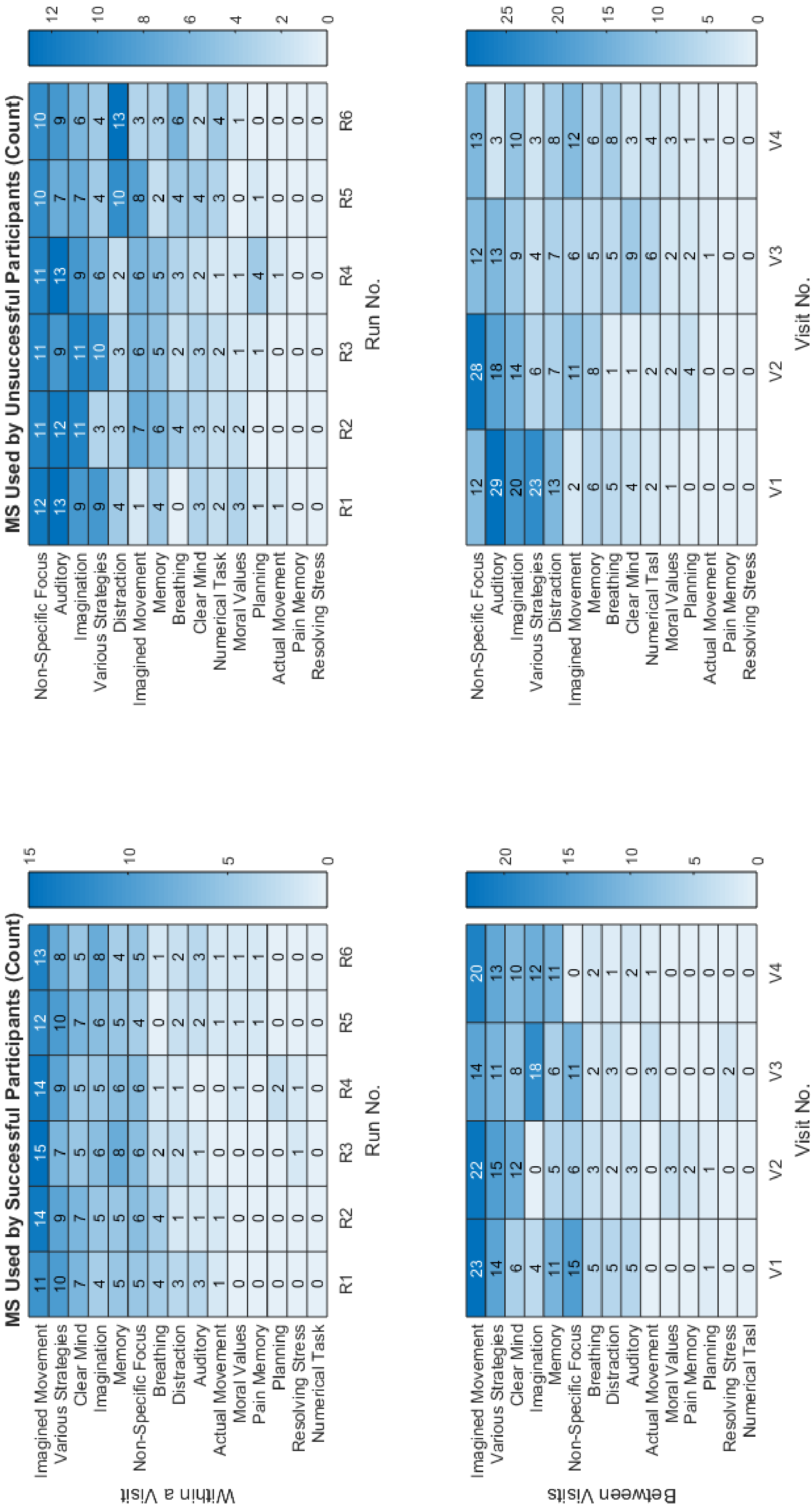


Figure 7.8 Heat map of changes in mental strategies used by successful and unsuccessful participants, within and between visits

Affect During Neurofeedback Training

Able-bodied and CNP participants shared all identified affects, and there were no clear differences in the prevalence of affect type between the able-bodied participants and CNP participants**.** Table 7.8 displays the reported affects and their respective success rates. The number of participants who reported each affect have a considerable size (compared to mental strategies) to make an inference, excluding the “excited” affect. No affect can be said to be associated with success at neurofeedback; however, it seems that “mentally tired” and “discontent” are more often associated with being unsuccessful than successful at the neurofeedback task. This cannot be concluded for the “neutral” affect, as a closer inspection revealed that seven of the unsuccessful participants that reported this affect felt they could not accomplish the neurofeedback task no matter what they tried. They reported that because they felt this way, they did not care about failing at the neurofeedback task and described their affect during the remaining neurofeedback training as “neutral”. This indicates that the success rate for the “neutral” affect may be more related to some participants’ effort and not the affect itself. These participants were kept in the analysis because they continued to attempt the neurofeedback task.

Table 7.8 The success rates of each affect and the number of successful participants that reported that affect; ordered from most used to least used

Affect	No. of SP* Reporting Affect (Total n** Reporting Affect)	Success Rate (%)
Discontent	13 (30)	43.33
Relaxed	12 (24)	50
Neutral	11 (28)	39.29
Happy	10 (18)	55.56
Mentally Tired	8 (22)	36.36
Excited	2 (4)	50

*SP = Successful Participants
**n = No. of participants

Figures 7.9 shows "heat maps" of changes in affects reported by successful and unsuccessful participants, within and between visits. Successful participants reduced their Relaxed, Neutral and Discontent affect, while their Mentally Tired affect increased within a visit. Other affects remain relatively similar. Unsuccessful participants also increased their Mentally Tired affect and reduced their Neutral affect within a visit; however, their Discontent increased. Successful participants show a similar trend between visits compared to within a visit, except their Mentally Tired affect decreased. Unsuccessful participants Neutral and Discontent affects are similar between visits compared to within a visit; however, their Mentally Tired and Happy affects decreased while their Relaxed affect increased in V4.

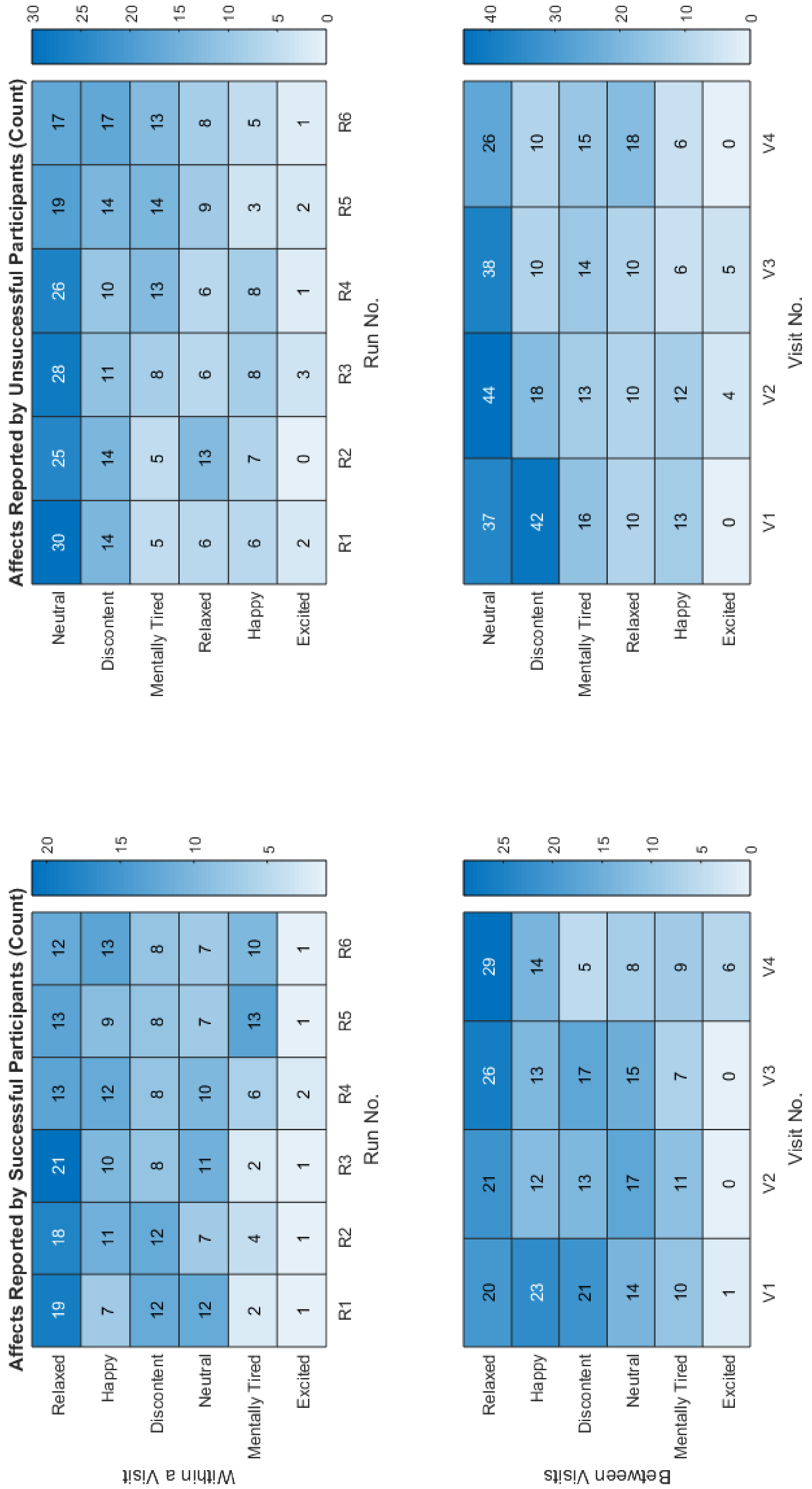


Figure 7.9 Heat map of changes in affects used by successful and unsuccessful participants, within and between visits

A Sole Theme: Insight into Neurofeedback Success

The interview analysis also revealed a theme separate from mental strategies or affect: "to keep oneself stimulated", which is the concept of keeping your mind attentive or entertained enough to last the entire five-minute training run.

"*… But the ski jump itself lasts twenty [or] thirty seconds… so for a five minute [training run], for the time that the exercise takes, that's not long enough… so I had the feeling that if I can give new information to my brain for five minutes rather than having to reiterate sitting on the bar and jumping off, that might work better*" – P4A

"*I feel I can maybe do twenty or thirty seconds of one thing and it'd be good, so like for twenty to thirty seconds of kite surfing or something I can picture myself doing, it's all good [but then] my brain runs out of memory*" – P6A

While this theme was only found in eight of the thirty-five participants (23%; six from able-bodied participants and two from CNP participants), all eight of these participants were identified as successful (53% of the total successful participants). This theme seems to be a revelation that allowed these participants to identify mental strategies that aided their performance at the neurofeedback task.

7.2.3 General Learning Factors Analysis

A Pearson's correlation was conducted to determine the relationship between general learning factors (SE, task load, motivation, and LoC) and success; this was conducted for each visit (descriptive statistics for each measure are shown in Table 7.9). Correlation for LoC was only conducted for able-bodied participants as CNP participants completed a different LoC questionnaire and there were only 10 CNP participants. There was a statistically significant, moderate correlation between SE and success (V1: $r = -0.430$, $p = 0.010$, $n = 35$; V2: $r = -0.505$, $p = 0.004$, $n = 31$; V3: $r = -0.587$, $p = 0.001$, $n = 27$; V4: $r = -0.461$, $p = 0.020$, $n = 25$), where higher SE scores were associated with success (Figures 7.8 – 7.11). All other correlations were low ($r < 0.300$) and non-significant. As LoC correlations for able-bodied participants were low and non-significant, the trend in LoC scores for able-bodied and CNP participants were not compared in the main text as it did not add value to the current study. However, this trend is briefly compared in Appendix F.

Table 7.9 Descriptive statistics for questionnaire data

	Visit 1 (N = 35)		Visit 2 (N = 31)		Visit 3 (N = 27)		Visit 4 (N = 25)	
SE	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	33.53	3.44	34.07	4.14	34.69	3.99	34.00	4.53
Unsuccessful	29.55	4.77	28.82	4.97	28.07	5.34	29.54	4.41
	Visit 1 (N = 35)		**Visit 2 (N = 31)**		**Visit 3 (N = 27)**		**Visit 4 (N = 25)**	
Task Load	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	58.11	17.87	56.90	18.51	50.67	13.86	43.42	14.35
Unsuccessful	60.70	17.98	56.18	13.56	58.31	19.87	55.49	15.55
	Visit 1 (N = 35)		**Visit 2 (N = 31)**		**Visit 3 (N = 27)**		**Visit 4 (N = 25)**	
Motivation	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	7.33	1.35	7.43	1.79	7.23	1.64	6.67	1.97
Unsuccessful	7.50	1.67	6.76	2.02	6.21	2.64	6.54	2.03
	Visit 1 (N = 25)		**Visit 2 (N = 23)**		**Visit 3 (N = 22)**		**Visit 4 (N = 22)**	
^{AB}LoC – Internality	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	34.00	4.32	36.70	4.79	36.00	4.57	36.30	5.23
Unsuccessful	30.53	5.22	30.69	6.64	32.75	5.75	32.17	7.71
	Visit 1 (N = 25)		**Visit 2 (N = 23)**		**Visit 3 (N = 22)**		**Visit 4 (N = 22)**	
^{AB}LoC – Chance	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	17.70	7.24	15.60	7.29	16.90	8.27	17.60	9.37
Unsuccessful	17.33	6.83	15.69	5.68	16.58	5.14	16.92	5.82
	Visit 1 (N = 25)		**Visit 2 (N = 23)**		**Visit 3 (N = 22)**		**Visit 4 (N = 22)**	
^{AB}LoC – Others	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	16.80	7.10	14.20	7.01	16.50	7.63	15.70	6.99
Unsuccessful	17.20	7.03	16.46	4.89	15.83	6.10	15.42	5.76
	Visit 1 (N = 10)		**Visit 2 (N = 8)**		**Visit 3 (N = 5)**		**Visit 4 (N = 3)**	
^{C}LoC – Internality	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	14.00	6.86	15.25	5.38	13.33	8.51	17.00	.
Unsuccessful	16.20	4.49	11.50	4.66	7.50	2.12	6.00	.
	Visit 1 (N = 10)		**Visit 2 (N = 8)**		**Visit 3 (N = 5)**		**Visit 4 (N = 3)**	
^{C}LoC – Chance	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	21.60	7.09	20.75	6.85	22.00	9.54	17.50	.
Unsuccessful	18.80	4.71	15.25	7.85	7.00	1.41	8.00	.
	Visit 1 (N = 10)		**Visit 2 (N = 8)**		**Visit 3 (N = 5)**		**Visit 4 (N = 3)**	
^{C}LoC – Doctors	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	8.60	5.59	9.25	2.63	10.67	3.21	8.50	.
Unsuccessful	6.20	5.02	8.00	5.77	10.50	6.36	3.00	.
	Visit 1 (N = 10)		**Visit 2 (N = 8)**		**Visit 3 (N = 5)**		**Visit 4 (N = 3)**	
^{C}LoC – Others (Non-Doctors)	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	15.40	7.06	16.50	4.73	18.33	5.51	17.50	.
Unsuccessful	12.60	9.74	14.00	10.10	17.50	12.02	6.00	.

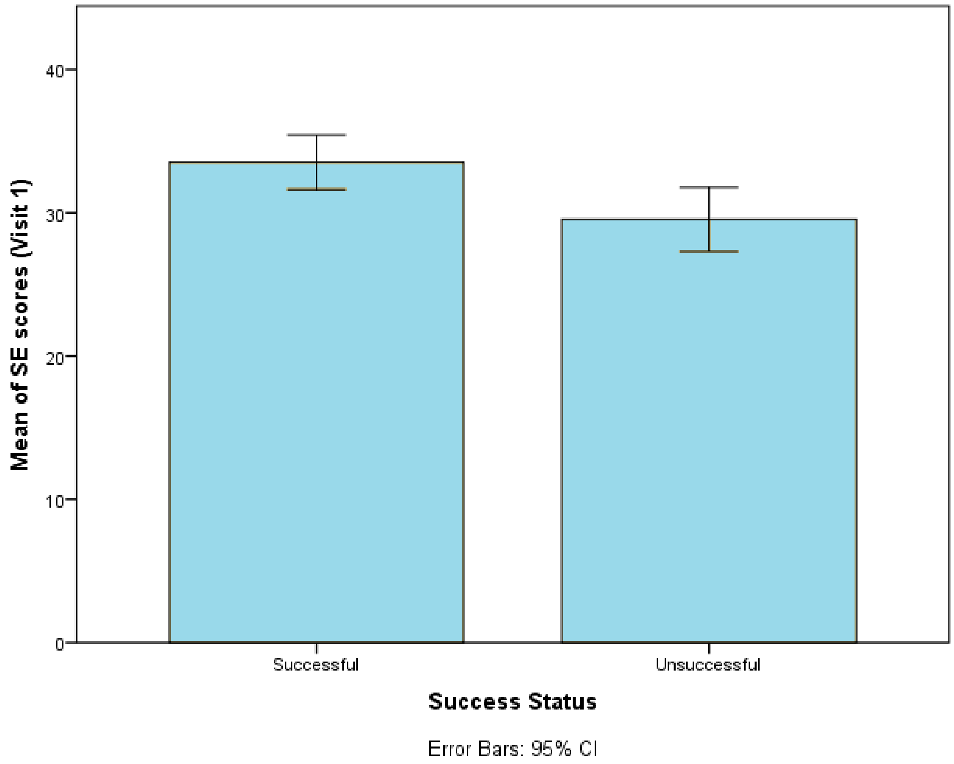


Figure 7.10 Bar graphs depicting correlation between SE and neurofeedback success (Visits 1)

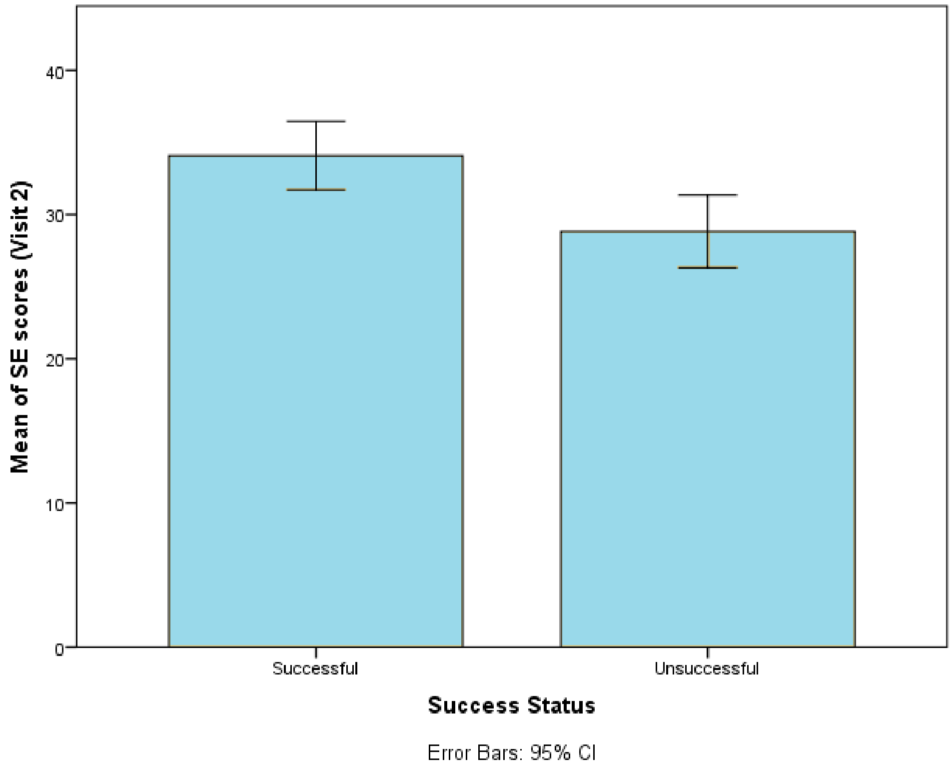


Figure 7.11 Bar graphs depicting correlation between SE and neurofeedback success (Visits 2)

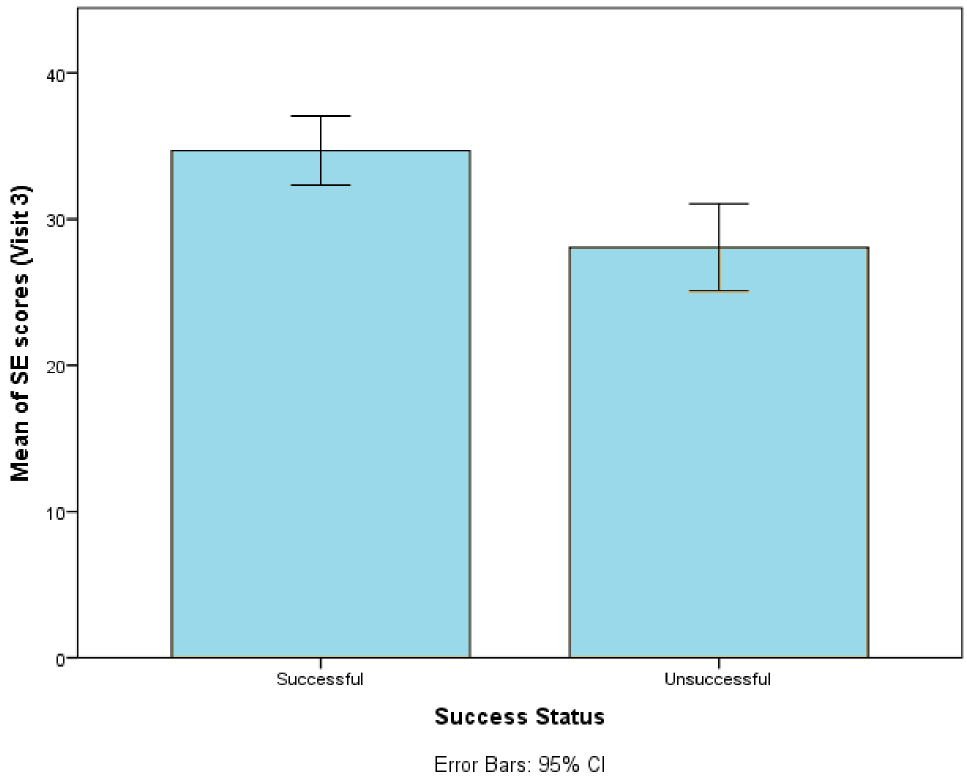


Figure 7.12 Bar graphs depicting correlation between SE and neurofeedback success (Visits 3)

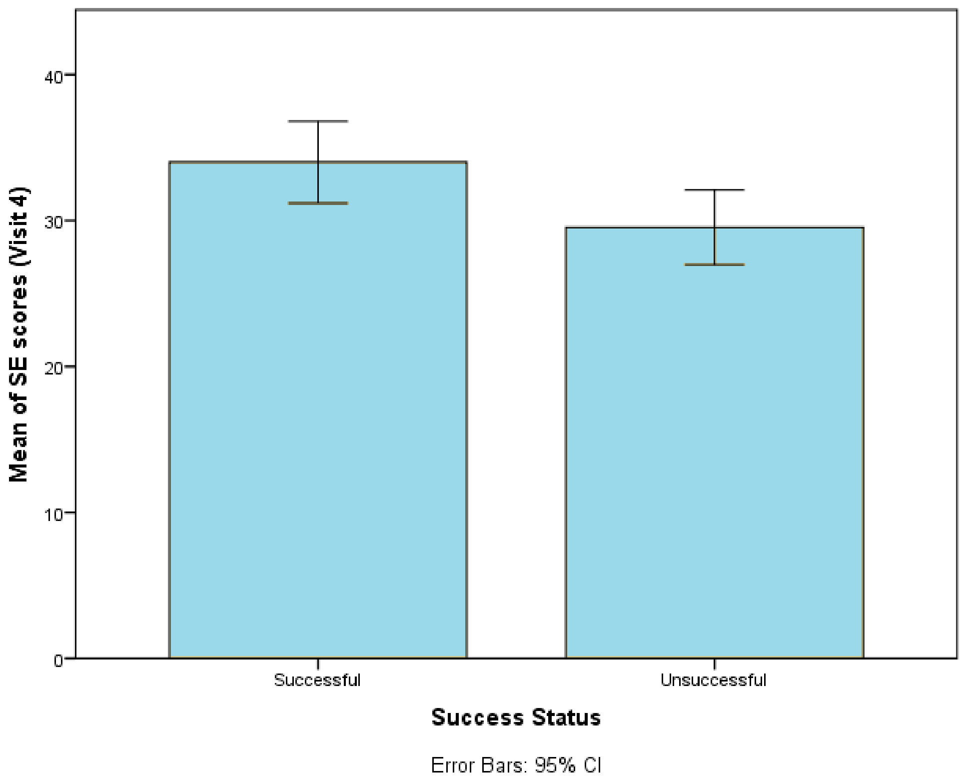


Figure 7.13 Bar graphs depicting correlation between SE and neurofeedback success (Visits 4)

7.2.4 Autonomic Response Analysis

A Pearson's correlation was conducted to determine the relationship between the average change in autonomic responses (ECG, RSP, and GSR; descriptive statistics for each response is shown in Table 7.10) and success; this was conducted for each visit. Sample size related to RPS is lower than samples sizes of other responses because the RPS equipment malfunctioned for a small number of participants. Appendix G.1 shows boxplots comparing the autonomic responses and success (plots were too large for the main text). All correlations were low (r < 0.300) and non-significant. This indicates that there is no linear relationship between autonomic responses and neurofeedback success. However, this thesis included participants' perception of their neurofeedback performance as part of the success criteria. It maybe that autonomic responses only had a relationship with changes in EEG activity. Thus, another Pearson's correlation was conducted to determine the relationship between average change in autonomic responses (ECG, RPS, and GSR) and change in power of each EEG frequency band (theta, alpha, and beta); this was conducted for each visit. All of these correlations were low (r < 0.300) and non-significant. This indicates that there is no linear relationship between autonomic responses and changes in EEG activity. Scatter plots are provided in Appendix G that show this correlation (plots were too large for the main text).

Table 7.10 Descriptive statistics of autonomic responses shown in percentage of relative change (absolute response during neurofeedback training compared to absolute baseline response)

	Visit 1 (N = 35)		**Visit 2 (N = 31)**		**Visit 3 (N = 27)**		**Visit 4 (N = 25)**	
Heart Rate	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	3.61	6.19	7.08	6.50	2.56	5.30	-0.24	4.44
Unsuccessful	4.66	4.47	3.72	3.23	1.84	4.32	2.37	3.65
	Visit 1 (N = 35)		**Visit 2 (N = 31)**		**Visit 3 (N = 27)**		**Visit 4 (N = 25)**	
Heart Rate Variability	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	-7.29	42.04	-0.93	32.72	12.03	36.55	9.76	42.15
Unsuccessful	-7.85	31.41	9.33	46.30	6.55	45.01	1.74	35.45
	Visit 1 (N = 30)		**Visit 2 (N = 26)**		**Visit 3 (N = 22)**		**Visit 4 (N = 22)**	
Breathing Rate	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	15.46	23.39	17.19	28.91	25.93	34.80	12.47	32.83
Unsuccessful	13.78	23.59	17.67	27.29	13.84	21.71	9.08	13.57
	Visit 1 (N = 30)		**Visit 2 (N = 26)**		**Visit 3 (N = 22)**		**Visit 4 (N = 22)**	
Breathing Rate Variability	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	9.42	48.10	-0.30	43.17	10.39	31.59	6.77	33.02
Unsuccessful	8.71	43.72	1.43	31.38	15.94	52.84	32.15	44.59
	Visit 1 (N = 35)		**Visit 2 (N = 31)**		**Visit 3 (N = 27)**		**Visit 4 (N = 25)**	
Galvanic Skin Response	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Successful	-18.66	37.91	-3.77	29.36	7.89	26.48	-3.12	51.94
Unsuccessful	-17.62	32.26	-8.06	35.55	2.47	26.91	-12.11	51.77

7.2.5 Pain Questionnaire Analysis

Five out of ten CNP participants were identified as successful at neurofeedback, however, only two of these five participants (3B and 12B) reported pain relief similar to the pain relief observed by the University of Glasgow (pain relief with a warm tingling sensation in the lower limbs [8]). This observed pain relief will be called the "expected pain relief (EPR)" to avoid confusion of other pain relief. The other three successful CNP participants also reported pain relief, however this did not accompany the warm tingling sensation (i.e. not EPR); this pain relief was due to sitting still for 30 to 45 minutes (the length of the neurofeedback training in one visit), as reported by CNP participants. Unsuccessful CNP participants also reported pain relief, which was also reportedly due to sitting for 30 to 45 minutes. Pain scores from questionnaires are shown individually for all CNP participants in Table 7.11. Only data from the first training visit was analysed here as two CNP participants only completed one training visit. Table 7.11 shows that 3B and 12B, the two participants who reported EPR, had pain reduction in all dimensions compared to other participants, and reported the greatest neuropathic pain relief. However, whether or not neurofeedback training can provide pain relief cannot be firmly concluded due to the small number of successful and total CNP participants. Cases where pain increased were reportedly due to environmental factors such as sitting uncomfortably, the EEG headset being too tight, or concentrating too hard on the neurofeedback task causing a headache. EEG activity was not examined due to the unfortunate data file corruption of 12B.

Table 7.11 Pain scores of successful and unsuccessful CNP participants from V1

ID	**Continuous Pain**			**Intermittent Pain**			**Affective Pain**			**Neuropathic Pain**			**Discomfort**		
Successful CNP Participants															
	B	*A*	*RelC*	*B*	*A*	*RelC*	*B*	*A*	*RelC*	*B*	*A*	*RelC*	*B*	*A*	*RelC*
3B[a]	18	7	-61.11	46	19	-58.70	15	3	-80.00	34	11	-67.65	7	3	-57.14
4B	3	1	-66.67	3	4	33.33	0	2	2PI*	0	1	1PI*	1	1	0.00
5B	40	34	-15.00	36	21	-41.67	26	23	-11.54	10	10	0.00	10	10	0.00
8B	24	26	8.33	27	29	7.41	9	12	33.33	30	30	0.00	7	7	0.00
12B[a]	23	20	-13.04	10	4	-60.00	13	1	-92.31	15	6	-60.00	8	3	-62.50
Unsuccessful CNP Participants															
	B	*A*	*RelC*	*B*	*A*	*RelC*	*B*	*A*	*RelC*	*B*	*A*	*RelC*	*B*	*A*	*RelC*
1B	23	25	8.70	52	49	-5.77	7	6	-14.29	7	7	0.00	8	9	12.50
6B	10	6	-40.00	9	3	-66.67	4	1	-75.00	7	3	-57.14	2	2	0.00
7B	10	4	-60.00	0	0	0.00	0	0	0.00	5	3	-40.00	4	1	-75.00
9B	16	10	-37.50	0	0	0.00	4	7	75.00	14	15	7.14	8	6	-25.00
10B	20	18	-10.00	13	13	0.00	15	13	-13.33	42	36	-14.29	10	10	0.00

B = Pain reported before neurofeedback training
A = Pain reported after neurofeedback training
RelC = The relative change in pain score, where A is compared to B (e.g. 3B had a 61.11% decrease in continuous pain after the neurofeedback training)
[a] = Indicates CNP participants that reported EPR
*PI = Point Increase; In cases where B is 0 and A is higher than 0, a percentage cannot be calculated as it is not possible to divide by 0. In place of a percentage, a value representing how many points the score increased is shown.

7.3 Discussion

This chapter compared mental behaviour (i.e. mental strategies and affects) during neurofeedback learning and successful neurofeedback performance, where no distinct relationship was found between them. The theme, “to keep oneself stimulated”, was found only in successful participants, indicating that this theme may be relevant to successful performance. The discussion compares mental behaviour findings to previous research, concluding that mental strategies likely do not contribute to neurofeedback performance. However, affect and the “to keep oneself stimulated” theme may somewhat influence neurofeedback performance. SE was the only general learning factor to be associated with neurofeedback performance, where SE increased with successful performance. SE has not previously been examined as an influencer of neurofeedback performance, and is discussed in terms of conscious effort required for neurofeedback. No autonomic responses were associated with neurofeedback performance; this finding is compared to the relationship between general EEG activity and autonomic responses. Two out of five successful CNP participants reported EPR; unfortunately, the relationship between pain scores and EEG activity could not be conducted due to corrupted EEG files. The possibility of a placebo effect regarding pain relief is discussed.

The below discussion is divided into the following sections, each comparing their respective data with neurofeedback performance: mental behaviours, general learning factors, autonomic responses, and pain scores. This chapter ends with its limitations and conclusion.

7.3.1 Mental Behaviours

No mental strategies were clearly associated with success; this is likely due to the varied use of mental strategies across participants. Other studies examined mental strategies, where participants were asked to identify their own mental strategies, such as Nan et al [117] and Kober et al [98]. Nan et al [117] (regulating the alpha frequency) found that 61.29% of mental strategies used were positive, 33.87% were neutral, and 4.84% were negative; Kober et al [98], (regulating SMR) found seven categories of mental strategies where usage varied from 45% in “concentration” to 5% in “breathing”. Although these studies infer the relationship between mental strategies and neurofeedback success, the varied usage of mental behaviours makes it difficult to draw confident conclusions. The studies that provided mental strategies to participants (instead of participants developing their own mental strategies) do not have a control group and have small samples [116, 256], which further complicates conclusions of this relationship. It is likely that more types of mental strategies can be found with larger sample sizes, where uncommon or unique mental strategies are used by a small number of participants. For example, this thesis found Pain Memory and Planning were used by a relatively small number of participants. This indicates that mental strategies do not have a crucial relationship with neurofeedback success. This is further supported by Siniatchkin et al [257], who reversed neurofeedback conditions (i.e. increasing slow cortical potentials (SCP) to decreasing SCP) halfway through neurofeedback training without informing participants. Participants initially performed worse after the reversal but were able to improve their performance after realisation of the reversal; participants also reported using the same mental strategies throughout the entire neurofeedback training. Siniatchkin et al [257] concluded that knowledge of the neurofeedback conditions were more important that using the “correct” mental strategy. Therefore, mental strategies may not be of importance to neurofeedback success. In terms of neurofeedback learning, this suggests that neurofeedback users have flexibility in the mental behaviour that they use. Whether or not this flexibility facilities neurofeedback learning should be further examined.

Davelaar et al [258] also qualitatively examined mental behaviour during neurofeedback training; however, they did not identify specific mental strategies but instead compared the overall behavioural approach between learners (successful participants) and non-learners (unsuccessful participants). They found that learners tended to “sense” or focus on their environment (e.g. sensing the patterns in their EEG representation or being aware of bodily sensations) whereas non-leaners engaged in deliberate mental effort of the neurofeedback task (e.g. trying to force their EEG representation to move correctly). This is in contrast to the current findings, which show that both successful and unsuccessful individuals used both mental strategies of focusing on their environment and engaging in deliberate effort. This contrast may, firstly, be due to the small number of learners (n = 4) compared non-learners (n = 12) in Davelaar et al’s [258] study. Secondly, they excluded mental strategies that were used by only a single participant in their analysis to improve generalisability of their data, whereas this thesis included all mental strategies. Removing such qualitative data within a small sample size reduces the depth of information that can be gained, which is one of the strengths of qualitative approaches. These reasons make it difficult to be confident in Davelaar et al’s [258] conclusions, and further suggests that mental strategies (or in this case, overall behavioural approaches) do not play a crucial role in neurofeedback performance.

This study found no relationship between affect and success; however, Mentally Tired and Discontent were more associated with being unsuccessful. These affects can be seen as negative, indicating that inducing a negative affect may reduce chances of success at the neurofeedback task. Yet, it may also be that the challenging nature of neurofeedback caused these negative affects, which prompted participants to reduce their efforts (i.e. give up) during neurofeedback training. Nan et al [117] similarly found that negative mental strategies were less successful than positive mental strategies. However, as mentioned previously, a confident conclusion cannot be made because more participants used positive mental strategies than negative mental strategies. Furthermore, it is unknown whether the affects were accurate as Nan et al [117] deduced affects post-data collection without confirmation from participants. Nijboer et al [113] found that a more positive mood was associated with better performance at their neurofeedback task (changing the amplitude of SMR). However, in a later study, Nijboer et al [112] found that mood did not influence neurofeedback performance (influencing SMR and ERP (event-related potential)). Thus, there is conflicting evidence from the literature for the influence of emotion on neurofeedback performance. This may be due to the different methods of measuring emotion, where one study used a standardised questionnaire (e.g., Nijboer et al [112, 113]) and another study used a qualitative approach (e.g., Nan et al [117]). There is also substantial evidence from the literature that general EEG activity is highly associated with emotion [259-261]. Therefore, further research is needed to understand how emotion specifically influences neurofeedback performance, such as conducting research to replicate previous findings or examining the type of emotion and source of emotion (e.g. negative emotion resulting from perceived poor neurofeedback performance) and its influence on neurofeedback learning.

The “to keep oneself stimulated” theme was only reported by participants who were successful. This theme suggests that these participants were aiming to identify mental strategies that will allow them to keep their mental state constant throughout the five-minute training run. Thus, this theme can be seen as attempting to hold continuous focus on the task, and compliments the current understanding of the role of attention and neurofeedback performance; focus ability is a cognitive variable that is seen by the literature as central to achieving the neurofeedback task [97]. This is further supported by the finding that the affect Mentally Tired was associated with lower neurofeedback success rates. Thus, the “to keep oneself stimulated” theme may be an insight that facilitated neurofeedback learning resulting in successful performance. However, it is important to note that this was only reported by 23% of successful participants (this theme was reported by participants without prompts and was not asked to other participants); therefore, this finding may not be related to neurofeedback success. Furthermore, no other studies have reported this insight; thus, future research is needed to replicate this finding.

7.3.2 General Learning Factors

SE was the only general learning factor that had a significant correlation with success, where higher SE was moderately associated with success. This indicates that those who have lower SE may give up on accomplishing the neurofeedback task earlier than those who have higher SE, thus reducing the likelihood of finding an appropriate mental behaviour that improves neurofeedback performance. Current literature examines how neurofeedback influences SE as a clinical outcome

[262, 263], where the consensus is that neurofeedback has the potential to improve SE. However, there is no research that examines SE as a predictor of neurofeedback learning. Gruzelier [264] relates SE to conscious awareness, where SE in the context of neurofeedback is a conscious realisation and assessment of self-neuromodulation. He argues that while conscious realisation is commonly associated with better self-neuromodulation performance, it may not be a prerequisite to successful performance. However, the thesis disagrees with Gruzelier's [264] statement as some unsuccessful participants who were reportedly "neutral" refrained from using high efforts to achieve the neurofeedback task indicating that some conscious realisation is needed. Furthermore, the ability to correctly self-assess performance is considered an important skill for any task according to general learning literature [89-91, 265]. The significant relationship between SE and neurofeedback success found in this study also supports the prerequisite of conscious realisation. However, this relationship was only moderate. Further examination is needed to identify the specific relationship between SE and neurofeedback success, where SE may play a mediating role between neurofeedback performance and other factors such as attention or task engagement.

It is unclear why all dimensions of LoC yielded non-significant, low correlations. Burde and Blankertz [129] examined the relationship between Loc (internal, external, and technology-related) and neurofeedback performance (using cortical-motor activity to move an on-screen cursor). Only technology-related LoC was found to have a significant relationship with neurofeedback performance, where technology-related LoC increased with better performance. The non-significant finding of internal and external LoC in this thesis is similar to the finding in Burde and Blankertz [129], indicating perception of control over situations and events (other than technology) is unrelated to neurofeedback performance. Witte et al [133] also found a significant relationship between technology-related LoC and neurofeedback performance (SMR regulation); however, they found that this LoC decreased with better performance. The conflicting results may be due to the different neurofeedback protocol in each study; however, this is discussed further in chapter 9.

Although task load scores were generally lower in the successful group compared to the unsuccessful group, the standard deviation was high and the correlation was not statistically significant. This indicates that success can be achieved despite perception of task load needed for the neurofeedback task. However, other studies have reported that monitoring task load, or aspects of task load such as mental effort [200], and adapting the neurofeedback task accordingly may increase the likelihood of neurofeedback success. Bauer et al [104] implemented a threshold adaption where participants input their perception of required mental effort after each neurofeedback training run. The neurofeedback software would alter the difficulty of the task according to the input (e.g. increasing difficulty if a participant states mental effort was low). This adaption was found to facilitate neurofeedback performance. Adapting task difficulty according to task load may also reduce the risks of individuals with low SE giving up on achieving the neurofeedback task at an early stage. Thus, further research is needed to understand the relationship between task difficulty and neurofeedback performance. This can be done by comparing high and low neurofeedback difficulty conditions or by examining neurofeedback learning when participants can change difficulty settings.

All participants had moderately high motivation to complete the study, which may be why motivation was not found to be associated with neurofeedback success. This may be an example of recruitment bias, where individuals who volunteer for research studies are likely to provide different results than those who do not volunteer for research studies [266]. Although Kadosh and Staunton [97] also state that motivation tends to be high due to recruitment bias, they found that five out of eight studies examining motivation established it as a positive influence on neurofeedback performance [97]. As explained in section 3.3.4, these positive findings are not conclusive due to inconsistent measures of motivation and insufficient sample sizes. Specifically, the stronger findings in section 3.3.4 (Enriquez-Geppert et al [109] and Hammer et al [108] who had larger sample sizes) suggests that motivation does not influence neurofeedback performance, concurring with the motivation finding in this thesis. This suggests that motivation only reflects participants' willingness to engage with the task and not their neurofeedback ability. This inference may be difficult to confirm due to recruitment bias, yet it is an important aspect to asses for neurofeedback learning.

7.3.3 Autonomic Responses

The non-significant relationship between autonomic responses (ECG, RSP, and GSR) and neurofeedback performance indicates that neurofeedback performance may not be directly related to the autonomic nervous system. However, the literature strongly suggests a relationship between EEG and physiological measures (as described in section 3.4). The non-significant relationship found in this study is likely due to the varied frequency of mental strategies and affects reported by the participants. A relationship may be found if there were a consistent number of participants using mental strategies and inducing affects, as emotion and mental states have been associated in the literature [267, 268]. Furthermore, only the average change in autonomic responses were examined; there are further examinations that can be conducted (such as a frequency analysis of the ECG data or a time-change analysis to examine how autonomic responses change within a neurofeedback training run) that may have shown a relationship between autonomic responses and neurofeedback performance. These further examinations were not conducted due to the limited time to complete the PhD. However, there is still a possibility that autonomic responses do not have a relationship with neurofeedback performance; this relationship should be investigated by future research that use experimental designs comparing specific mental strategies/affects and examine autonomic responses using other methods of analysis.

7.3.4 Pain Scores

Two CNP participants reported EPR out of the five CNP participants who were identified as successful at the neurofeedback task. Unfortunately, EEG activity of these participants could not be analysed post-processing due to corrupted files; thus, it is unclear whether or not this difference in pain relief was due to specific EEG changes. However, pain scores revealed that CNP participants with EPR reported greater neuropathic pain relief than CNP participants who did not reported EPR. While this result should be taken with caution due to the small sample size, this provides some incentive to further investigate the relationship between EEG activity and EPR. There is also a possibility that the EPR was due to a placebo effect; however, CNP participants were not told about the warm tingling sensation that might occur if they experience pain relief. CNP participants reported the warm tingling sensation when asked how they felt after the neurofeedback training compared to before the training began. Furthermore, CNP participants who reported pain relief (not EPR) stated that the relief was due to resting for the duration of the neurofeedback training, as they had previously experienced this pain relief when resting for a similar period. This suggests the absence of a placebo effect; however, further investigation is needed on a significantly larger sample size with an inclusion of a sham trial.

7.3.5 Limitations

There are several limitations to this chapter's findings. Firstly, this study did not provide guidance to participants; the same instruction, to "try and make the bars green", was given to all participants. It is likely that providing guidance may change the success rates. However, no guidance was given to discourage any biases or assumptions of neurofeedback learning made by the researcher. Another limitation is that the neurofeedback training visits varied amongst participants due to dropouts. However, the primary aim of this study was to qualitatively explore neurofeedback learning. The qualitative approach relied on the depth of information given by the participants, which can be provided in a single visit. Thus, each visit presented valuable data that served the purpose of this study. While the sample size here is larger compared to most neurofeedback studies, the number of participants that used each mental strategy and affect varied greatly. This prevented the use of statistical tests to support any tangible relationship. Future research should design different conditions where the participants within each condition are asked to use only one type of mental strategy or induce one type of affect. Another limitation refers to the use of separate LoC measure for able-bodied participants and participants with CNP after SCI; this decreased statistical power of the correlation for CNP participants due to their small sample size. However, LoC was not found to significantly correlate with neurofeedback success in the able-bodied participant group, which indicates that LoC may also not correlate with neurofeedback success in CNP participants. Finally, the findings in this study may only be applicable to the current neurofeedback protocol, where findings may change with self-regulation of different features of EEG activity. Future research should compare neurofeedback learning in different protocols to understand if there is a common learning process.

It is also important to observe that the success criteria used in this study was binary, where participants were either successful or not, and rejects the possibility of a learning spectrum. However, an observation from this study (described below) provides some evidence for a neurofeedback learning spectrum. As this was an observation, it was not included in the results section. One criteria for success was the correct perception of task performance; this was examined by matching statements of runs within a visit (and between visits) to the corresponding EEG data for that run. However, the author observed that two participants showed correct perception of control between visits but were not correct regarding within visit performance. Although they were identified as unsuccessful in this study, they did show evidence of learning; thus, demonstrating the existence of a neurofeedback learning spectrum. Furthermore, there were some participants whose statements on perceived performance were at the border of the two-thirds threshold (participants needed to match at least two-thirds of their statements with actual performance to be successful, see section 6.1.1); yet, they were still identified as unsuccessful as they did not meet the threshold, further demonstrating a neurofeedback learning spectrum. Bauer et al [104] developed an adaptive neurofeedback system where the system’s task-difficulty setting changed depending on the perceived participant-rated difficulty of the neurofeedback task after each run. They found that this adaptive system facilitated neurofeedback learning, promoting the existence of a neurofeedback learning spectrum. Thus, establishing a spectrum can be used in the development of a guidance system to actively facilitate the success of neurofeedback users.

7.4 Conclusion

Although 13 mental strategies and 6 affects were identified, there was no clear relationship between mental behaviour and neurofeedback success, indicating that neurofeedback learning does not rely on any specific mental behaviour. SE was the only general learning factor to influence neurofeedback success, suggesting that those with high SE may exert greater effort than those with lower SE. However, SE only had a moderate influence and further examination of SE and neurofeedback success is needed. The overall findings of this chapter adds uncertainty to neurofeedback learning, further complicating its investigation. However, it has emphasised the complexity of behaviours involved in neurofeedback learning, such as the variety of mental behaviours involved and the influence of negative affect. Future research should examine the influence of negative affect by instructing one group of participants to induce negative affects during neurofeedback training and other groups of participants to induce other affects (e.g. positive or neutral) as well as a control group that are not told to induce any particular affect. The use of both qualitative and quantitative measures of affect may be useful in this type of research to better understand that extent of the relationship between affect and neurofeedback performance.

Chapter 8 Findings Part III: The Unexpected Influence of the Interface Design on Mental Behaviour

This thesis planned to use interview data to reveal information about mental behaviour and neurofeedback learning. However, one of the strengths of a mixed methods, explorative approach is its ability to highlight factors not previously considered by the researchers. The analysis of these interviews unexpectedly revealed that the interface design (three bars) influenced mental behaviour. This chapter details this influence and its implications on neurofeedback learning.

8.1 Analysis Plan

The interview data were analysed using the same methods described in chapter 6, except association with EEG activity changes were not considered. Thus, the analysis plan for interview data is not repeated here. The focus for the interview analysis was anything that related to the interface design in terms of its links to mental strategies, affect, and neurofeedback learning. Descriptive statistics were used to examine the frequency of each theme identified from the interview analysis.

8.2 Results

Re-examination of mental behaviour provided a new theme called “Display-Related Strategies” (see Table 8.1 for coding details). This theme encompassed mental strategies that were directly inspired by the design of the feedback display.

“*I was then also thinking about …things that were green, I was thinking about grass and trees and leaves*” – 14B

“*I was trying to simulate in my head like I’m stomping on the bar, just like how Mario does it, stomping on the bar*” – 22A

“*I just kept repeating the word green in my head just over and over and over again, just green green green*” – 1B

The display inspired participants to use the following types of mental strategies: chanting “*green*”, chanting “*up*” or “*down*” in reference to the height of the bars, cheering on the bars when they turn green, imagining a green object, imagining a green scene, and imagining physically affecting the bars (e.g. stomping on the bars).

Table 8.1 Categorisation of initial codes into the “Display-Related Strategies” theme

Initial Codes	Theme	Grouping Description
• Chanting green • Chanting up/down • Counting number of times bar went green • Imagining green object • Imagining green scene • Memory with green • Doing something to the bars • Ordering bars to become green	Display-Related Strategies	Mental strategies that were directly inspired by the design of the feedback display

“Display-Related Strategies”, when considered as a mental strategy to achieve the neurofeedback task, was found to be the most used mental strategy; twenty-five out of thirty-five participants used this strategy (71%). This indicated that the interface design may have had a considerable influence in the choice of mental strategy, and prompted a closer examination of the relationship between mental behaviour and the interface design. The re-analysis of the interview data focusing on the interface design provided two types of results (detailed below): (1) success goals, where participants created their own criteria for neurofeedback success, and (2) information overload, where users could not process all information provided by the interface at once. Differences in these results between successful and unsuccessful participants were not examined because these results originated from a re-analysis of the interview data and not explicitly asked during the interview process. The lack of explicitly risks inconsistent reports from participants that may skew findings that may be exacerbated if they are divided into groups. These results instead provide insight into an area that contributes to the development and of neurofeedback.

8.2.1 Success Goals

All participants created their own criteria for success at the neurofeedback task by on the interface design (Table 8.2): (1) trying to keep the bars green before going back to red, (2) controlling height instead of colour, (3) trying to keep the bars stable (i.e., keeping the bars as still as possible), (4) increasing the end score that was displayed after each run, and (5) trying to "see more green" on the screen. To clarify the difference between the first goal and the fifth goal: participants who were focusing on a single bar used the first goal while participants who were focusing on the general colour of the screen used the fifth goal. Not all five strategies are aligned with the study's goal of success: to "make the bars green", which is similar to goal 1 and 5. Goal 2 also seems to align with the study's goal; however, some participants reported disregarding the colours and were satisfied if they were able to keep all the bars high. To remind the reader, only the middle bar became green when it was high while the side bars became green when they were low. These participants disregarded the colour despite reminding them about the connection between height and colour. Goal 3, similar to goal 2, risks ignoring the colour of the bars, where some participants reported satisfaction in keeping the bars stable despite the bars being red. Goal 4 was associated with the study's goal; however, only relying on the end score suggests that the participant may not be paying attention to their real-time EEG feedback. This feedback is an important part of neurofeedback that cannot be initially implemented without it. Table 8.3 displays how many goals were used by each participant, showing that majority of participants used more than one goal (mean = 1.90, SD = 0.700). Table 8.3 displays how many participants used each goal, showing that goal 1 and goal 2 were the most used goals. It is unknown whether participants used different goals simultaneously or one at a time as this was not systematically asked during the interviews. Four participants were not included in the goals analysis as they did not report a specific goal, and reported that they "could not tell" their status of performance at the neurofeedback task.

Table 8.2 Number of goals used by participants

	Three Goals	**Two Goals**	**One Goal**
n* (Out of 31)	6	16	9

n = No. of participants

Table 8.3 Prevalence of use of each goal

Goal	% of Participants Using Goal (Out of 31 total participants)
1. Keeping bars green	59% (n = 19)
2. Controlling height	50% (n = 16)
3. Stabilising bars	31% (n = 10)
4. Increasing end score	25% (n = 8)
5. Seeing more green	9% (n = 3)

8.2.2 Information Overload

Twenty-four participants (69%) focused on regulating one bar to accomplish the neurofeedback task. Participants who focused on regulating more than one bar were further questioned on details of their focus (at time of questioning, this probe was to clarify their perceived performance of the bars, not to understand the influence of the display). This probe revealed that these participants were focusing on regulating one bar then switching to another bar, they did not focus on regulating multiple bars at once. Ten participants (29%) did not focus on any particular bar, but instead focused on the general colour of the screen. This indicates that participants could not focus on more than one piece of information from the screen at a time when attempting the neurofeedback task.

Eleven participants (31.43%) reported that the movement of the bars distracted them from performing the neurofeedback task, indicating that the feedback display itself may have hindered their neurofeedback performance as evidenced by the following example quotes:

"*[The bars] were a lot more active than I was expecting them [to be], they moved around a lot and changed colour a lot more than I was expecting. So it was quite hard to connect them with what I was doing*" – P24A

"*I think… that seeing the bars [were] distracting me from keeping focus on the [mental] strategy*" – P6A

"*[The] bars going up and down all the time, it becomes frustrating*" – P3B

Participants P6A and P3B attempted to improve their neurofeedback performance by focusing on the general colour of the screen rather than the individuals bars, as indicated by the quotes below. These quotes are in response to the question "how much focus was on the screen?"

"*Pretty much none… I was probably looking at my hands more than anything or looking just below the screen, and if it was kind of like a darker glow I knew that the bars were [green]… because I think I knew my strategy was working so I just focused on [my mental strategy]*" – P6A

"*I think [my focus] was mostly on the mental strategy, which then manifested itself in a smoothing of the bars on the screen, more green bars*" – P3B

8.3 Discussion

This chapter qualitatively examined the relationship between the interface design and mental behaviour during neurofeedback training. The most widely used type of mental strategy, "display-related", was directly inspired by the interface design. Through informal interactions with participants (e.g. chatting while equipment was attached to the participant), it was observed that neurofeedback was a novel task to all participants in this study. Participants did not have previous knowledge or experience of neurofeedback and relied on information provided by the feedback interface to inform their mental behaviour, such as thinking of green scenery. This indicates that the interface design may dictate intuitive responses to accomplish the neurofeedback task. This is supported by the results of this chapter and the implications for future research is discussed below.

Participants created their own goals to assess their neurofeedback performance, where not all goals aligned with the study's goal. Individuals who use unaligned goals may risk incorrect control of their EEG activity. It is important to note that these goals were created despite reminders of the instructions to "make the bars green", indicating that the instruction itself was vague and can be interpreted in various ways. Multiple pieces of information provided by the feedback interface may have also contributed to the creation of these goals. For example, neurofeedback performance can be assessed by either focusing on the colours of the bars or the height of the bars. This suggests that participants may have been overloaded with information resulting in inapplicable interpretation of task instructions. It was also found that no participant could focus on all three bars at the same time and that a third of participants reported that the display itself was a distraction, further suggesting information overload. This information overload is likely due to confusion in making sense of the interface rather than too much information being provided to the participant.

This is because the interface design is relatively simple: the bars change colour and height. Other neurofeedback interfaces have more complicated designs such as moving an object across a screen within set boundaries (similar to the game Pong) [269] or moving and selecting letters from an array of random letters to spell out various words [270]. These neurofeedback studies report success rates of approximately 75% suggesting that participants did not have much difficulty in achieving the neurofeedback task. Although there are other factors that may have contributed to this success rate (e.g. guidance given by the neurofeedback trainer, discussed in more detail in the next chapter), it is possible that participants made sense of moving an object or spelling a word despite relatively complicated interface designs. It is also possible that the mental strategies used for moving an object or spelling a word is simpler than the mental strategies required to turn red bars to green.

Successful performance with complicated designs can also be seen outside of neurofeedback research, within the video gaming industry. For example, a video game called Dragon Age: Inquisition provides an interface with multiple pieces of information (health bar of four different characters, status of potion and magic effects, status of characters' special powers, local map, location of enemies, and more). Yet this complexity is not a hindrance as most players can make sense of the information provided by the interface. Thus, complex interfaces are suitable if individuals can make sense of the design. The creation of success goals and ignoring parts of the interface within this study were likely methods for participants to make sense of the neurofeedback task. This concurs with literature stating that human beings may create or ignore certain information in an attempt to make sense of their environment [271]. This is not an adverse phenomenon, but rather an adaptive skill that allows individuals to better focus on the task at hand. This is shown in the famous change blindness study that asked 228 participants to count how many times the people in a video pass a ball to each other [272]. Participants were able to count the passes but only 44% of participants noticed that a man in a gorilla suit walked through the video. The study explained that the gorilla was irrelevant information to the counting task, and was thus ignored by 56% of participants. Berg and Hoffrage [273] show that information is consciously ignored with the perceived prediction that it will lead to the maximum payoff in a given environment. The information overload found in this thesis is likely related to confusion over the interface display rather than too much information provided to the participants.

Overall, the findings of this research suggests that the interface design strongly influenced the mental behaviour of participants. This relates to the findings of Siniatchkin et al [257], who demonstrated that knowledge of the neurofeedback conditions were more important than mental strategies. Knowledge of neurofeedback conditions may also involve interpretation of the interface design, which can be facilitated by appropriate user interface development by researchers. The current feedback interface needs to be re-designed to facilitate engagement in the neurofeedback task. It is important to note that the current feedback interface is commonly used in other research and commercial neurofeedback systems. However, the development of these designs are not reported and, thus, it is unknown whether this development involved behavioural examination and participant feedback in relation to neurofeedback learning.

Designing a feedback interface to facilitate neurofeedback training will need careful consideration, which can be informed by findings from other studies. Kosmyna and Lécuyer [274] provides a sensible guide that deliberates important factors when designing a brain-computer interface. This guide suggests considering three main traits: timing of the feedback, the type of information given to participants, and the method of providing this information. Each of these traits are broken down into detailed components to assist in designing an appropriate feedback interface. While this detailed guide has potential value, it needs to be formally examined to determine the extent of its practical value. Zapała et al [275] suggests that providing task progress as well as highlighting the important information improves neurofeedback performance. The current feedback interface presents task progress in the form of the end score, but it was only shown after each neurofeedback training run. Task progress may be improved by presenting the score continuously throughout each run. Highlighting the positive feedback (green colour of the bars) and dimming the negative feedback (red colour of the bars) may also improve performance. It is possible that the final design may be entirely different to the current design, where the three bars may not be used at all. Kober et al [276] and Lécuyer et al [277] found that using a 3D, virtual reality design improved neurofeedback performance compared to a 2D design, as participants had more interest in accomplishing the neurofeedback task [276]. Alimardani et al [278] found that using feedback that is more realistic (e.g. a human hand instead of a robotic hand [278]) improves neurofeedback performance. Thus, creating a 3D feedback interface that features realistic situations familiar to participants may aid performance compared to the 2D bars of the current interface. Creating a 3D, realistic interface will require considerably more resources than a 2D interface; however, improving the interface design will ultimately assist in implementing neurofeedback as a treatment for CNP after SCI.

Beyond neurofeedback literature, research on general interface design may provide further support. Galitz [279] puts forward 14 steps that should be followed when designing a general interface that can be applied to neurofeedback interfaces, examples of some of these steps are as follows: knowing your users (step 1), developing appropriate navigation (step 4), and test-retesting of the interface (step 14). Galitz [279] also emphasises the success of a well-designed interface is based on the understanding of user behaviour, particularly how users innately react to the information provided by the interface. This not only includes what information is provided, but also how the information is provided (also emphasised by Kosmyna and Lécuyer [274]). The main information for the current neurofeedback system was the feedback signal for theta, alpha, and high beta. However, findings from this chapter show that participants struggle to focus on all three feedback signals at once, thus risking the possibility of individuals with CNP after SCI not receiving pain relief because they failed to regulate all three EEG frequencies. A more suitable presentation may be to condense the three feedback signals into one, where a positive signal is provided when all three EEG frequencies cross their respective thresholds. Thus, one bar instead of three bars may be provided to the user. However, it is questionable whether the representation should be a bar at all. As discussed previously, current research suggests that a realistic, 3D representation facilitates neurofeedback learning more than abstract, 2D representations. This further complicates the development of an interface design for the current neurofeedback system, as it is unknown what a realistic, 3D representation will look like in the context of relief for CNP after SCI.

Although the interface design seems to be important for mental behaviour, there is little information on whether or not change in design influences neurofeedback success. This influence must therefore be inferred from the broader literature on interface design. Liu and Osvalder [280] compared a graphical display (the new interface) to a numerical display (the old interface) of a ventilator machine to examine whether or not the new design reduced ventilation treatment errors made by nurses. They found no differences in error rate; however, the nurses preferred the graphical display over the numerical display. The preference was related to quicker detection of information even at a distance, resulting in quicker response times from nurses. Liu and Osvalder [280] suggest the knowledge and experience of the nurses plays a more crucial role in error rates than the interface design. This is unsurprising; an interface can only display information, the interpretation is dependent on the user. However, neurofeedback users likely do not have the knowledge to correctly interpret information provided by the neurofeedback interface; as stated previously, neurofeedback tasks are preformed through trial-and-error. The findings from Liu and Osvalder [280], however, shows that it is possible to ease detection of information. This is important to consider for the current neurofeedback system as participants reportedly could not detect all the information provided by the interface at once; this may have reduced their ability to appropriately interpret the information to achieve the neurofeedback task.

Tadema and Theunissen [281] show that combining important air traffic information on a flight control interface improved air traffic assessment by pilots during flight; it was suggested that combining information (e.g. in the current context, combining three bars into one) reduced the time taken for interpretation compared to separate information. Thus, the earlier suggestion of combining three bars into one bar may improve neurofeedback performance. Information integration is further supported by Wright et al's [282] meta-analysis of patient information interfaces in critical care environments; interfaces that integrated information produced quicker and improved responses from medical staff during their patient care. They also found that highlighting the important information in order to make relationships between data more visible also facilitated the care provided by medical staff; concurring with Zapała's [275] suggestion to highlight important features of the feedback signal to improve neurofeedback performance. Thus, neurofeedback performance can potentially be improved with appropriate changes in the interface design. Future research should investigate which design features facilitate neurofeedback learning using the support of both neurofeedback and general interface design literature.

8.3.1 Limitations

The main limitation to the findings of this chapter is that they are derived from an unexpected theme revealed during the interview analysis. A formal analysis may uncover further evidence concerning the relationship between the interface design and mental behaviour not found within the current findings. However, this can also be seen as one of the strengths of the explorative approach taken in this thesis, without which this finding would not have been revealed. Furthermore, these findings can inform future research about the relationship between interface design and neurofeedback performance, where experimental studies can be conducted to manipulate the interface design and determine its effects on neurofeedback performance. Another limitation was that only limited neurofeedback guidance was given to participants; they were only instructed to "make the bars green". It is likely that providing sufficient guidance may have led to different interpretations of the interface design. However, the misinterpretations (such as the creation of inapplicable success goals) were not expected, and thus these findings reveal the importance of an intuitive interface design to minimise these misinterpretations.

8.4 Conclusion

Neurofeedback is a novel task not previously encountered by most individuals who may consequently rely on information immediately presented to them, such as the interface design. This study suggests that the interface design has a considerable influence over mental behaviour during neurofeedback training, indicating that neurofeedback performance may also be influenced by the interface design. The findings may encourage other researchers to consider the interface design as a potential influencer of neurofeedback performance alongside the users' own ability. The limited attention currently given to the interface design should be addressed by future research given its potential influence on neurofeedback learning.

Chapter 9 General Discussion

This chapter commences by describing how this thesis addressed the research aim and objectives. It then progresses to summarise the findings from the three previous chapters (chapters 6-8) and this thesis's main contributions before discussing these findings in the light of current literature and their implications for practice and future research.

9.1 Summary of Thesis Aim and Findings

9.1.1 Thesis Aim and Objectives

This thesis aimed to better understand neurofeedback learning with minimum apriori assumptions using an exploratory approach. This was done by comparing data from in-depth interviews of mental behaviour during neurofeedback training and psychological measurements of general learning factors to EEG activity changes. This comparison provided a large dataset that emphasised the complicated behavioural nature of neurofeedback. While complicated, the findings have contributed new knowledge on neurofeedback learning; this contribution is detailed at the end of section 9.1. The research objectives are reiterated below, followed by their respective results:

1) *What mental behaviour(s) do participants use to succeed at neurofeedback?*
The in-depth interviews revealed detailed mental behaviours that were divided into 13 mental strategies (Actual Movement, Auditory, Breathing, Clearing Mind, Imagination, Imagined Movement, Memory, Moral Values, Non-Specific Focus, Numerical Task, Pain Memory, Planning, and Resolving Stress.) and 6 affects (Discontent, Excited, Happy, Mentally Tired, Neutral, and Relaxed). These mental behaviours were compared to neurofeedback performance; no clear relationships between them were identified. An additional theme, "to keep oneself stimulated", was found only in successful participants, indicating that this theme was likely relevant to facilitating neurofeedback learning. Finally, an unexpected finding revealed that the interface display (i.e. the three bars) influenced mental behaviours that may considerably affect neurofeedback performance.

2) *What is the relationship between general learning factors (i.e. LoC, SE, difficulty, and motivation) and neurofeedback performance?*

   Only SE was found to significantly correlate with neurofeedback performance, where SE increased with success at neurofeedback. Other general learning factors were not associated with neurofeedback performance.

4) *Do autonomic responses (i.e. heart rate, respiration, and galvanic skin response) directly relate to neurofeedback performance?*

   No direct relationship was found between any of the autonomic responses and neurofeedback performance.

9.1.2 Summary of Findings

Chapter 6 examines the qualitative results identifying the mental behaviour that occurred during neurofeedback training. Two types of mental behaviour were identified: 13 mental strategies and 6 affects. Mental strategies did not always induce the instinctive affect one would predict (e.g. Pain Memory induced the Happy affect), and the affect was not necessarily induced by the mental strategy (e.g. Discontent was induced by poor neurofeedback performance rather than by the mental strategy applied). An interesting finding was regarding the relationship between perceived success and whether or not participants tended to use the same mental strategy. Participants who perceived they were successful at neurofeedback performance tended to persist with the same mental strategy as neurofeedback training continued. Participants who perceived unsuccessful performance showed no particular trend towards changing or using the same mental strategy. Participants who were unsure of their performance tended to change their mental strategy. Whilst no specific strategy was associated with success, most participants who were successful suggested similar traits for a successful mental strategy: being calm and focused were reported to improve neurofeedback performance. Participants who perceived success and participants who were unsure believed that the neurofeedback task could be achieved; however, most participants who perceived unsuccessful performance believed that the neurofeedback task was not possible to achieve. This indicates that those who believe the task is achievable are more likely to engage with it.

Chapter 7 combines qualitative and quantitative data to understand how neurofeedback performance is related to mental behaviour, general learning factors (SE, LoC, difficulty (measured by task load) and motivation), and autonomic responses (ECG, RSP, and GSR). Before this examination, three different methods of identifying successful participants were compared: the thesis criteria (which included participants' perception of performance) produced the least number of successful participants (n = 15) compared to the threshold method (reaching the 10% +/- EEG threshold; n = 20) and time change method (changes in the correct EEG direction without needing to reach a threshold; n = 22). This showed that the method of defining success changed success rates, which likely would have changed the results of chapter 7. This thesis included participants' perception of success as a key component of successful performance because neurofeedback requires active participation of the user. No specific mental strategy or affect was associated with neurofeedback success; however, negative affects were weakly associated with non-successful neurofeedback performance. The emergent theme "to keep oneself stimulated" was associated with neurofeedback success as it was only found in successful participants; however, this theme was only found in eight successful participants. SE had a positive, moderate correlation with neurofeedback success (V1: r = -0.430, p = 0.010; V2: r = -0.505, p = 0.004; V3: r = -0.587, p = 0.001; V4: r = -0.461, p = 0.020). The relationship of all other learning factors were not statistically significant and had a low correlation with neurofeedback success; the same non-significant result was found for all autonomic responses. Pain relief was reported in 5 out of 10 CNP participants, but only 2 out of these 5 CNP participants reported EPR (expected pain relief, which was pain relief alongside a warm, pleasant sensation). Unfortunately the association of pain relief to EEG changes could not be examined due to data file corruption.

Chapter 8 examines the unanticipated influence of the interface design on mental behaviour during neurofeedback training; this was examined after the observation that 71% of participants used a mental strategy that was related to the interface design. Participants were found to create their own goals for success (controlling height instead of colour, trying to keep the bars green, increasing the end score, trying to "see more green", and stabilising the bars); not all of which aligned with the actual task goal. This creation of unaligned success goals indicates that the task itself may have been too vague and open to broad interpretations. Participants also reported being overloaded with information from the interface: participants could not focus on all the information at once and a third of participants reported the interface distracted them from focusing on the task. This information overload was likely caused by confusion in understanding the interface information, further supporting the vagueness of the task. Changing the interface to a more intuitive design to facilitate learning may improve neurofeedback performance.

9.1.3 Main Contributions

This thesis contributed to the current neurofeedback literature both in terms of study methods and findings. To the author's knowledge, this thesis is the first to examine neurofeedback learning using an explorative approach and combining in-depth qualitative interviews with quantitative measures of physiology signals (EEG, ECG, RSP, and GSR) and general learning factors (SE, LoC, motivation, and difficulty). This thesis is also the first to include users' perception of neurofeedback performance as part of the success criteria.

The main contribution of this thesis regards its mental behaviour findings. Firstly, this thesis highlighted the importance of measuring mental strategies and affect separately. Affect (specifically negative affect) was suggested to be more important than mental strategies for neurofeedback performance. Neither awareness/verbalisation of mental behaviour nor simply focusing on the feedback signal necessarily resulted in neurofeedback success, suggesting that other factors are also involved, such as implicit/innate learning or the guidance provided to participants. Perception of neurofeedback performance was associated with patterns in use of mental strategy that may be related to participants' belief in neurofeedback task achievability. Finally, SE was the only general learning factor that was positively correlated with neurofeedback success, suggesting that confidence is associated with achieving neurofeedback success. These findings contribute to current literature by emphasising which mental behaviours may be more important for neurofeedback performance and produces new answers for the question "what mental behaviours do users engage in during neurofeedback training?"

Beyond the relationship between mental behaviours and neurofeedback performance, an unexpected finding regarding the influence of the interface design on mental behaviours also contributes to current neurofeedback literature. This thesis found that users created their own success goals that did not always align with the actual neurofeedback goal and users reported being overloaded with confusing information that seemed to impede their performance. This finding contributes to current literature by identifying the interface design as a type of non-verbal guidance that users utilise when attempting to achieve the neurofeedback task. Overall, this thesis's main aim of better understanding neurofeedback learning was achieved and provided useful directions for future research (detailed in section 9.4).

9.2 Discussion

This section not only brings together the findings from chapters 6-8 but also considers other relevant topics, such as the findings' implication to current neurofeedback learning theories. This section is divided into the following: the implication of the interface design findings to findings from chapters 6 and 7, the trend in neurofeedback learning patterns, a comparison between the different neurofeedback success identification methods from chapter 7, a brief discussion on guidance for neurofeedback, neurofeedback learning theories, and a further discussion on the interface design. This section ends with general limitations, suggestions for future work, and a conclusion.

9.2.1 The Influence and Implications of the Interface Design on Mental Behaviour

This thesis explored the neurofeedback learning experience of individuals using a neurofeedback protocol designed to reduce CNP after SCI. This approach revealed an unexpected, yet important, finding: the influence of the interface design on the mental behaviour of neurofeedback users. This is a novel contribution to neurofeedback research as most current literature does not give importance to the interface design, where many studies do not justify their chosen design. The inefficiency problem may be partly caused by poor interface designs that do not facilitate, or worse, may even inhibit, neurofeedback learning. The influence of the interface design indicates that the findings from chapter 6 and 7 are dependent on the interface design. These findings are likely to change with changes in the interface design. For example, a more intuitive design may reduce confusion over the task resulting in an increased success rate. Changes in success rates may produce differences in the mental behaviour used by successful users compared to unsuccessful users. However, the interface design is dependent on the neurofeedback task. The current task for participants was to "make the bars green", which may need to be changed in order to facilitate neurofeedback learning. As this neurofeedback protocol was designed to induce pain relief in individuals with CNP after SCI, it may be advisable to create a task derived from pain management literature, such as imitating guided imagery used in cognitive behavioural therapy for chronic pain [283]. However, pain management methods are usually context-specific, developed for the individual's explicit situation, which may hinder clear identification of generally-applicable methods that can be adapted to a neurofeedback task. Yet, it is possible that examining the common link, if any, between these pain management methods may aid in informing the design of the current neurofeedback task, and thus inform the interface design. However, this does not imply that the interface design solely dictates neurofeedback performance. Once an appropriate interface is designed, neurofeedback learning can be re-examined to understand the factors that contribute to neurofeedback success.

An improved interface design may change the results of some of the general learning factors examined within this thesis. For example, task load (reflecting difficulty) was not associated with neurofeedback performance in this thesis; this may be because task load was instead related to the information overload from the interface design. Differences in task load may be revealed with an improved interface design, where the task load may reflect task achievability instead of confusion over the interface. It is difficult to say whether other factors, such as motivation, may change with an improved interface design. This is because evidence from previous research is inconsistent [109, 110, 129], resulting in ambiguity over whether or not these factors are related to neurofeedback learning. The interface design should first be improved before attempting to resolve this ambiguity. Section 8.3 discusses previous research on neurofeedback interface design, and provides advice on the general features a good neurofeedback interface design should consider: traits put forward by Kosmyna and Lécuyer [274] (timing of the feedback, the type of information given to users, and the method of providing this information), the provision of task progress [275], highlighting the important features of the feedback signal [275], using 3D instead of a 2D design [276, 277], and using a realistic over an abstract design [278]. Future research must examine how changes in the interface influence neurofeedback performance by designing experimental research comparing various interface that include analysis of qualitative (e.g. interviews) and quantitative (e.g. Likert scales) participant feedback. In practical terms, however, the interface design will likely develop alongside this examination as optimal design features may only become apparent with ongoing research and use of the neurofeedback system. Overall, the use of in-depth, qualitative analysis in this thesis contributed to a better understanding of mental behaviour during neurofeedback training by revealing the influence of the interface design, which can be potentially modified to actively facilitate neurofeedback learning instead of being a passive tool.

9.2.2 The Trend in Learning Patterns

The examination of perceived learning pattern trends contributed to the current neurofeedback literature by suggesting that satisficing and achievability beliefs influence neurofeedback learning. Other research has quantitatively examined beliefs in the form of LoC (e.g. [88, 131, 133]), but none, to the knowledge of the author, have investigated beliefs qualitatively. Learning patterns (changing or using the same mental strategy) were previously related to the concept of satisficing (section

6.3.2), where participants may have perceived neurofeedback performance based on their own satisfactory threshold of “more green”. Before discussing this concept further, it is important to note that “satisficing” is used to describe solutions that are non-optimal yet satisfy a given threshold that is considered “good enough” by the individual [284]. For example, satisficing is comparable to “looking for a needle sharp enough to sew with” while optimising is “looking for the sharpest needle” [285]. However, the threshold for “sharp enough” is dependent on the materials being sewn. Similarly, the threshold for “more green” is dependent on the goal of the neurofeedback task. However, a pre-assigned “greenness” threshold was not set for participants to target. It was thus unsurprising that participants created their own goals for success. Even within these goals, the participants did not report a specific goal (e.g. “high bars” were not reported with definitions such as “bars were high enough if they reached two-thirds of its potential height”). However, a limitation here is that this finding was only discovered after the interview data were collected, meaning that participants had not been explicitly asked about their success goals during the interviews. Nevertheless, the lack of a defined goal may have caused participants to create their own goals that were dependent on their implicit threshold for “greenness”. This may explain why some participants changed their mental strategy while others continued with the same mental strategy; as mentioned in section 6.3, those who perceived themselves successful may tend to use the same mental strategy because it satisfied (or satisficed) their implicit threshold for “greenness”. Unsure participants tended to change their mental strategy, suggesting a satisficing mental strategy was not found. However, no learning pattern was found for participants who perceived themselves unsuccessful or unsure (i.e. these participants did not trend towards either changing or using the same mental strategy). This casts doubt on the satisficing concept relating to neurofeedback, as it would be expected that these participants would show a trend for changing their mental strategy. This lack of trend may be due to sample size or because of the belief that these participants held about the achievability of the neurofeedback task: most of these participants believed that it could not be achieved. This may explain why no particular learning pattern was observed; an implicit threshold for “greenness” may not have been formed or was abandoned once this belief developed. Including a defined goal within the interface design (e.g. a counter showing whether or not you passed a pre-defined threshold for “greenness”) may allow for a clearer distinction between successful and unsuccessful performances and facilitate neurofeedback learning. Nevertheless, this thesis contributed to current neurofeedback literature by highlighting the influence of task achievability beliefs on neurofeedback learning and suggests that future research further investigate this influence.

It is possible that the observed learning pattern is not related to the interface design; it may instead be related to metacognitive abilities. As mentioned in section 3.2.2, metacognition is the ability to think about one's own thinking [122], where some participants may not be aware of their mental behaviour during neurofeedback to be able to verbalise it. This awareness may also influence participants' perceptions of their neurofeedback performance: individuals who are not aware of their mental behaviour may struggle to associate this behaviour with their performance. Weaker metacognitive abilities may be the cause of "unsure" participants being unable to report their performance status. However, this explanation is doubted because some participants in this study were able to perceive successful performance but could not verbalise their mental behaviour(s). Furthermore, participants from Kober et al [98] who had 'no mental strategy' (i.e. could not verbalise their mental strategy) were more successful than those who had a mental strategy (i.e. could verbalise their mental strategy); this raises further doubts about the need for high metacognitive abilities for neurofeedback learning.

9.2.3 Methods for Identifying Neurofeedback Success

It was interesting to observe the difference in the number of participants who were identified as successful (n = 15) compared to the number of participants who perceived they were successful (n = 18), as mentioned in section 7.2.1. This difference suggests that some participants tended to overestimate their neurofeedback performance. However, this direction changes when only using EEG measures to identify successful participants (n = 20 with the threshold method and n = 22 with the time change method), suggesting that some participants tended to underestimate their neurofeedback performance. The change in direction is due to the thesis criteria for identifying successful participants, which required participants to correctly report their neurofeedback performance. However, this may not be related to over or under estimating performance; Instead, this may be related to a disparity in their expectations of what success looks like and what was happening on the neurofeedback interface. Designing a more intuitive interface may resolve this issue; however, this reflects a limitation of neurofeedback in general: the goal given to participants is not what the researcher is examining. This study instructs participants to "try and make the bars green". Yet, examination of success is not based on whether the participants can "make the bars green", but the examination of EEG activity. The bars are only a representation and not a direct display of EEG activity. The representation presented to the participants includes artefacts, such as body movements; however, these artefacts were removed by the researcher in preparation for examination of 'actual' EEG activity. Therefore, the "underestimation" of neurofeedback performance may be because the participants' interpretation of "making the bars green" was not the same as the researcher's interpretation.

This explanation is supported by this thesis's contribution of the variety of success goals created by participants, some of which do not align with the researcher's success goal. This discrepancy of success between participants and the researcher may be a general risk across various neurofeedback systems. Participants may believe they are being successful or unsuccessful when the researcher observes the opposite. Therefore, it is critical to ensure that the represented feedback accurately captures the expected goal defined by the researcher; this further supports the importance of the interface design in neurofeedback learning. However, this thesis did not provide guidance (i.e. verbal directions regarding how to accomplish the neurofeedback task) to participants, only the instruction to "make the bars green". Such guidance may have reduced the discrepancy of success between the participants and the researcher. While guidance may reduce this discrepancy, the extent of the reduction is questioned. As it is not reported in current literature, it is unknown whether neurofeedback trainers recognise the difference in goals of the participants compared to the goals of the researchers. If this risk is not known to neurofeedback trainers, guidance may do little in addressing discrepancies in success criteria. Further research is needed to determine the extent of this risk. One way this can be done is to examine the relationship between the EEG represented to participants and the processed EEG that has its artefacts removed. Another way is to examine the extent to which participants understand whether their neurofeedback performance was due to voluntary changes in brain activity or due to artefacts such as body movements.

9.2.4 A Brief Discussion on Neurofeedback Guidance

Guidance is a factor not examined by this thesis, yet it should be considered by neurofeedback researchers. Neurofeedback requires active involvement of the user; however, this involvement is guided by the researcher who instructs the user of the neurofeedback task and supports them in identifying mental behaviours that improves neurofeedback performance. The quality of this guidance is likely to influence neurofeedback success rates; although current research does not examine this relationship, the literature acknowledges its importance [82, 88]. Strehl [88] considers neurofeedback treatment as a behavioural therapy, where the focal point is the user's behavioural ability to become successful at neurofeedback in order to induce a clinical outcome. Strehl [88] emphasises that neurofeedback treatment "*will always take place within a patient-therapist* *interaction*", where the therapist is the neurofeedback trainer. This suggests that neurofeedback learning can vary greatly even when using the same neurofeedback protocol and the same participants, as the approach to guidance can vary between trainers. This can be seen across the examinations of the current neurofeedback protocol by Hassan et al [8] and Vuckovic et al [286], where guidance was provided to their participants (specifics of guidance are unknown as it is not reported). In their studies, four out of five and twelve out of fifteen participants respectively were successful. These success rates (80%) are considerably higher than the success rate in this study (fifteen out of thirty-five participants, 43%). However, Hassan et al [8] and Vuckovic et al [286] had smaller sample sizes compared to this thesis and only used EEG measures to identify successful participants (i.e. they did not include participants' perception of performance), which also likely contributed to the difference in success rates.

Future research should examine guidance within the trainer-user relationship to understand the extent of its influence on neurofeedback performance. However, this requires understanding of what guidance looks like in the neurofeedback context. For example, what type of guidance should be given (e.g. appraisal or emotional guidance, or both) and when should this guidance be given? The SE finding within this thesis (SE moderately correlated with neurofeedback success) can be used to develop this guidance, as it suggests that boosting users' confidence and self-appraisal can influence neurofeedback performance. Thus, participants may benefit from appraisal and understanding how to effectively self-evaluate neurofeedback performance. This is supported by previous research in the general learning literature. For example, Margolis and McCabe [287] state that struggling academic learners benefit from guidance that emphasises recent learning-related successes (such as a good exam result) and the specific reasons for that success, which is a way to verbally improve self-efficacy. However, the influence of SE must be confirmed in future research before relying on it for guidance development. Once guidance is developed, it can be examined in experimental designs involving various conditions, where each condition provides a specific type of guidance and one condition provides no guidance.

9.2.5 Neurofeedback Learning Theories

It is important to relate the findings from this thesis to the neurofeedback learning theories mentioned in section 3.2. Operant conditioning [118] is the main learning theory put forward by neurofeedback literature to explain neurofeedback learning; mental behaviour is conditioned by providing reinforcements (rewards) (and sometimes punishments (penalties)) to encourage successful neurofeedback. These rewards refer to indicators of correct self-regulation of brain activity; for example, the current neurofeedback system rewards users with a green bar. However, section 3.2.1 argued that users are unlikely to perceive correct self-regulation as a reward, where the real reward would be a positive clinical outcome. However, operant conditioning requires the reward to occur immediately after a behaviour, otherwise the behaviour is only reinforced and not conditioned. Thus, section 3.2.1 suggested that mental behaviour during neurofeedback is not conditioned but reinforced; that section also suggested that reinforcement without conditioning indicates that the behaviour is only performed to achieve a goal. Reiterating the example from section 3.2.1, an injured individual may decide to engage in physiotherapy to regain mobility. Although the reward of mobility is not immediate, the individual engages in physiotherapy to achieve that eventual goal of mobility. This suggestion is somewhat supported by the following findings: (1) seven unsuccessful participants that reported the Neutral affect also reportedly gave up in attempting to achieve the neurofeedback study (section 7.2.3), suggesting they did not have a goal they wanted to achieve, and (2) most participants who perceived themselves to be unsuccessful (and were identified as unsuccessful) believed the neurofeedback task could not be accomplished (Table 7.6), therefore the “goal” could not be achieved. These two groups of unsuccessful participants continued to attempt the neurofeedback task yet they had a low desire to accomplish the task; this suggests that desirability plays a role in neurofeedback learning. However, confidence in this suggestion is uncertain as the thesis did not examine desirability. Furthermore, motivation scores were moderately high across all participants; however, as mentioned previously, this may be related to willingness to engage in the neurofeedback task rather than desire to achieve the task. The current discussion provides further uncertainty to the role of motivation, as it may also be possible that motivation influence task engagement and not neurofeedback ability. This may explain why there were moderately high motivation scores yet the interview data showed low desirability from some unsuccessful participants to accomplish the neurofeedback task. Further research is needed to establish the relationship between motivation and desirability to achieve the task, and whether desirability influences neurofeedback learning differently to motivation. Combining qualitative and quantitative research approaches may be useful in understanding this relationship; participants can be interviewed on their motivations and desires regarding accomplishing the neurofeedback task (e.g. asking participants about why they chose to participate in a neurofeedback study, and their levels of motivation/desirability during the neurofeedback training) and these interviews can be complemented by questionnaire data that measures their motivation and desirability.

Another neurofeedback learning theory is the dual-process theory [121], which states that both automated and controlled processes are required for effective neurofeedback learning. Specifically, controlled processes consist of self-instruction indicating that some level of mental behaviour awareness is needed for neurofeedback learning. However, the previously mentioned doubts regarding the need for high metacognitive abilities in neurofeedback learning (end of section 9.2.2) suggests that controlled processes are not necessarily required for neurofeedback learning; thus, the dual-process theory does not seem to align well with the data from this thesis raising questions about its suitability as an explanation for neurofeedback learning. Global Workspace Theory [123] stated that conscious reception of the feedback signal (i.e. the real-time representation of brain activity) triggers activity in the entire brain so that each cortical region contributes to neurofeedback learning. However, the only behavioural aspect required by this theory is conscious reception. This thesis revealed the behavioural complexity behind neurofeedback learning, thus conscious reception alone is not enough. This thesis cannot comment on the global activity presented in this theory as the thesis only measured EEG activity from one channel.

Although other learning theories have been put forward (e.g. awareness theory [125]), they do not satisfactorily explain neurofeedback learning. It appears that a new neurofeedback learning theory should be developed that addresses its behavioural complexity. Based on the findings within this thesis, new theories should consider the importance of the following behavioural concepts: SE, beliefs regarding neurofeedback achievability (i.e. outcome expectancy), negative affects, and the role of the interface design. Beyond these concepts, new theories should also address the relationship between implicit learning and neurofeedback learning. This thesis did not examine implicit learning but discussed it in relation to previous neurofeedback research (i.e. Kober et al [98] found that participants who could not verbalise their mental behaviour during neurofeedback were more successful than participants who could verbalise their mental behaviour) and regarding the satisficing concept (i.e. participants' of this thesis may have developed an implicit threshold for "greenness" to self-assess their neurofeedback performance). Furthermore, some successful participants in this thesis could not verbalise their mental behaviour yet knew they were achieving the neurofeedback task, concurring with findings from Kober et al [98]. Previous research and the current findings indicate that a considerable portion of neurofeedback learning is implicit, where explicit learning may not be required. However, the extent of this implicit learning is doubted as there were some successful participants in this thesis that could verbalise their mental behaviour. The dual-process theory [121] attempts to address the involvement of implicit and explicit learning, which states that both implicit (automated) and explicit (controlled) learning in its model. However, this theory states that both implicit and explicit learning are required for neurofeedback learning.

This findings of this thesis and previous neurofeedback research suggest that explicit learning is not as crucial as implicit learning. Thus, the dual-process theory may need to be re-developed to allow for different levels or a spectrum of interaction between explicit and implicit learning.

Future neurofeedback research may look to other fields for insight into learning. For example, Strehl [88] compares explicit and implicit neurofeedback learning to motor learning. Three overall stages are involved in motor learning [288]. The first stage is the "cognitive phase" that requires a high level of attention while initial motor movements are learned, where the learner will identify the "correct" movements through trial-and-error. The second stage is the "associative phase", where the learner will practice the "correct" movement to improve that movement. The final stage is the "automated phase", where the "correct" movement is executed reliably with little error. It can be seen how motor learning stages transitions from a deliberate, explicit process to an automated, implicit process. This can be translated to neurofeedback learning if neurofeedback is regarded as a skill, where initial attempts at neurofeedback are deliberate trial-and-error responses and later attempts become automated. Furthermore, this thesis previously suggested that neurofeedback users may learn to reduce unnecessary mental strategies over time (section 6.3.2) as participants who perceived successful performance were inclined to use fewer mental strategies. This suggestion can be compared to the above "associative phase" of motor learning, where individuals may learn to reduce unnecessary movements over time [245]. Thus, motor learning literature may assist in understanding explicit and implicit neurofeedback learning. Motor learning has been used to explain neurofeedback learning in the form of motor learning theory [124]; however, empirical research has only examined this theory within other biofeedback systems, such as heart rate biofeedback [124], not neurofeedback. Some research shows that neurofeedback can be used to improve motor learning [289]; however, this research does not examine the application of motor learning as an explanation for neurofeedback learning.

9.2.6 Implications for Individuals with CNP after SCI

In section 5.2, it was stated that there may be a difference in mental behaviour between able-bodied individuals and those with CNP after SCI. However, the findings showed no clear difference between the mental behaviours used by able-bodied participants and those used by CNP participants. This was also true for psychosocial factors and autonomic responses. This indicates that future neurofeedback learning research may not necessarily need to recruit individuals with CNP after SCI, only able-bodied individuals. The only difference that could be seen was between attrition rates, where 12% of able-bodied participants (3 out of 25) dropped out of the study compared to 70% of CNP participants (7 out of 10). This likely reflects the different motivation behind participating in this study as well as the different study burdens between able-bodied participants and CNP participants. Able-bodied participants participated in the study due to interest in the study topic, the financial incentive, or to contribute to research (as understood by the researcher through casual chats during the study procedure). Additionally, able-bodied participants did not have mobility issues, pain, or any severe physical health condition; therefore, these participants had a low participation burden compared to CNP participants. CNP participants, on the other hand, participated in the study to relieve their pain or to contribute to research that may assist in pain relief in the future (also understood via casual chats). Pain relief motivation is emphasised by two CNP participants who travelled over 4 hours to participate in the study. CNP participants also had a higher participation burden, as their mobility and chronic pain issues adds additional stresses when planning for an event. For example, some CNP participants had to arrange for patient transport or ensure their carer was available to come with them. Although attrition causes were not examined, the differences in motivation and participation burden may have led to considerably more CNP participants dropping out of the study. However, the pain relief motivation also indicates that CNP participants are more likely to continue study participation if the neurofeedback provided effective pain relief. This is in line with the pain findings from Chapter 7, where only two successful CNP participants reported EPR (i.e. the expected pain relief due to neurofeedback). One of these participants did not drop out while the other dropped out due to a non-study related reason yet stated that they would have otherwise continued with the study. While the findings did not show a difference in mental behaviour during neurofeedback, it emphasised the motivation and study participation burdens of CNP participants that may dictate attrition rates.

9.3 Limitations

Specific limitations of this research were reported at the end of chapters 6, 7, and 8; they will not be repeated here. The main limitation that should be considered regards generalisability for future neurofeedback systems: the interface design seems to influence mental behaviour and thus may dictate neurofeedback performance. Improving the interface design may change the findings from chapters 6 and 7. However, this work could not have been achieved prior to designing the interface, where, at the time, the design was thought to be adequate. Furthermore, these findings provided insight into the complexity of neurofeedback learning that informs future research of the importance and depth of behaviour involved in neurofeedback success.

As this study used convenience sampling, it is important to understand its implications. Convenience sampling is a type of non-random sampling that involves easy recruitment of individuals meeting the study criteria [290]. Easy recruitment addresses the practical issues of conducting a study, such as geographical proximity to the study site and time limit to conduct the study. This inherently leads to a biased participant sample as they were recruited from a specific environmental context [291]. For example, the able-bodied participant group of this thesis were recruited from a university environment; they may have characteristics inherent to that environment that may impact the findings, such as a younger age range contributed by the student population. Therefore, caution should be taken when generalising findings stemming from convenience sampling. Random sampling, or probability sampling, recruits participants at random from the targeted population, and is used to reduce the risk of bias as seen in convenience sampling [292]. For example, instead of recruiting participants from a single location, one may randomly select multiple geographical areas and randomly select a certain number of participants who meet the study criteria from those areas; this is called cluster random sampling. However, the practical restrictions of this research, such as limited funding and a single researcher conducting majority of the study within a time limit, did not allow for random sampling.

9.4 Future Research

This neurofeedback protocol seems to be a promising treatment for CNP after SCI; however, its success is dependent on the individual's ability to accomplish the neurofeedback task. Further research into neurofeedback may aid future guidance and maximise chances of neurofeedback success. Below are suggested directions for future research that extends the research reported in this thesis:

- The interface design should be optimised to ensure participants are not overloaded with information and reduce the risk of participants creating goals that do not align with the instructed task goal. Examining the designs in current literature, within areas of neurofeedback and general interface design, may provide ideal design features that facilitate neurofeedback learning.
- Re-examining neurofeedback learning with the updated interface design, specifically investigating the following:
    - Whether or not mental behaviour differs with changes in the interface design, and its impact on neurofeedback success

  - Whether or not SE continues to maintain a relationship with neurofeedback success
  - Understanding the influence of affect, particularly negative affect, on neurofeedback success
  - The use and extent of explicit versus implicit neurofeedback learning abilities
  - Examining the role of the theme “to keep oneself stimulated” in neurofeedback success
- Examining the relationship between metacognitive abilities and neurofeedback performance to understand the conscious effort needed for neurofeedback success
- Investigating the extent of the discrepancy between the researcher’s concept of success and the users’ concept of success in a given neurofeedback task
- Evaluating the influence of the type and quality of guidance provided by the neurofeedback trainers to users that result in successful neurofeedback performance
- Examining the difference between motivation and desirability in relation to neurofeedback performance
- Examining the relationship between global EEG activity and neurofeedback performance to understand implicit neurofeedback learning

9.5 Conclusion

Current neurofeedback literature does not report the behavioural complexity that is involved in neurofeedback training, which is exacerbated with the lack of reporting success rates. A small number of previous studies (e.g. motivation [109], LoC [129], and depression [115]) have aimed to address this by examining neurofeedback learning to provide insight into behavioural factors that influence neurofeedback success. Yet, the findings from these studies were inconsistent and conflicting, failing to provide clarity about behavioural influences. This may have been due to factors such as sampling (e.g. different sample sizes and populations), methods (e.g. varying neurofeedback protocols and behaviour questionnaires), and analysis (e.g. different success criteria). More importantly, previous research was not explicitly based on neurofeedback learning theories, such as operant conditioning or dual-process theory. The inconsistency prompted this thesis to explore neurofeedback learning by combining qualitative and quantitative methods to generate evidence-based directions for future research. The explorative approach attempted to avoid assumptions and provided flexibility during analysis, revealing a vast and complex dataset. The following are the key contributions of this thesis:

- To the author's knowledge, this is the first study to use an in-depth explorative, mixed methods approach to understand mental behaviours during neurofeedback learning.
- To the author's knowledge, this is the first study that combined objective (i.e. EEG activity) and subjective (i.e. user perception) criteria to categorise successful and unsuccessful participants.
- Mental strategies were not always associated with the expected intuitive affect, suggesting that emotional experience must be measured separately from mental strategies in future neurofeedback research.
- Perception of neurofeedback performance was associated with patterns in use of mental strategy (i.e. changing mental strategies or using the same mental strategy); this may be related to participants' belief in achievability of the neurofeedback task.
- Negative affect, not mental strategies, seemed to be associated with unsuccessful neurofeedback performance.
- SE was the only general learning factor to have a relationship with neurofeedback success, which is a finding not previously reported (as SE was not previously examined as a learning factor) to the author's knowledge.
- Awareness or verbalisation of mental behaviour did not seem to be a requirement for neurofeedback success, yet simply focusing on the feedback signal did not necessarily result in success. This suggests the involvement of other factors, such as implicit or innate learning, the guidance available to user, or other behavioural variables.
- An unexpected relationship was found between the interface design and mental behaviour during neurofeedback training, where participants created their own success goals and seemed to be overloaded with confusing information.
- The thesis demonstrated the complexity of behaviour involved in neurofeedback learning that future research should acknowledge when examining their own neurofeedback system.

Appendix A Consensus on the Reporting and Experimental Design of clinical and cognitive-behavioural Neurofeedback studies (CRED-nf): Best practices checklist (2020)

The below table is a checklist to uphold reporting standards for neurofeedback studies [185]. Darker shaded boxes represent *essential* checklist items; lightly shaded boxes represent *encouraged* checklist items.

Table A.1 CRED-nf Checklist

Domain	Item #	Checklist item	Reported on page #
Pre-experiment			
	1a	Pre-register experimental protocol and planned analyses	Not pre-registered
	1b	Justify sample size	P91
Control groups			
	2a	Employ control group(s) or control condition(s)	Not an experimental study; no control group involved
	2b	When leveraging experimental designs where a double-blind is possible, use a double-blind	N/A
	2c	Blind those who rate the outcomes, and when possible, the statisticians involved	N/A
	2d	Examine to what extent participants and experimenters remain blinded	N/A
	2e	In clinical efficacy studies, employ a standard-of-care intervention group as a benchmark for improvement	N/A
Control measures			
	3a	Collect data on psychosocial factors	P48-50
	3b	Report whether participants were provided with a strategy	P56
	3c	Report the strategies participants used	P65-74
	3d	Report methods used for online-data processing and artifact correction	P91-95

	3e	Report condition and group effects for artifacts	N/A
Feedback specifications			
	4a	Report how the online-feature extraction was defined	Reported in previous work [8]
	4b	Report and justify the reinforcement schedule	Reported in previous work [8]
	4c	Report the feedback modality and content	Reported in previous work [8]
	4d	Collect and report all brain activity variable(s) and/or contrasts used for feedback, as displayed to experimental participants	P55
	4e	Report the hardware and software used	P50-52
Outcome measures			
Brain	5a	Report neurofeedback regulation success based on the feedback signal	P102-106
	5b	Plot within-session and between-session regulation blocks of feedback variable(s), as well as pre-to-post resting baselines or contrasts	P103-104
	5c	Statistically compare the experimental condition/group to the control condition(s)/group(s) (not only each group to baseline measures)	N/A
Behaviour	6a	Include measures of clinical or behavioural significance, defined a priori, and describe whether they were reached	N/A
	6b	Run correlational analyses between regulation success and behavioural outcomes	P115-118
Data storage			
	7a	Upload all materials, analysis scripts, code, and raw data used for analyses, as well as final values, to an open access data repository, when feasible	Data will be uploaded to a depository by the University of Southampton when feasible

Appendix B Participant Information Sheets

B.1 Able-Bodied Participant Information Sheet

Study title: Investigating the processes of an EEG-based neurofeedback device in healthy individuals
Researcher: Krithika Anil **ERGO number**: 29852

Please read this information carefully before deciding to take part in this research. If you are happy to participate, you may be asked to sign a consent form.

What is this research about?
This research will evaluate a neurofeedback system. Neurofeedback is where your brain activity (here we will use electrical brain activity: EEG) is visualised for you with the aim of helping you to control it. The purpose of our neurofeedback system is to provide pain relief for people with central neuropathic pain (pain caused by damaged nerves) after a spinal cord injury. This study on healthy people without pain is about understanding how this EEG activity is controlled, and how physiology (heart and respiratory rate, and galvanic skin response) and physical sensations change during the neurofeedback. Understanding these topics will help us to develop the effectiveness of the neurofeedback, which will greatly help those with central neuropathic pain who seek pain relief.

Why have I been asked to take part?
You have been asked to participate in this study because you are between 18 and 69 years old (inclusive) and do not have, or ever had, any chronic pain conditions, brain injury, or any other neurological condition. This study focuses on people who do not have central neuropathic pain, so that we can make comparisons to people who do have this pain.

What will happen to me if I take part?
If you let us know that you are interested in taking part, we will send you this information sheet and ask you some simple questions to ensure you are suitable for taking part in the study. If you are, we will then invite you to come to the allocated study site. At this site, you will have the opportunity to ask further questions about taking part and be asked to give your written informed consent. <u>Taking part in the study will require you to attend the study site on four occasions, at least once a week</u>. Each visit will last between and 1 and 2 hours. During each visit, the following will happen:

1. We will ask you to give us some background information about yourself and your beliefs about control over responsibilities in daily life. We will be recording galvanic skin response, breathing and heart rate during the study. To do this, we will put a band around your chest (over your clothes) to record your breathing rate, and we will put electrodes on your fingers, wrists, and feet to record your skin response and heart rate. We will also ask you about any physical sensations you are experiencing at the time of the study.

2. You will then be asked to wear a headset, which will translate your EEG activity into a video on a tablet screen. The video will present your EEG as three moving bars, and you will be asked to try to control the movement of these bars through mental strategies of your choice.

3. After using the headset for about 30 to 45 minutes, we will again ask you about your control beliefs and any physical sensations you are experiencing. The headset will then be removed

and we will interview you about how you controlled the bars. This interview will last about 10-15 minutes and will be audio recorded. You may take breaks at any time during the study if you wish.

If you are uncomfortable with permitting us to put the equipment on you to record your physiological responses (band and electrodes), you may bring a friend along with you to attend the study while the equipment is being set up. Otherwise, you may ask the researcher to provide someone else to attend the study during the equipment set up. If you prefer not to have the equipment set up at all, you may still take part in the study without this equipment. Please let the researcher know if this equipment causes you any discomfort.

At the end of the four occasions, you will receive £40 for taking part in the study. If you take part in less than four occasions, you will be reimbursed for the number of occasions you attended for the study (£10 per occasion).

Will my personal details be confidential?
Yes. The researcher carrying out the study will maintain a record of your details in a secure location. All recorded data for further analysis will be anonymised. In accordance with the University of Southampton Research Data Management Policy, all significant research data will be held for a minimum of ten years after the end of the study. Informed consents forms and any other personal information will be kept in a secure and locked office and not be stored digitally. If you would prefer your anonymised data not be accessible to third parties at any time during or after the study, please inform the researcher. The University of Glasgow (main collaborator), The University of West of England and Stoke Mandeville Hospital (UK) are collaborating institutions of this study. University of Southampton, and Defence Science and Technology Laboratory (DSTL) funds this study with a view to improving recovery after injury. Any data that are shared with the mentioned organisations or future third parties will be anonymised.

What are the risks involved in taking part?
There is a very small risk of electric shock – though all devices are commercial equipment designed for safe use on humans. The simple purpose of the EEG device is to show you your EEG activity so that you can learn to control it. If you do feel any physical discomfort at all, you may ask to stop the study and withdraw from it. There are no known harmful side effects of this neurofeedback activity.

This study will ask you questions about topics about yourself that may make you feel uncomfortable. If this is the case, you do not have to answer any questions that you do not want to, and you are free to withdraw yourself and the data you have given to the study.

What happens if I change my mind?
Your participation is voluntary and you may withdraw from the study at any time. You do not have to give a reason for withdrawal and it will not affect your legal and medical rights.

What happens if something goes wrong?
In the case of concern or complaint, you should contact the Head of Research Governance (02380 595058, rgoinfo@soton.ac.uk). Please note that the researchers, supervisors or any other persons involved in the study will not deal with any complaints. If you experience any persisting psychological or physical discomfort after the study, we advise you to consult your GP.

Any further questions?
Should you require any further information regarding this study, please contact:
Krithika Anil (project researcher)
k.anil@soton.ac.uk

B.2 CNP Participant Information Sheet

Study title: Investigating the processes of an EEG-based neurofeedback device in people with central neuropathic pain after a spinal cord injury
Researcher: Krithika Anil
NHS Ethics Reference: 234857 **University of Southampton Ethics Reference**: 30254

Please read this information carefully before deciding whether or not to take part in this research. If you are happy to participate, you will be asked to sign a consent form.

What is this research about?
This research will test a neurofeedback system. Neurofeedback is where your brain activity (here we will use electrical brain activity, which is called EEG) is pictured on a video for you with the aim of helping you to control it. The purpose of our neurofeedback system is to provide pain relief for people with central neuropathic pain (nerve pain) after a spinal cord injury. This study is about understanding how this EEG activity is controlled, and how physiology (heart and respiratory rate, and skin sweat response) and physical sensations may change during the neurofeedback. Understanding these topics will help us to improve the neurofeedback, which will greatly help those with central neuropathic pain who seek pain relief. This study is a student project for the completion of a PhD, and has been reviewed and approved by the Berkshire REC committee.

Why have I been asked to take part?
You have been chosen for this study because:
- You are at least 18 years old
- Your spinal cord injury was at least one year ago
- You have had treatment for central neuropathic pain for at least six months
- Your pain is at least greater than or equal to five on a visual numerical scale (zero: no pain, ten: worst pain), and your pain is consistent
- You do not have/had a brain injury, epilepsy, stroke, or any other neurological condition

Do I have to take part?
No. Your participation is voluntary. There are no consequences if you decide not to take part; your legal and medical rights will not be affected. You will still receive your current care from your health professionals whether or not you decide to take part in this study.

What will happen to me if I take part?
If you let us know that you are interested in taking part, we will ask you some simple questions to ensure you are suitable for the study. If you are, we will then invite you to come to the allocated study site. At this site, you will have the opportunity to ask further questions about taking part and be asked to give your written informed consent. Your GP may be informed of your participation in this study, with your consent. This is to make sure your GP is informed of any research participation that may influence your pain. In the case of this research, your pain might be reduced.

A screening test will be conducted at the beginning of the study, and will only be done once. This screening test will be conducted to ensure you are eligible for participation in this study. The test is short, and involves answering four questions. The first two questions only require a verbal response from you regarding pain sensations; the next two questions involve a physical examination where the researcher will gently touch areas of pain to reveal traits of neuropathic pain (reduced sensitivity to touch or burning sensation). No other procedures are involved in the screening test.

After the screening test, you will arrange visits with the researcher to participate in the rest of the study. Taking part in the study will require you to attend the study site on eight visits, at least once a week. Each visit will last approximately 2 hours. During each visit, the following will happen:

4. We will ask you to give us some background information about yourself and your beliefs about control over responsibilities in daily life. We will be recording sweat response from your fingers, breathing and heart rate during the study. To do this, we will put a band around your chest (over your clothes) to record your breathing rate, and we will put sensors on your fingers, wrists, and feet to record your skin sweat response and heart rate. We will also ask you about any physical sensations you are experiencing at the time of the study.

5. You will then be asked to wear a headset, which will translate your EEG activity into a video on a computer screen. The video will present your EEG as three moving bars, and you will be asked to try to control the movement of these bars through mental strategies of your choice.

6. After using the headset for about 30 to 45 minutes, we will again ask you about your control beliefs and any physical sensations you are experiencing. The headset will then be removed and we will interview you to find out about how you controlled the bars. This interview will last about 15 minutes and will be audio recorded. You may take breaks at any time during the study if you wish.

If you are uncomfortable with permitting us to put the equipment on you to record your physiological responses (band and sensors), you may bring a friend along with you to attend the study while the equipment is being set up. If you prefer not to have the equipment set up at all, you may still take part in the study without this equipment. Please let the researcher know if this equipment causes you any discomfort. At the end of each study session, you will receive up to £30 to compensate you for travel to the study site.

Can I bring someone (a trusted other) with me while I do the study?
Yes. You may bring someone along with you during all visits of the study. This can be a friend, family member, carer, or anyone you trust to attend the study visits with you. This trusted other may also do any study-related written work (signing the consent form, completing questionnaires) for you, if you are unable to do so. To clarify, this trusted other will be doing the written work under your direct, explicit instructions. They cannot do any written work that you do not wish them to.

Will my personal details be confidential?
Yes. The researcher carrying out the study will maintain a record of your details in a secure location. All recorded data for further analysis will be pseudo-anonymised, where a participant identification number will be linked with personal information to arrange your study sessions. In accordance with the University of Southampton Research Data Management Policy, all significant research data will be held for a minimum of ten years after the end of the study. Informed consents forms and any other personal information will be kept in a secure and locked office and not be stored digitally. The University of Glasgow (main collaborator), Stoke Mandeville Hospital (main collaborator), and The University of West of England are collaborating institutions of this study. University of Southampton, and Defence Science and Technology Laboratory (DSTL) jointly funds this study with the aim of identifying ways to improve recovery after injury. Any data that are shared by the research team of the University of Southampton with these organisations, DSTL or future third parties will be anonymised (excluding Stoke Mandeville Hospital). This means the data will only be shared after removing all the links to the participant identification number and personal information. If you would prefer that your anonymised data are not accessible to third parties at any time during or after the study, please inform the researcher. Please see the end of this document for further details about how your data will be handled.

What are the risks involved in taking part?
The simple purpose of the device is to show you your EEG activity so that you can learn to control it, and therefore, nothing will be done to you. You might be concerned that this neurofeedback method may cause you pain. Current research does not indicate that this is a risk, so it is very

unlikely that the neurofeedback will cause pain. However, if you feel any painful sensations during the neurofeedback, please let the researcher know and the study will be halted. Other sensations (non-painful) may be induced by the neurofeedback. While these sensations are not painful, the study can be halted if these sensations causes you any discomfort. When the study is halted, the researcher will remove all research equipment from your person, and call for a trained clinical staff member to attend to any immediate distress you may have.

The questions we ask you about your control beliefs may make you feel uncomfortable. If this is the case, you do not have to answer any questions that you do not want to, and you may also ask to stop the study and are free to withdraw from it without giving any reason. You may also request that any data we have collected from you are destroyed. If you have any emotional distress caused by the study, an appointment with a clinical psychologist can be arranged so you may discuss this distress.

Electronic equipment will be used throughout the study to gather physiological data from you (EEG, heart rate, breathing rate, and skin sweat response). These equipment have been assessed and tested to ensure equipment safety for use in this study. However, in the unlikely case of equipment failure causing distress, the study will be halted immediately and you will be attended to by the researcher and a clinical staff member.

A headset will be used to gather EEG data, which may cause mild discomfort. If the headset is uncomfortable, the researcher will adjust the headset so that it sits comfortably. If the headset continues to cause discomfort for you, the study can be halted.

This study appreciates that you may have increased sensitivity to touch due to your neuropathic pain. Equipment used to gather physiological data will be put on your person, where most equipment will touch your skin directly (e.g., fingers, wrists, ankle, head). Before the equipment is put on, the researcher will detail where each equipment will go, where the equipment will only be put on your person if you agree to it. If this equipment causes any painful sensations after it is put on, please let the researcher know and the equipment can be removed immediately. If any painful sensations persist after the removal of the equipment, a clinical staff member will be called to attend to you.

Medical tape and liquid for sensors will be used in this study. These items may cause some discomfort, e.g., skin irritation. Both items are made to be sensitive for skin; however, a small sample of each will be put on your hands and neck at the start of the study. These samples will be checked several minutes later for any signs of irritation. The study will continue if there are no signs of irritation. If there are signs of irritation, the study will be halted. Additionally, the medical tape may cause some discomfort, as it may pull on hair when taken off. The researcher will take care when removing the tape.

During the neurofeedback, you will be asked to stay as still as possible. This may cause some mild discomfort. There are multiple opportunities to take breaks throughout the study, during which you may move your body to relieve any tension from staying still.

What happens if I change my mind?

Your participation is voluntary and you may withdraw from the study at any time. You do not have to give a reason for withdrawal and it will not affect your legal and medical rights. You also have the opportunity to ask any further questions during your first study visit before signing the consent form.

What happens if something goes wrong?
In the case of concern or complaint, you should contact the Head of Research Governance (02380 595058, rgoinfo@soton.ac.uk). You may also contact the Stoke Mandeville PALS (Patient Advice and Liaison Service; 01296 316042, pals.office@buckshealthcare.nhs.uk). Please note that the researchers, supervisors or any other persons involved in the study will not deal with any complaints. If you experience any persisting emotional or physical discomfort after the study, we advice you to consult your GP.

Any further questions?
Should you require any further information regarding this study, please contact:
Krithika Anil (Main researcher)

Tel: 07761657043
Email: k.anil@soton.ac.uk

Further Details About Your Personal Data

University of Southampton is the sponsor for this study based in the United Kingdom. We will be using information from you and your medical records in order to undertake this study and will act as the data controller for this study. This means that we are responsible for looking after your information and using it properly. University of Southampton will keep identifiable information about you until the study is completed, and will only use it for the purposes of carrying out our research. Data protection law requires us to have a valid legal reason ('lawful basis') to process and use your personal data. The lawful basis for processing personal information in this research study is for the performance of a task carried out in the public interest. Personal data collected for research will not be used for any other purpose.

Your rights to access, change or move your information are limited, as we need to manage your information in specific ways in order for the research to be reliable and accurate. If you withdraw from the study, we will keep the information about you that we have already obtained. To safeguard your rights, we will use the minimum personally-identifiable information possible.

If you have any questions about how your personal data is used, or wish to exercise any of your rights, please consult the University's data protection webpage (https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page). If you need further assistance, please contact the University's Data Protection Officer (data.protection@soton.ac.uk).

Buckinghamshire Healthcare Trust will use your name and contact details to contact you about the research study, and make sure that relevant information about the study is recorded for your care, and to oversee the quality of the study. Individuals from the University of Southampton and regulatory organisations may look at your medical and research records to check the accuracy of the research study. Buckinghamshire Healthcare Trust will pass these details to University of Southampton along with the information collected from you and your medical records. The only people in University of Southampton who will have access to information that identifies you will be people who need to contact you to arrange your study sessions or audit the data collection process. The people who analyse the information will not be able to identify you and will not be able to find out your name or contact details. Buckinghamshire Healthcare Trust will keep identifiable information about you from this study until the completion of the study.

For further information on the University of Southampton's privacy notice for research participants, please go to:
https://www.southampton.ac.uk/about/governance/regulations-policies-guidelines.page

Appendix C Questionnaires

C.1 Standardised Questionnaires

C.1.1 Douleur Neuropathique 4

To estimate the probability of neuropathic pain, please answer yes or no for each item of the following four questions.

PATIENT INTERVIEW

Q1. Does the pain have one of more of the following characteristics?		
• Burning	Yes	No
• Painful cold	Yes	No
• Electric shocks	Yes	No
Q2. Is the pain associated with one or more of the following symptoms in the same area?		
• Tingling	Yes	No
• Pins and needles	Yes	No
• Numbness	Yes	No
• Itching	Yes	No

PATIENT EXAMINATION

Q3. Is the pain located in an area where the physical examination may reveal one or more of the following characteristics?		
• Hypoesthesia to touch	Yes	No
• Hypoesthesia to prick	Yes	No

Q4. In the painful area, can the pain be caused or increased by:

• Brushing?	Yes	No

C.1.2 General Self-Efficacy Scale

Each item below is a belief statement about your general abilities. For each item we would like you to circle the number that represents the extent to which you the statement is true. Please make sure that you circle ONLY ONE number per item. Please answer as honestly as you can, you may ask any questions you may have to the researcher. This is a measure of your personal beliefs; there are no right or wrong answers.

Please rate the following statements with either:
1=Not at all true 2=Hardly true 3=Moderately true 4=Exactly true

I can always manage to solve difficult problems if I try hard enough	1	2	3	4
If someone opposes me, I can find the means and ways to get what I want	1	2	3	4
It is easy for me to stick to my aims and accomplish my goals	1	2	3	4
I am confident that I could deal efficiently with unexpected events	1	2	3	4
Thanks to my resourcefulness, I know how to handle unforeseen situations	1	2	3	4
I can solve most problems if I invest the necessary effort	1	2	3	4
I can remain calm when facing difficulties because I can rely on my coping abilities	1	2	3	4
When I am confronted with a problem, I can usually find several solutions	1	2	3	4
If I am in trouble, I can usually think of a solution	1	2	3	4
I can usually handle whatever comes my way	1	2	3	4

C.1.3 General Locus of Control Scale

Each item below is a belief statement about your general abilities with which you may agree or disagree. Please make sure that you circle ONLY ONE number per item. Please answer as honestly as you can, you may ask any questions you may have to the researcher. This is a measure of your personal beliefs; there are no right or wrong answers.

Please rate the following statements with either:

1=Strongly disagree	4=Slightly agree
2=Moderately disagree	5=Moderately agree
3=Slightly disagree	6=Strongly agree

Whether or not I get to be a leader depends mostly on my ability	1	2	3	4	5	6
To a great extent my life is controlled by accidental happenings	1	2	3	4	5	6
I feel like what happens in my life is mostly determined by powerful people	1	2	3	4	5	6
Whether or not I get into a car accident depends mostly on how good a driver I am	1	2	3	4	5	6
When I make plans, I am almost certain to make them work	1	2	3	4	5	6
Often there is no chance of protecting my personal interests from bad luck happenings	1	2	3	4	5	6
When I get what I want, it's usually because I'm lucky	1	2	3	4	5	6
Although I might have good ability, I will not be given leadership responsibility without appealing to those in positions of power	1	2	3	4	5	6
How many friends I have depends on how nice a person I am	1	2	3	4	5	6
I have often found that what is going to happen will happen	1	2	3	4	5	6
My life is chiefly controlled by powerful others	1	2	3	4	5	6

Whether or not I get into a car accident is mostly a matter of luck	1	2	3	4	5	6
People like myself have very little chance of protecting our personal interests when they conflict with those of strong pressure groups	1	2	3	4	5	6
It's not always wise for me to plan too far ahead because many things turn out to be a matter of good or bad fortune	1	2	3	4	5	6
Getting what I want requires pleasing those people above me	1	2	3	4	5	6
Whether or not I get to be a leader depends on whether I'm lucky enough to be in the right place at the right time	1	2	3	4	5	6
If important people were to decide they didn't like me, I probably wouldn't make many friends	1	2	3	4	5	6
I can pretty much determine what will happen in my life	1	2	3	4	5	6
I am usually able to protect my personal interests	1	2	3	4	5	6
Whether or not I get into a car accident depends mostly on the other driver	1	2	3	4	5	6
When I get what I want, it's usually because I worked hard for it	1	2	3	4	5	6
In order to have my plans work, I make sure that they fit in with the desires of people who have power over me	1	2	3	4	5	6
My life is determined by my own actions	1	2	3	4	5	6
It's chiefly a matter of fate whether or not I have a few friends or many friends	1	2	3	4	5	6

C.1.4 Multidimensional Health Locus of Control

Each item below is a belief statement about your medical condition with which you may agree or disagree. Beside each statement is a scale which ranges from strongly disagree (1) to strongly agree (6). For each item we would like you to circle the number that represents the extent to which you agree or disagree with that statement. The more you agree with a statement, the higher will be the number you circle. The more you disagree with a statement, the lower will be the number you circle. Please make sure that you answer EVERY ITEM and that you circle ONLY ONE number per item. This is a measure of your personal beliefs; obviously, there are no right or wrong answers.

Please rate the following statements with either:

1=Strongly disagree	4=Slightly agree
2=Moderately disagree	5=Moderately agree
3=Slightly disagree	6=Strongly agree

If my condition worsens, it is my own behavior which determines how soon I will feel better again	1	2	3	4	5	6
As to my condition, what will be will be	1	2	3	4	5	6
If I see my doctor regularly, I am less likely to have problems with my condition	1	2	3	4	5	6
Most things that affect my condition happen to me by chance	1	2	3	4	5	6
Whenever my condition worsens, I should consult a medically trained professional	1	2	3	4	5	6
I am directly responsible for my condition getting better or worse	1	2	3	4	5	6
Other people play a big role in whether my condition improves, stays the same, or gets worse	1	2	3	4	5	6
Whatever goes wrong with my condition is my own fault	1	2	3	4	5	6
Luck plays a big part in determining how my condition improves	1	2	3	4	5	6
In order for my condition to improve, it is up to other people to see that the right things happen	1	2	3	4	5	6

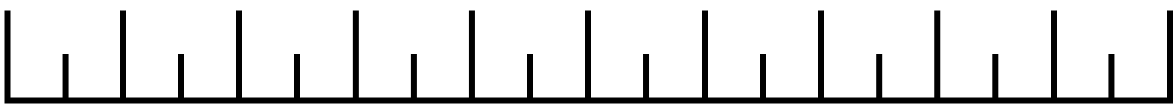
Whatever improvement occurs with my condition is largely a matter of good fortune	1	2	3	4	5	6
The main thing which affects my condition is what I myself do	1	2	3	4	5	6
I deserve the credit when my condition improves and the blame when it gets worse	1	2	3	4	5	6
Following doctor's orders to the letter is the best way to keep my condition from getting any worse	1	2	3	4	5	6
If my condition worsens, it's a matter of fate	1	2	3	4	5	6
If I am lucky, my condition will get better	1	2	3	4	5	6
If my condition takes a turn for the worse, it is because I have not been taking proper care of myself	1	2	3	4	5	6
The type of help I receive from other people determines how soon my condition improves	1	2	3	4	5	6

C.1.5 NASA Task Load Index

The following items ask you about your workload experience of the neurofeedback task. Workload involves the effort you put into the task and any stress or frustration you experienced. Rate each item by placing an X in the appropriate spot on the scale. Please answer as honestly as you can, you may ask any questions you may have to the researcher. This is a measure of your personal beliefs; there are no right or wrong answers. There is a second part to these items, which will start after completion of the below scales.

Mental Demand

Low *High*



Physical Demand

Low *High*

Temporal Demand

Low *High*

Performance

Good *Poor*

Effort

Low *High*

Frustration

Low *High*

C.1.6 McGill Pain Questionnaire – Short Form 2

The following items describe some different qualities of pain and related symptoms. Please rate the intensity of each item based on how you currently feel. Use 0 if the word does not describe your current feelings.

	None	*Lowest*									*Highest*
Throbbing Pain	0	1	2	3	4	5	6	7	8	9	10
Shooting Pain	0	1	2	3	4	5	6	7	8	9	10
Stabbing Pain	0	1	2	3	4	5	6	7	8	9	10
Sharp Pain	0	1	2	3	4	5	6	7	8	9	10
Cramping Pain	0	1	2	3	4	5	6	7	8	9	10
Gnawing Pain	0	1	2	3	4	5	6	7	8	9	10
Hot-burning Pain	0	1	2	3	4	5	6	7	8	9	10
Aching Pain	0	1	2	3	4	5	6	7	8	9	10
Heavy Pain	0	1	2	3	4	5	6	7	8	9	10
Tender	0	1	2	3	4	5	6	7	8	9	10
Splitting Pain	0	1	2	3	4	5	6	7	8	9	10
Tiring-exhausting	0	1	2	3	4	5	6	7	8	9	10
Sickening	0	1	2	3	4	5	6	7	8	9	10
Fearful	0	1	2	3	4	5	6	7	8	9	10
Punishing-cruel	0	1	2	3	4	5	6	7	8	9	10
Electric-shock pain	0	1	2	3	4	5	6	7	8	9	10
Cold-freezing pain	0	1	2	3	4	5	6	7	8	9	10
Piercing	0	1	2	3	4	5	6	7	8	9	10
Pain caused by light touch	0	1	2	3	4	5	6	7	8	9	10

Itching	0	1	2	3	4	5	6	7	8	9	10
Tingling or "pins and needles"	0	1	2	3	4	5	6	7	8	9	10
Numbness	0	1	2	3	4	5	6	7	8	9	10

C.2 Numerical Ratings Scales

C.2.1 Pain Intensity and Motivation

The below items asks you about your CURRENT state. Please make sure that you circle ONLY ONE number per item. Please answer as honestly as you can, you may ask any questions you may have to the researcher. This is a measure of your personal beliefs; there are no right or wrong answers.

Please rate the following items on a scale of 0 to 10 based on how you feel at the moment

	Lowest									*Highest*	
Pain Intensity	0	1	2	3	4	5	6	7	8	9	10
Motivation	0	1	2	3	4	5	6	7	8	9	10

Appendix D Blank Consent Forms

D.1 Able-Bodied Consent Form

Consent Form (A)

Study title: Investigating the processes of an EEG-based neurofeedback device in people with central neuropathic pain after a spinal cord injury

Researcher name: Krithika Anil
NHS Ethics Reference: 234857 **University of Southampton Ethics Reference**: 29852

Please read the following carefully, and then **initial the adjacent boxes** if you agree:

Please initial the boxes

1. I have read and understood the participant information sheet PISA.8 dated 03.07.2018 and have had the opportunity to ask questions about the study. ☐

2. I agree to take part in this research project and agree for my anonymised data to be used for the purpose of this study, for pseudo-anonymised data to be shared with Stoke Mandeville Hospital and for anonymised data to be shared with the University of Glasgow. ☐

3. I agree for my anonymised data to be shared with any current or future collaborators or third parties (excluding the University of Glasgow and Stoke Mandeville Hospital) to be used for research purposes (you may still take part in this study if you do not consent to this; please refer to the information sheet PISA.8 dated 03.07.2018 for information of current collaborators). ☐

4. I understand my participation is voluntary, and I may withdraw at any time for any reason without my rights being affected. ☐

5. I understand that my interview will be audio recorded, and direct written quotations may be published without revealing my identity. ☐

6. I understand my responses will be anonymised in reports of the research. ☐

7. I give permission to be contacted by phone/text/email during the study period. ☐

____
Participant ID

______________________________	______________	____________________________
Participant's name	Date	Signature
______________________________	______________	____________________________
Researcher's name	Date	Signature

D.2 CNP Participant Consent Form

Consent Form (B)

Study title: Investigating the processes of an EEG-based neurofeedback device in people with central neuropathic pain after a spinal cord injury
Researcher name: Krithika Anil

NHS Ethics Reference: 234857 **University of Southampton Ethics Reference**: 30254

Please read the following carefully, and then **initial the adjacent boxes** if you agree:

Please initial the boxes

1. I have read and understood the information sheet PISB.7 dated 03.07.2018 and have had the opportunity to ask questions about the study. ☐

2. I agree to take part in this research project and agree for my data to be used for the purpose of this study, and for pseudo-anonymised data to be shared with Stoke Mandeville Hospital and for anonymised data to be shared with the University of Glasgow. ☐

3. I agree for my anonymised data to be shared with any current or future collaborators or third parties (excluding the University of Glasgow and Stoke Mandeville Hospital) to be used for research purposes (you may still take part in this study if you do not consent to this; please refer to the information sheet PISB.7 dated 03.07.2018 for information of current collaborators). ☐

4. I understand my participation is voluntary and I may withdraw at any time for any reason without my medial or legal rights being affected. ☐

5. I understand that sections of my medical notes may be looked at by the research team and the regulatory authorities where it is relevant to my taking part in the research. I give my permission for members of the research to have access to my records only for the genuine purposes for this study. ☐

☐

6. I understand that my interview will be audio recorded and direct quotations may be published without revealing my identity. I understand my responses will be anonymised in reports of the research.

7. I give permission for my GP to be notified of my participation. ☐

8. I give permission to be contacted during the study period. ☐

9. I understand that I may have a trusted other to do all related written work (including this consent form) on my behalf (see information sheet PISB.7 dated 03.07.2018 regarding a trusted other's role). ☐

____
Participant ID

______________________________	_______________	____________________________
Participant's name	Date	Signature
______________________________	_______________	____________________________
Trusted other's name (Only use if participant is not signing themselves)	Date	Signature
______________________________	_______________	____________________________
Researcher's name	Date	Signature

One copy to the participant, one copy to the researcher, one copy for participant's notes

Appendix E Consolidated Criteria For Reporting Qualitative Research (COREQ)

The table below provides additional information regarding the interview methods and analysis.

Table E.1 COREQ Checklist

Topic	Item No.	Guide Questions/Description	Responses
Domain 1: Research team and reflexivity			
Personal characteristics			
Interviewer/facilitator	1	Which author/s conducted the interview or focus group?	KA (first author)
Credentials	2	What were the researcher's credentials? E.g. PhD, MD	BSc (Hons), MSc
Occupation	3	What was their occupation at the time of the study?	KA was a PhD candidate at the time of the study
Gender	4	Was the researcher male or female?	Female
Experience and training	5	What experience or training did the researcher have?	KA completed modules in qualitative and quantitative methods during their BSc and MSc. Further methodological training was completed during the PhD. KA also had experience working as a research assistant on a project related to the management of general chronic pain.
Relationship with participants			
Relationship established	6	Was a relationship established prior to study commencement?	No relationship was established with CNP participants prior to the study commencement. The first five recruited able-bodied participants were colleagues of KA.
Participant knowledge of the interviewer	7	What did the participants know about the researcher? E.g. personal goals, reasons for doing the research	During recruitment, KA explained the study aim and procedure. Participant colleagues of KA knew none of KA's personal or professional goals as KA had little contact with these colleagues prior to the study.
Interviewer characteristics	8	What characteristics were reported about the interviewer/facilitator? e.g. Bias, assumptions, reasons and interests in the research topic	KA was the lead researcher and had an academic interest in the study. No assumptions were made by KA. Bias was reduced by using an independent qualitative researcher to validate the data analysis.
Domain 2: Study design			
Theoretical framework			

Methodological orientation and Theory	9	What methodological orientation was stated to underpin the study? e.g. grounded theory, discourse analysis, ethnography, phenomenology, content analysis	This study was part of a mixed-methods design including qualitative and quantitate measures. Thematic analysis and a framework model was used for analysis.
Participant selection			
Sampling	10	How were participants selected? e.g. purposive, convenience, consecutive, snowball	Convenience sampling was used for recruitment.
Method of approach	11	How were participants approached? e.g. face-to-face, telephone, mail, email	Able-bodied participants were approached face-to-face. Able-bodied and CNP participants were also recruited using posters, and could volunteer for the study by contacting KA using the email or phone number listed on the posters.
Sample size	12	How many participants were in the study?	Thirty-nine initial participants (twenty-seven able-bodied and twelve CNP participants), reduced to thirty-five participants (twenty-five able-bodied and ten CNP participants) after four participants were removed due to unusable data.
Non-participation	13	How many people refused to participate or dropped out? Reasons?	No participants refused to participate. Ten participants (two able-bodied and eight CNP participants) dropped out due to perception of poor neurofeedback performance or non-study related events (unavailable transport, feeling unwell, or an unexpected personal event).
Setting			
Setting of data collection	14	Where was the data collected? e.g. home, clinic, workplace	Interviews were carried out at a designated study site at a university or the hospital.
Presence of non-participants	15	Was anyone else present besides the participants and researchers?	During one interview, a supervisor observed the study procedure. No third person was present at all other study procedures.
Description of sample	16	What are the important characteristics of the sample? e.g. demographic data, date	All participants were aged eighteen or over. Able-bodied participants had no chronic pain or neurological conditions. CNP participants had chronic neuropathic pain after a spinal cord injury, and had no other neurological conditions.
Data collection			

Interview guide	17	Were questions, prompts, guides provided by the authors? Was it pilot tested?	Interview questions were devised by KA and SD (second author, an experienced qualitative researcher and supervisor), and discussed within the research team. The interview questions were piloted with KA's colleagues who did not participate in the main study.
Repeat interviews	18	Were repeat interviews carried out? If yes, how many?	Four interviews on separate occasions were conducted per participant.
Audio/visual recording	19	Did the research use audio or visual recording to collect the data?	All interviews were audio-recorded.
Field notes	20	Were field notes made during and/or after the interview or focus group?	Brief field notes were made during the interview, and reflections were noted after each interview.
Duration	21	What was the duration of the interviews or focus group?	Interviews ranged from six minutes to forty-five minutes, but were generally fifteen to twenty minutes.
Data saturation	22	Was data saturation discussed?	Data saturation was discussed between KA (first author) and SD (second author), and were confident saturation had been achieved within the recruited sample.
Transcripts returned	23	Were transcripts returned to participants for comment and/or correction?	Transcripts were not returned to participants.
Domain 3: analysis and findings			
Data analysis			
Number of data coders	24	How many data coders coded the data?	KA coded all the interview data. An independent qualitative researcher coded transcripts of six randomly chosen participants.
Description of the coding tree	25	Did authors provide a description of the coding tree?	Coding is summarised in Chapter 6, detailing the categorisations of initial codes into the main theme.
Derivation of themes	26	Were themes identified in advance or derived from the data?	Themes were derived from the data.
Software	27	What software, if applicable, was used to manage the data?	Nvivo, version 12.
Participant checking	28	Did participants provide feedback on the findings?	No.
Reporting			
Quotations presented	29	Were participant quotations presented to illustrate the themes/findings? Was each quotation identified? e.g. participant number	Quotations are provided throughout the results of the paper to illustrate each theme. Quotation are identified by the participant number, and a 'A' for able-bodied participants and a 'B' for CNP participants.

Data and findings consistent	30	Was there consistency between the data presented and the findings?	The themes were derived from the data, therefore there is consistency between the data presented and the findings.
Clarity of major themes	31	Were major themes clearly presented in the findings?	The major themes are clearly presented within the paper.
Clarity of minor themes	32	Is there a description of diverse cases or discussion of minor themes?	Diverse cases and minor themes are presented in the results.

Appendix F Plots Comparing LoC Scores Between Able-Bodied Participants and CNP Participants

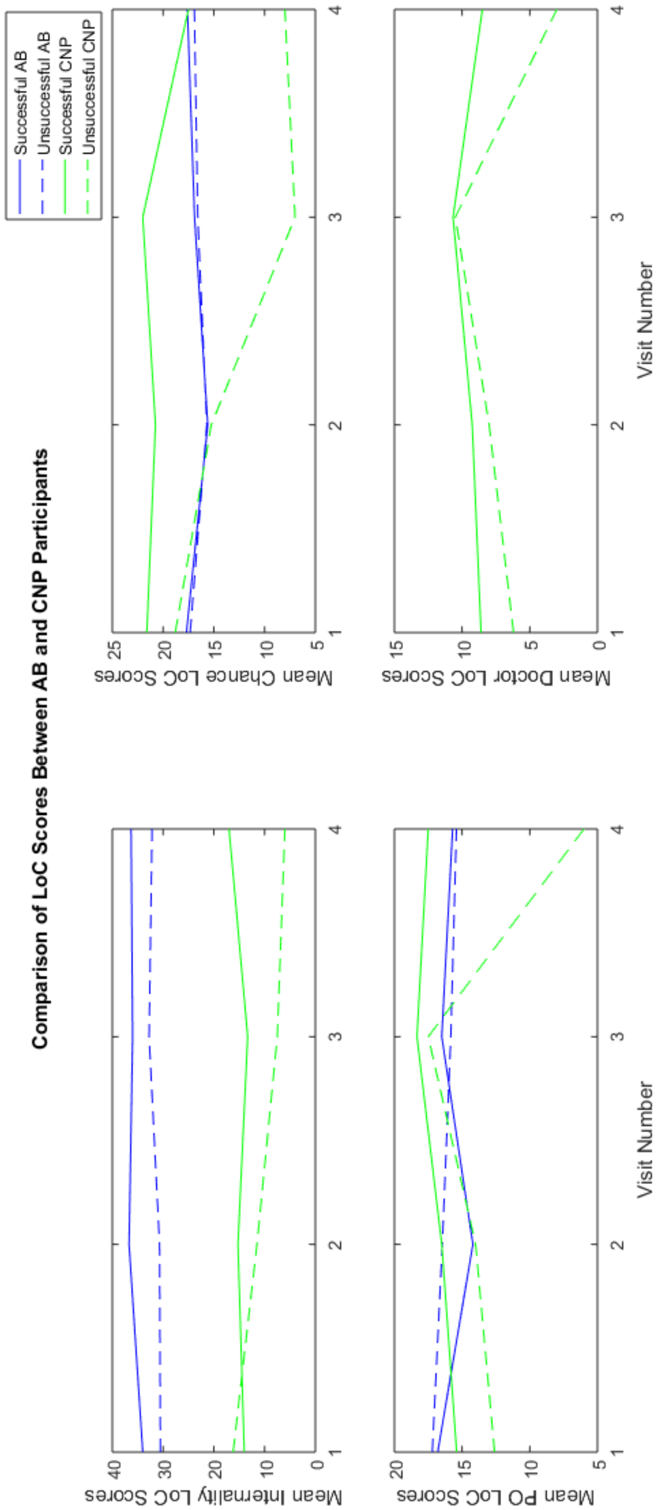


Figure F.1 Plots comparing the different dimensions of LoC between successful/unsuccessful able-bodied participants and successful/unsuccessful CNP participants. The dimension of "doctors" is only available to the LoC questionnaire completed by the CNP participant

Figure E shows that successful able-bodied participants and CNP participants have a similar trend in all comparable dimensions. However, from visit 3 to 4 of the “chance” dimension, “chance” LoC increase for the able-bodied participants while it decreases for the CNP participants. Similarly, from visit 1 to 2 of the “powerful others” dimension, “powerful others” LoC decrease for the able-bodied participants while it increases for the CNP participants. It is unclear why these opposing trends occurred; however, this finding is likely not meaningful as these opposing trends were not found consistently throughout the visits for these dimensions. The trends for unsuccessful participants in all comparable dimensions show neither a similar or opposing trend. The reason for this finding is unclear; it is speculated that there may be greater variation in control beliefs amongst unsuccessful participants. Findings from this graph must be taken with caution as LoC correlations for able-bodied participants were low and non-significant, and only 10 CNP participants completed the LoC questionnaire.

Appendix G The Relationship Between EEG And Autonomic Responses

G.1 Boxplots Showing The Relationship Between Success And Autonomic Responses

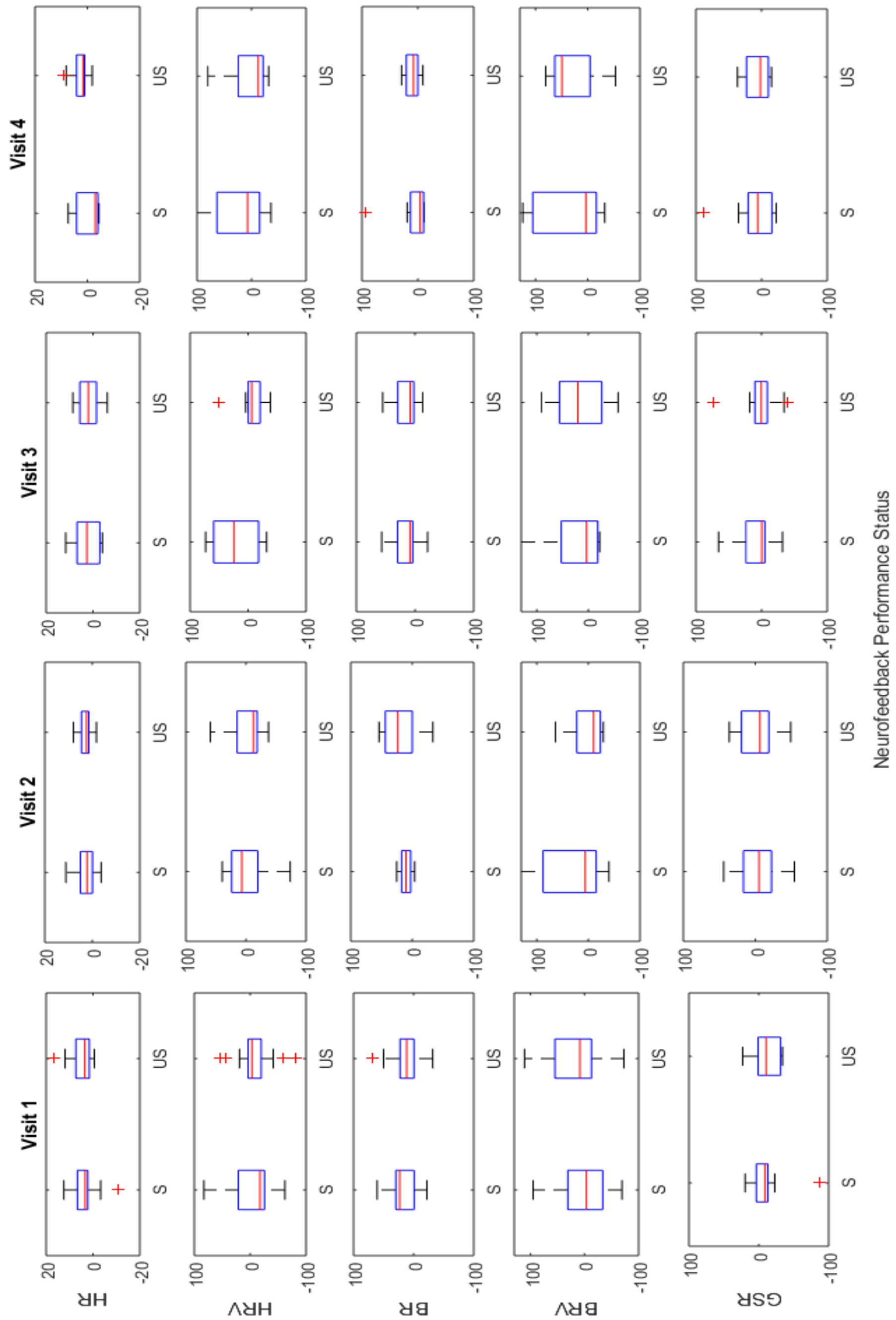


Figure G.1 Boxplots comparing success at neurofeedback (S = successful; US = unsuccessful) to relative change in autonomic repsonses (heart rate (HR), heart rate variability (HRV), breathing rate (BR), breathing rate variability (BRV), and galvanic skin response(GSR))

G.2 Scatter Plots Showing The Relationship Between Relative EEG Changes And Autonomic Responses

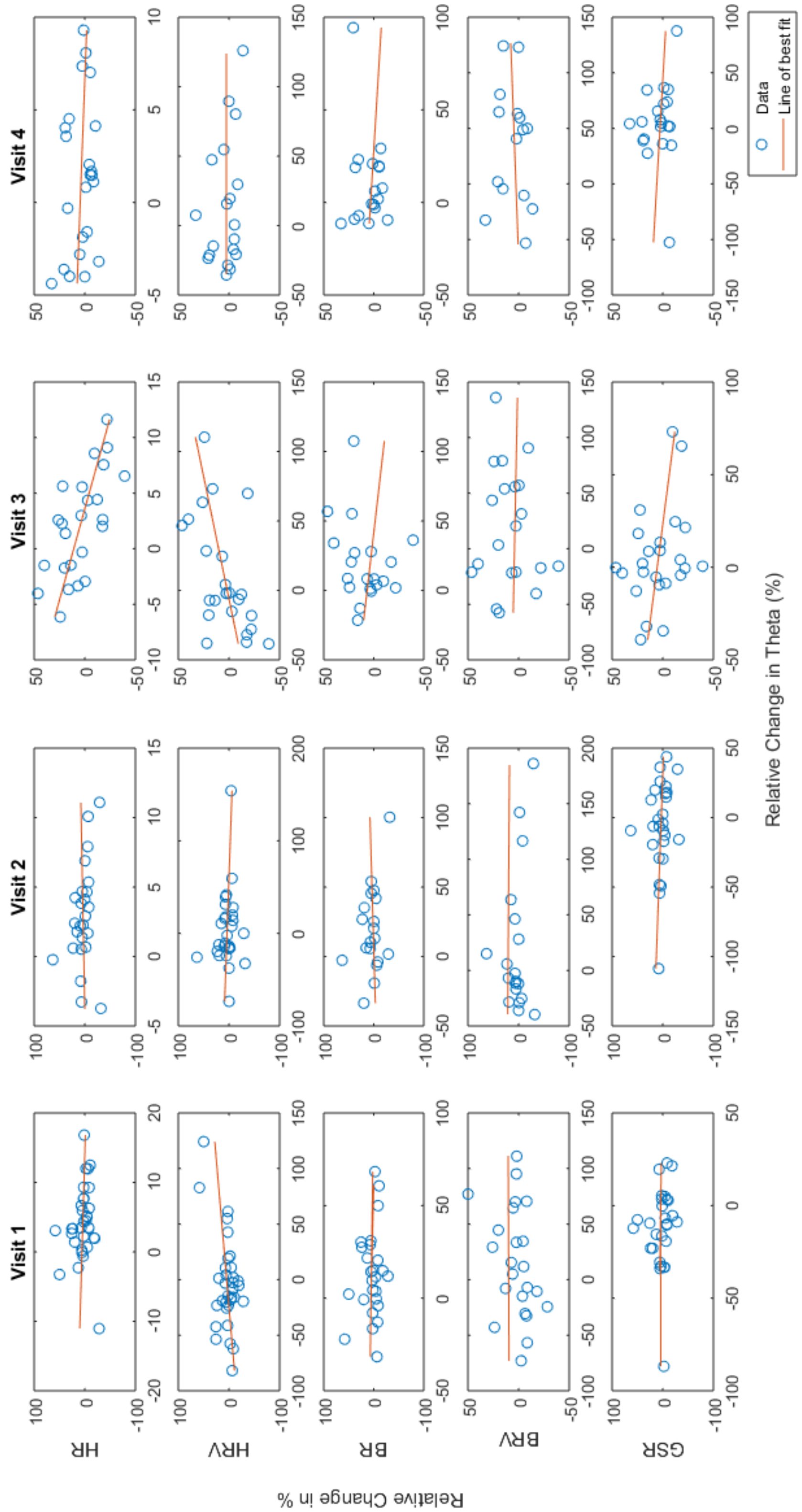


Figure G.2 Scatter plots comparing relative change in theta (%) to relative change in autonomic repsonses (heart rate (HR), heart rate variability (HRV), breathing rate (BR), breathing rate variability (BRV), and galvanic skin response(GSR))

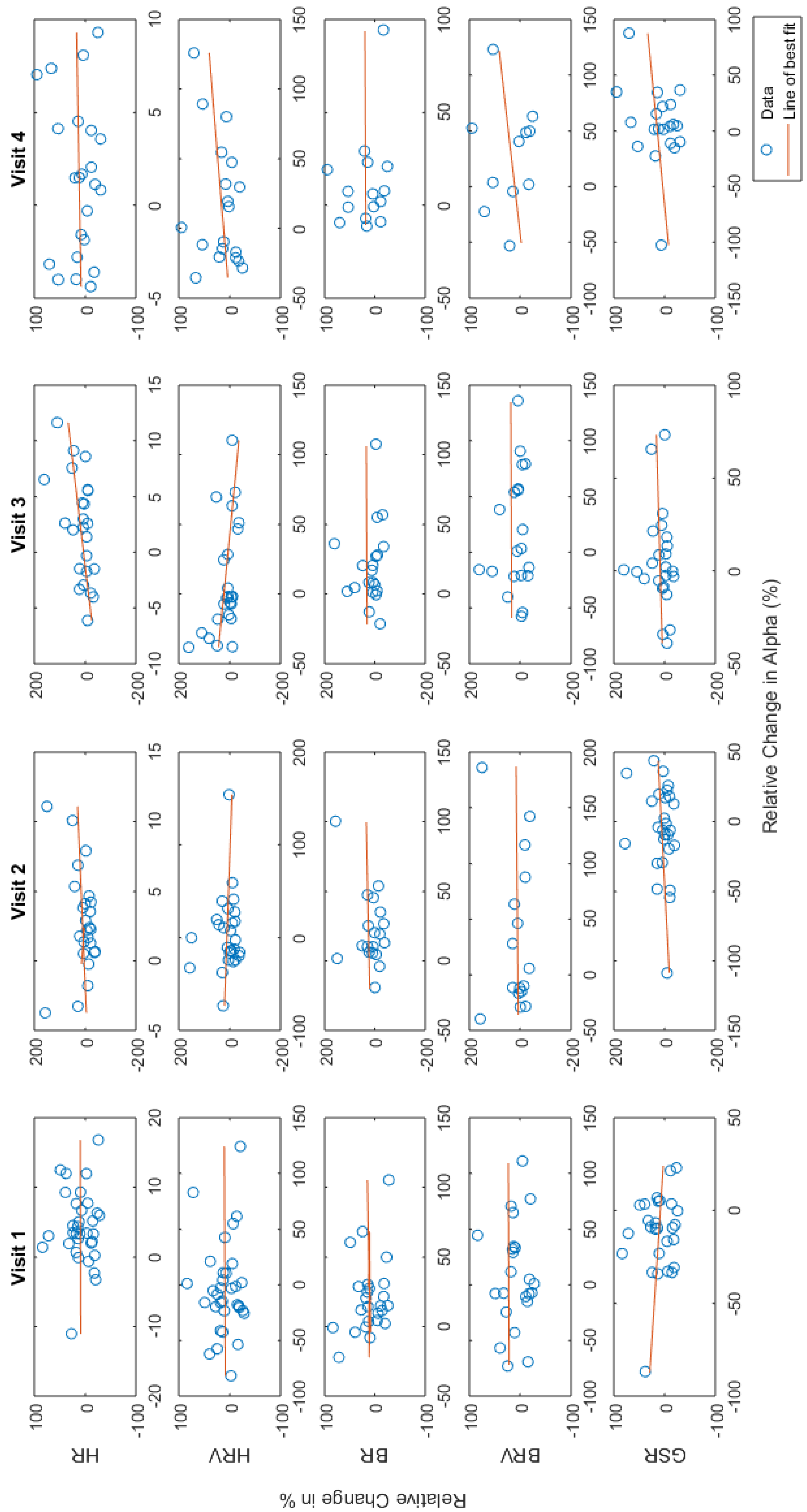


Figure G.3 Scatter plots comparing relative change in Alpha (%) to relative change in autonomic responses (heart rate (HR), heart rate variability (HRV), breathing rate (BR), breathing rate variability (BRV), and galvanic skin response(GSR))

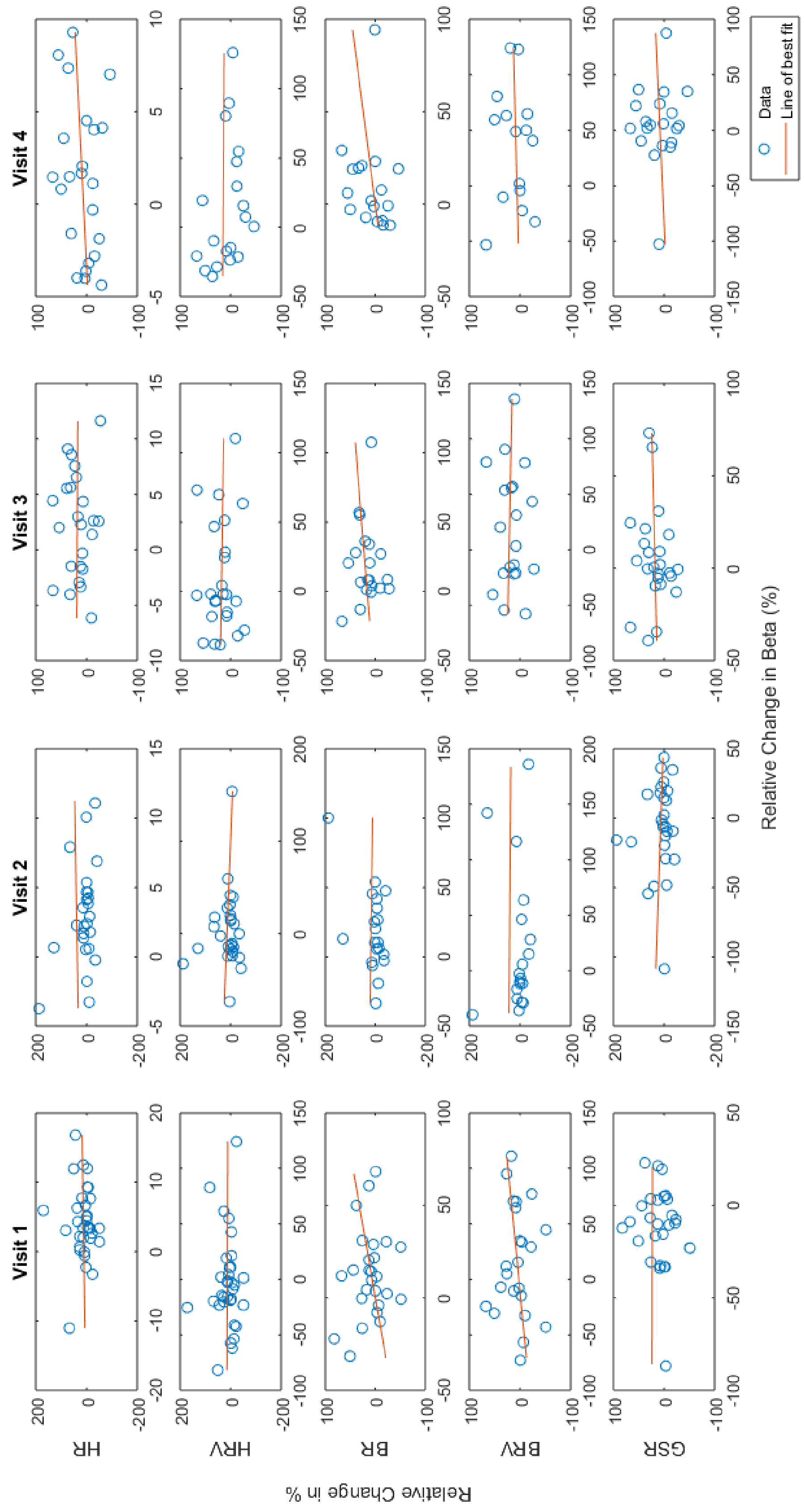


Figure G.4 Scatter plots comparing relative change in beta (%) to relative change in autonomic responses (heart rate (HR), heart rate variability (HRV), breathing rate (BR), breathing rate variability (BRV), and galvanic skin response(GSR))

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