MOVEMENT-RELATED CORTICAL POTENTIAL MARKERS OF MOTOR SKILL LEARNING

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Publications and presentations associated with this thesis

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Based on the literature review section of this thesis

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Abstract

In this thesis the cortical processes involved in motor skill learning were examined. Electroencephalography (EEG) was used to record the movement-related cortical potential (MRCP): an event-related potential reflecting the cortical activity involved in motor planning and preparation, prior to performance of a guitar playing task. A series of five experiments was conducted to investigate how the MRCP may vary depending on a performer's skill level and how it may change with skill learning.

In Study 1 a scale-playing task on the guitar, from which it was possible to accurately record the MRCP, was identified. In Study 2, the MRCP was recorded during scale-playing on the guitar from a group of experienced guitarists and a group of non-musicians who had no prior musical training and no experience of playing any musical instrument. Differences in the amplitude and onset times of the MRCP components were compared across groups, with results indicating that the experienced guitarists allocated less cortical activity to planning the performance of the scale than the non-musicians. The purposes of Studies 3, 4, and 5 were to establish the extent to which these between-group differences were the result of training by the experienced guitarists. In Study 3 the effect of short-term practice on movement-related cortical activity was investigated and, contrary to the hypothesis, found an increase in cortical activity involved in movement preparation following practice on the guitar. In Studies 4a and 4b the effect of long-term motor practice on the MRCP was explored. Non-musicians took part in a five and ten week training programme, learning to play the guitar. Study 4a reported a decrease in cortical activity in certain parts of the motor cortex following five weeks of learning to play a scale on the guitar. When the training programme was extended to ten weeks in Study 4b however, an increase in cortical activity was found in certain areas of the motor cortex. Study 4c investigated the effect of a period of de-training on the MRCP in five

participants. Results from these participants indicated a decrease in MRCP amplitude following training. This reduced amplitude was also found following a five-week period of de-training. Finally, in Study 5, within-session changes in cortical activity were investigated over an extended ten-week learning period. The combined results of Studies 3 and 5 indicate that there may be an increase in both pre- and primary motor cortex activity during the initial phase of motor skill learning, followed by a decrease in motor cortex activity once the performer becomes competent in the task. From the results of these studies, it was concluded that the process of motor skill learning is likely to be more complex than is currently stated in the literature. Rather than a simple linear decrease in the amount of cortical activity involved in motor planning as a result of learning, it is more likely that fluctuations in cortical activity occur at different stages in the learning period, which may, over time, lead to a reduced activity being required during motor preparation.

List of abbreviations used throughout the thesis

Ag/AgCl – Silver/Silver Chloride

ANOVA – Analysis of Variance

BOLD – Bold Oxygen Level Dependent

BP – Bereitschaftspotential

bpm – Beats per Minute

CNV – Contingent Negative Variation

DC – Direct Current

EEG – Electroencephalography

EMG - Electromyography

EOG – Electroculography

ERD – Event-Related Desynchronisation

fMRI – Functional Magnetic Resonance Imaging

HEOG – Horizontal Electroculography

MP – Motor Potential

MRCP – Movement-Related Cortical Potential

ms – Milliseconds

MVC – Maximum Voluntary Contraction

NaCl – Sodium Chloride

NS' – Negative Slope

SMA – Supplementary Motor Area

TMS – Transcranial Magnetic Stimulation

VEOG – Vertical Electroculography

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Chapter 1

Introduction

A motor skill is an action that requires the voluntary movement of the body or a limb to achieve a specific goal (Magill, 2011). Actions such as shooting a gun, dribbling a basketball, playing a musical instrument, or driving a car are all different types of motor skills. Motor skill learning is the process associated with practice or experience that leads to a relatively permanent change in a performer's ability to perform a motor skill (Schmidt & Lee, 2011). The learning of motor skills, such as walking or reaching and grasping for an object, is fundamental to human development. Despite the importance of motor skill learning in human development, the process is not yet fully understood.

Early theories and models of motor skill learning, such as the Three Stage Model proposed by Fitts and Posner (1967), focused on describing changes in performance characteristics as an individual improved their motor skill performance through practice. Other early models of motor skill learning, such as the Degrees of Freedom Problem outlined by Bernstein (1967), attempted to explain how the body and nervous system learn to control movements. Neither of these early models however offered any explanation as to what may occur within the brain as an individual goes through the process of motor skill learning. Recent developments in neuroscience are now providing researchers with unprecedented insight into the cortical processes involved in human motor development, although research using neuroscientific techniques to study motor skill learning is still at an early stage. This thesis first examines the published neuroscientific research in the area of motor skill learning that has been conducted to date. A series of five experiments addressing limitations within the current literature are then presented.

1.1 – Statement of the problem

Most research conducted to date regarding the neuroscience of motor skill learning has employed a cross-sectional approach, whereby differences in the brains of experts and novices in a particular skill are compared (e.g., Di Russo, Pitzalis, Aprile, & Spinelli, 2005; Fattapposta et al., 1996; Hatta, Nishihira, Higashiura, Kim, & Kaneda, 2009; Kita, Mori, & Nara, 2001). Differences found between the two groups are generally attributed to the long-term training in the skill undertaken by the experts. Although this body of research has yielded some interesting results, there are two fundamental omissions from the neuroscience and motor skill learning literature. First, possibly as a result of equipment limitations, most researchers have tended to measure participants' cortical activity during the performance of simple motor actions and have then extrapolated the findings to more complex motor skills. This is problematic because the movement tasks used in these experiments are often far removed from the motor skills under scrutiny. A common example is that the act of pressing a button has been applied to shooting sports (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996), with the rationale being that the biomechanical action required to perform both movements is similar. A consequence of this reductionist approach is that many aspects of the motor skill performance, for example, aiming the gun, keeping the gun steady, and controlling breathing and posture, are not accounted for. The results of these studies therefore provide an incomplete picture of the skill-related cortical differences between the two groups. As such, there is a need for researchers to attempt to replicate these results during the performance of more ecologically valid motor skills (Nakata, Yoshie, Miura, & Kudo, 2010).

A second significant omission within this body of research is the absence of longitudinal evidence. Without this, it is problematic to claim that the differences

reported in cross-sectional studies are the result of the long-term training undertaken by the experts. It is possible that individuals who become skilled musicians or athletes start out with a different cerebral structure (Poldrack, 2000). For example, skilled performers may have a predisposition to require fewer cortical resources when preparing to perform certain motor skills. Such a predisposition may make them more likely to excel at the skill initially, continue to train in that skill, and reach an expert level. The differences in cortical activity reported in previous cross-sectional studies may therefore be inherent to the performers, as opposed to an adaptation resulting from long-term training (Hatfield, Haufler, & Spalding, 2006). Research by Maguire and colleagues (e.g., Maguire et al., 2000; Maguire et al., 2003; Maguire, Woollett, & Spiers, 2006) has shown that this is unlikely to be the case, reporting that the hippocampus of London taxi drivers becomes enlarged after years of experience learning and remembering driving routes. It should be acknowledged however that the research by Maguire and colleagues concerned changes in the hippocampus associated with spatial navigation tasks. This does not automatically mean that the same phenomenon occurs in the motor cortex as a result of motor skill learning. To address this concern, longitudinal studies are warranted, whereby possible changes in cortical activity associated with motor skill learning are investigated over weeks and months (Nakata et al., 2010). These limitations are discussed in more detail in section 3.4 of the literature review section of the thesis.

1.2 – Outline of the thesis

This series of five experiments advanced the cognitive and behavioural neuroscience and motor skill learning literature by addressing the limitations outlined above. The experiments in this thesis used a neuroscientific technique called electroencephalography (EEG) to record the movement-related cortical potential (MRCP); a low frequency, negative, slow potential shift in the EEG recording that reflects the

cortical activity involved in the preparation and planning for voluntary movements (Shibasaki & Hallett, 2006). In Study 1, it was established that it was possible to record the MRCP accurately prior to the ecologically valid task of playing a scale on the guitar, which requires the use of motor skills as each necessary action is undertaken. This experiment was necessary as it is not always possible to accurately record the MRCP during the performance of motor tasks. For example, Holmes (2000) was unable to record any meaningful slow potential activity during rifle shooting, and he speculated that the slow potential activity recorded during rifle shooting performance by Konttinen and Lyytinen (1992, 1993) was contaminated by signal drift. In Study 2 the current cross-sectional MRCP literature was advanced by replicating previous cross-sectional research using the ecologically valid motor task identified in Study 1. Study 2 represents the first time that research of this kind has been conducted in an ecologically valid way, and therefore the results contribute significantly to the literature. In Studies 3, 4, and 5 the lack of longitudinal research in the literature was addressed. The purpose of these studies were to verify the claims made in the cross-sectional literature that the consistently reported differences in the MRCP between groups of experts and novices were the result of the long-term training undertaken by the experts. In Study 3 changes in cortical activity associated with short-term practice of the scale-playing motor task over the course of a single testing session were examined. Studies 4a and 4b further extended the cognitive and behavioural neuroscience and skill learning literature by demonstrating changes in cortical activity associated with learning to play a scale on the guitar over extended training periods of five and ten weeks. In Study 4c, the extended training study was completed by investigating changes in cortical activity that were associated with a period of motor skill de-training. This three-part experiment represented the first attempt to explore the cortical changes involved in motor preparation as a result of longitudinal

training and de-training in a motor task. Finally, within-session changes in cortical activity that occurred throughout the training programme were examined in Study 5. The results of these studies were discussed in relation to the concept of *neural efficiency* following motor skill learning (Babiloni et al., 2010; Del Percio et al., 2008), and in relation to the Five-A model of technical change (Carson & Collins, 2011).

In conclusion, this research is novel. Some of this work has been published, whilst other parts are currently in press for publication. As mentioned above, this research contributes new ideas to the area of cognitive and behavioural neuroscience and motor skill learning. Chapters 4 – 10 in this thesis provide further details regarding the studies summarised above. Before discussing the experiments undertaken in this thesis, the following chapters will discuss technical aspects of an EEG recording (Chapter 2), and the relevant literature that has informed this thesis (Chapter 3).

Chapter 2

Technical considerations in EEG recording

This thesis reports a series of five experiments that used electroencephalography (EEG) to study the cortical processes involved in motor skill learning. Before discussing the relevant literature in the area and describing the studies that make up this thesis, it is first important to understand what EEG is, and what conducting an EEG experiment entails. This section of the thesis will therefore explain EEG, before describing the process of preparing a participant for an EEG recording and discussing the important technical aspects of EEG that must be considered and understood before any EEG experiment can be conducted.

2.1 – Electroencephalography (EEG)

Electroencephalography (EEG) is a non-invasive neuroscientific technique that records the electrical signals generated by the brain through electrodes attached to the scalp (Ward, 2010). EEG measures the voltage generated by currents flowing during synaptic activation of the dendrites of many pyramidal neurons in the cerebral cortex (Bear, Connors, & Paradiso, 2007). The existence of these electrical currents in the brain was first discovered by Caton (1875), who reported 'feeble oscillations' in his recordings from the exposed cortex of rabbits and monkeys at rest. It was over 50 years later that Berger (1929) reported recording similar electrical signals from the intact scalps of human participants, paving the way for the use of EEG in research into human brain functioning. Since then there has been a wealth of research using EEG to try to understand human brain function in different contexts. Typically, researchers have adopted one of two approaches when investigating human brain functioning with EEG. Researchers will generally examine either background EEG or event-related EEG (Srinivasan, 2007).

Background EEG researchers tend to investigate the ongoing activity of the brain and focus on how this activity fluctuates depending on the cognitive state of the individual. Event-related EEG examines very low frequency cortical activity that is time-locked to a specific event. Using this approach, researchers generally describe the EEG signal in terms of its amplitude and onset latency (Srinivasan, 2007). Researchers of event-related EEG may then attempt to determine how the characteristics of the signal may change in relation to different types of events or activities. Of this large quantity of research, it is a component of the low frequency event-related EEG concerning movement planning and preparation, called the movement-related cortical potential (MRCP), that is of greatest relevance to this thesis. The MRCP will therefore be discussed in the following section.

2.2 – The movement-related cortical potential (MRCP)

In the 1960s, Kornhuber and Deecke conducted a number of landmark experiments investigating low frequency cortical activity associated with voluntary movements of the limbs (Kornhuber & Deecke, 1964, 1965). They reported that voluntary hand and foot movements were preceded by a slowly increasing negative cortical potential of between 10-15 μV in amplitude, which was maximal over the contralateral pre-central region of the brain. The authors termed this the Bereitschaftspotential (BP, or readiness potential). As this negative shift is time-locked to voluntary movement production it has become known as a movement-related cortical potential (MRCP). Eccles (1977) proposed that the MRCP is generated by neuronal activity at the synapses within the motor cortex, whereby when the synapses are activated prior to movement, a negative shift in the EEG recording occurs. Elbert (1993) confirms this proposal, suggesting that the negative shift reflects the sum of excitatory post-synaptic potentials at the apical dendrites of cortical pyramidal neurons.

In the years since Kornhuber and Deecke's (1964, 1965) seminal experiments, up to eight different components of the MRCP have been identified (Shibasaki & Hallett, 2006). The pre-movement components of the MRCP are examined in this series of experiments. The earliest component of the MRCP, generally occurring around 1.5 – 2 seconds prior to movement onset is the slowly increasing negative BP reported by Kornhuber and Deecke. It is maximal at the midline centro-parietal area and widely distributed symmetrically over the scalp (Shibasaki & Hallett, 2006). The BP is followed by a negativity of a much steeper gradient called the negative slope (NS'), which typically occurs around 500 ms prior to movement onset (Shibasaki, Barrett, Halliday, & Halliday, 1980). The NS' is localised to the primary motor cortex and lateral pre-motor cortex (Shibasaki & Hallett, 2006). The final pre-movement component of the MRCP is called the motor potential (MP; Deecke, Scheid, & Kornhuber, 1969) and occurs immediately prior to movement onset. It is usually identified as the negative pre-movement peak and is localised to the contralateral primary motor cortex and sensorimotor cortex (Toma & Hallett, 2003). These three pre-movement components of the MRCP are illustrated schematically in Figure 2.1.

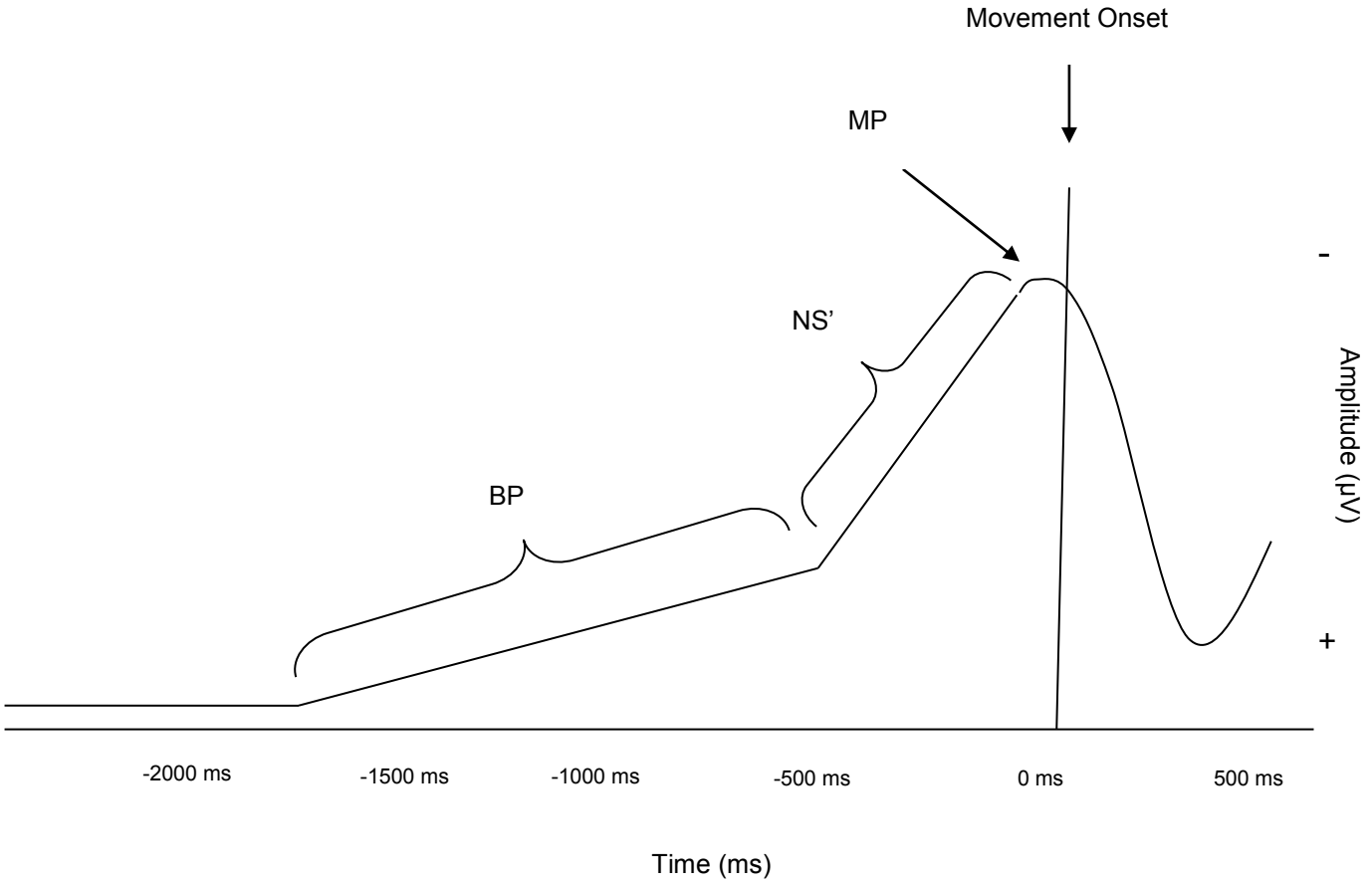

Figure 2.1: A schematic representation of the movement-related cortical potential (MRCP). On the horizontal axis, Time 0 ms indicates the point of movement onset. The pre-movement components, termed the Bereitschaftspotential (BP), the negative slope (NS') and the motor potential (MP) are thought to reflect the cortical activity involved in planning and preparing to perform a voluntary movement.

Researchers typically investigate the MRCP in terms of the amplitude of the negativity and the onset time of the MRCP components. Negativity in the EEG has been related to increased activity, whilst positivity in the EEG has been related to inactivity in the cortical area beneath the electrode (Deecke, 1996). The negative profile of the MRCP is therefore indicative of an increase in cortical synaptic activity prior to movement production. As such, it is likely that the MRCP reflects the cortical activity involved in planning and preparing to perform a specific movement (Hallett, 1994; Rockstroh, Elbert, Birbaumer, & Lutzenberger, 1982; Shibasaki & Hallett, 2006). The amplitude and onset time of the negativity are often taken as markers of the amount of effort required to plan the performance of the forthcoming movement, with smaller amplitude and later onsets thought to indicate less effort during motor preparation (e.g., Di Russo, Pitzalis, et al., 2005). Specifically, the amplitude may reflect the amount of cortical resources allocated to a cognitive process (i.e., motor preparation), whilst the time course of these components may be related to the duration of the cognitive process (Rosler, Heil, & Roder, 1997).

Both the onset times and the amplitude of the MRCP may vary depending on physical and psychological parameters of the planned movement (Birbaumer, Elbert, Canavan, & Rockstroh, 1990). Further evidence for the functional significance of the MRCP in movement preparation is provided by experiments that have investigated how these parameters influence the MRCP. Research has shown that physical characteristics of a movement such as force (Becker & Kristeva, 1980; Kutas & Donchin, 1974); rate of force development (Siemonow, Yue, Ranganathan, Liu, & Sahgal, 2000); speed (Becker, Iwase, Jurgens, & Kornhuber, 1976; Hazemann, Metral, & Lille, 1978); and complexity (Kristeva, 1984; Lang, Obrig, Lindinger, Cheyne, & Deecke, 1990) of the movement can all

influence the MRCP profile. For example, it has been reported that handgrip movements requiring a greater force will produce a MRCP of larger amplitude than movements requiring a smaller force (Becker & Kristeva, 1980; Kutas & Donchin, 1974; Siemonow et al., 2000). Additionally, when planning to perform a movement with a high rate of force development the amplitude of the NS' component of the MRCP has been reported to be larger than when planning a movement with a low rate of force development (Siemonow et al., 2000). Force however only seems to influence the amplitude of the MRCP when there is a large difference between the force of the movements being investigated. For example, Kutas and Donchin reported differences in the MRCP amplitude between grasping movements performed at either 25%, 50%, or 75% of the participants' maximum voluntary contraction (MVC). When examining the effect of much smaller increments in the force of a movement, no changes in amplitude of the MRCP are typically reported (e.g., Hazemann et al., 1978; Wilke & Lansing, 1973). In relation to the speed of the planned movement, an earlier MRCP onset time and smaller amplitude has been reported when preparing to perform fast movements, compared to slower movements (Becker et al., 1976). In terms of the complexity of the movement, actions that are more complex may produce a larger MRCP than more simple actions. For example, in a study that required pianist participants to perform finger tapping actions, Lang et al. (1990) reported a larger amplitude MRCP when one hand tapped a rhythm at two beats per second and the other hand tapped at 3 beats per second, compared to when both hands tapped a rhythm in synchrony. As finger tapping with both hands at different speeds is more complex than tapping both hands in synchrony, Lang et al. suggested that more complex actions produce MRCPs of larger amplitude, compared to simpler actions. Similarly, in a study by Kristeva (1984), experienced pianists played either a single note or a melody with their right hand on the piano. A larger BP, that began earlier, was found

prior to melody playing compared to single note playing. Kristeva concluded that melody playing requires a more complex motor programme than single note playing, and proposed this as the reason for the difference in amplitude and onset time between conditions. Although this is a plausible explanation it is worth noting that, in addition to the difference in complexity of the movements, the different duration of the movements may have been a confounding factor in the different BP amplitude and onset times.

In relation to psychological constructs, it has been reported that the low-frequency EEG activity involved in movement preparation may be influenced by factors such as a participant's level of motivation (McAdam & Seales, 1969), boredom (Kornhuber & Deecke, 1965), anxiety (Ansari & Derakshan, 2011), arousal (Masaki, Takasawa, & Yamazaki, 2000), or attention (Masaki, Takasawa, & Yamazaki, 1998). For example, in relation to boredom, Kornhuber and Deecke (1965) reported in their early experiment examining the MRCP that the amplitude of the BP became reduced when participants became bored and uninterested in the task. This indicates that as attention to the task decreases, the amplitude of the MRCP becomes reduced. This finding was verified more recently by Masaki et al. (1998), who demonstrated that increased attention to the task produces an increase in the amplitude of the NS' component of the MRCP. To study the effect of motivation on the MRCP, McAdam and Seales (1969) examined differences in the amplitude of the MRCP when monetary rewards were given for performing correct movements, compared to a baseline condition when no rewards were given. Compared to the baseline condition, they reported larger amplitude MRCPs in the reward condition, when participants' motivation to engage in the task would arguably have been higher. This led the authors to suggest that participants' motivation to take part in the task could influence the amplitude of the MRCP. Recently, research has also begun to examine the

influence of anxiety on the cortical activity involved in motor planning. For example, Ansari and Derakshan (2011) investigated differences in the contingent negative variation (CNV) between participants classified as either high- or low-anxious individuals, based on their responses to an anxiety questionnaire. They reported that the CNV, an event-related potential that is produced between a warning stimulus and an imperative stimulus that requires a rapid motor response, and is thought to reflect the cortical activity involved in movement preparation (Smith & Collins, 2004), was larger in high-, compared to low-anxious participants. In line with Attentional Control Theory (Eysenck, Derakshan, Santos, & Calvo, 2007), this finding indicates that high-anxious individuals must devote a greater amount of cognitive effort to movement preparation to perform to the same standard as low-anxious individuals.

The research reviewed in this section discussing the way in which the amplitude and onset times of the MRCP vary depending on different physical and psychological characteristics of the planned movement provides strong support for the notion that the MRCP reflects the cortical activity involved in planning and preparing to perform a voluntary movement. The evidence also highlights that it is important for researchers who investigate the MRCP to attempt to control for these physical and psychological aspects of the movement as they are likely to influence researchers' dependant variables.

2.3 – Preparation for an EEG experiment

The process of preparing a participant for an EEG recording and the technical considerations that accompany this procedure must be understood before the literature in the area of EEG and motor skill learning can be discussed. If the technical details regarding the labelling of electrode locations or the process of extracting the MRCP

waveform from the raw EEG data are not understood, it is difficult to interpret the literature.

2.3.1 – Marking the electrode locations

When preparing a participant's scalp for an EEG recording, the first step is to mark out the sites on the scalp from which the EEG is to be recorded. One of the key principles of scientific investigation is that it must be possible to replicate the methods used in an experiment. To ensure that the results of an EEG study can be replicated by other laboratories, it is crucial that the electrode locations are stated and are positioned over the same areas of the scalp across participants. To make this possible, Jasper (1958) devised a standardised system of electrode placement, known as the International 10-20 System of Electrode Placement, commonly referred to as the 10-20 system. The name of the 10-20 system is derived from the fact that all electrodes are positioned in either 10% or 20% deviations from four anatomical landmarks of the skull. These landmarks are: the nasion (the bridge of the nose), the inion (the small bump at the back of the skull), and the left and right pre-auricular points (the indentations at the insertion of the mandible bone to the skull). As all the electrodes are placed in relation to these landmarks, their relative position on the scalp is always the same. The electrode locations are assigned letter labels reflecting which of the brain lobes or brain regions they are situated over (F – Frontal lobe; T – Temporal lobe; P – Parietal lobe; O – Occipital lobe, and C – Central region), and a number corresponding to the distance of that electrode to the central line of the head. A lower numbered electrode position indicates a more medial placement, whereas a higher numbered electrode position indicates a more lateral placement. Electrodes assigned an odd number are located over the left hemisphere, whilst those assigned an even number are located over the right hemisphere. A 'z' label is assigned to

electrodes placed on the central line from the nasion to the inion landmarks. An electrode placed at Cz would therefore be over the exact centre of the head, whilst an electrode placed at F7 would be placed in a lateral location over the frontal lobe of the left hemisphere. Occasionally, researchers may record from an area close to, but not exactly at, one of the electrode locations in the 10-20 system. If a researcher wanted to record EEG from a more dense montage than is possible with the 10-20 system, an electrode may be placed at a modified 10-20 location, and marked with a quotation mark after the electrode label. For example, an electrode placed 2 cm anterior of C3 would be referred to as modified C3, and labelled C3".

Technological advances, and the desire to localise various components of the EEG signal, have since brought about the need to record EEG from a greater number of scalp locations than the 21 sites permitted by the 10-20 system. As a result, the 10-20 system was extended to a new system referred to as the 10-10 system (Chatrian, Lettich, & Nelson, 1985, 1988). With this system, electrodes are located at 10% (rather than 20%) deviations from each other, allowing EEG to be recorded from 81 scalp locations as opposed to only 21 channels in the original 10-20 system. After some debate about the labelling of these new electrode positions it was suggested that the new labelling should be kept in line with the original 10-20 system, with electrode locations positioned half way between two original sites adopting both their labels (Nuwer et al., 1998). For example, an electrode located half way between F3 and C3 was assigned the label FC3. As a result of this technological advancement is that it is now less common for electrodes to be reported at modified 10-20 locations. With the development of the 126 and even 256 channel EEG equipment, this system has since been extended even further to the 10-5 system (Oostenveld & Praamstra, 2001), enhancing the spatial resolution of EEG by

allowing reproducible recording from dense electrode montages of up to 345 electrodes. Such dense montages tend to be used more in EEG source localisation research and background EEG recordings. When investigating event-related potentials, such as the MRCP, smaller electrode montages using parts of the 10-20 or 10-10 system are more common.

The EEG activity recorded by the electrodes is a measure of the voltage difference between the electrical activity at an active site (over a cortical area) and the electrical activity at an inactive, electrically silent, reference site. As such, in addition to attaching electrodes to the scalp it is essential to also record the EEG from one or more reference sites. The ideal reference site would be one that is unaffected by electrical activity. Unfortunately, there are no such sites on the scalp that are entirely unaffected by electrical activity. Researchers can minimise the activity at the reference site by selecting the most neutral reference possible (Luck, 2005); common sites include the chin, earlobes, mastoids, or the tip of the nose. Luck (2005) suggested that when selecting a reference site there are three factors to consider. First, as no site is truly neutral, Luck advised that researchers select as convenient and comfortable a site as possible. This may rule out the tip of the nose as an appropriate reference site as it may interfere with a participant's vision. Second, he suggested that using the same sites as previous studies was desirable as this allows more accurate comparison across laboratories. Third, and most importantly, he stressed the importance of avoiding a site that is biased towards one hemisphere. If a left earlobe reference is chosen then the voltage at left hemisphere sites will be different to those at right hemisphere sites. Selecting a reference site that is the same distance from all electrodes is therefore important.

The most common reference sites are the earlobes or the bony mastoid processes behind the ears. These sites satisfy the first two criteria of being easy to apply and consistent with other laboratories but, if only one reference is used, the final criterion of being equidistant to all electrodes is not met (Luck, 2005). Placing an electrode at both the left and right earlobes/mastoids and physically linking them together avoids this bias. This is referred to as linked earlobes/linked mastoids. Although it is appropriate to use either a linked earlobe or linked mastoid reference, Luck (2005) proposed that the skin tends to be less tough at the mastoids than the earlobes, and so it is easier to obtain a good electrical connection when using a linked mastoids reference. It is also important to refer the active and reference electrodes to a ground electrode, typically located on the forehead. This electrode prevents the static charge accumulating (Picton et al., 2000) and allows common mode voltage to be rejected, preventing noisy signals in the EEG recording (Butler, 1993).

In addition to attaching electrodes to the active scalp, reference, and ground electrode sites, it is standard practice to record electroculography (EOG) alongside the EEG to measure the electrical activity generated by eye-movements and blinks. The EOG activity is thought to reflect the fact that the cornea is positively charged, whilst the retina is negatively charged, forming an electric dipole (Gratton, 1998). When this dipole moves, for example when the participant blinks or looks up, the electric field around the eyes changes and this in turn affects the electric fields over the scalp (Croft & Barry, 2000). The electrical activity generated by eye saccades or blinks can be up to 10 times larger than that of cortical signals and can propagate across most of the scalp, masking and distorting the EEG signals (Joyce, Gorodnitsky, & Kutas, 2004). Lins, Picton, Berg, and Scherg (1993) studied the extent of this propagation at a number of scalp locations. They

reported that between 17-19% of the eye blink artefact amplitude was present at anterior scalp locations (e.g., Fz, F3 or F4), around 8-10% at central locations (e.g., Cz, C3 or C4) and around 3-4% at posterior locations (e.g., Oz, O1 or O2). This is clearly of great significance when recording EEG, as if the EOG is not adequately controlled for, it may have a confounding effect on the results. For example, Hillyard and Galambos (1970) calculated that, on average, across all participants, 6.4 μV (equating to 23% of the amplitude) of the CNV they recorded in their study was composed of ocular artefact. As such, in their published guidelines for recording event-related potentials, Picton et al. (2000) stated that it is essential to monitor ocular artefacts using electrodes located near the eyes. This is typically done by placing an electrode approximately 1-2 cm above or below the centre of the eye to measure vertical eye movements (VEOG) and another electrode approximately 1-2 cm from the outer canthus of the eye to measure horizontal eye movements (HEOG). Electrical activity from these electrodes is then recorded alongside the EEG recording, with any eye movements showing up as a sharp deflection on the EEG trace.

A number of techniques, including rejecting or correcting ocular artefacts, can be applied to ensure that they do not contaminate the results. The rejection technique involves discarding any epochs from the analysis that are deemed to contain ocular artefacts (Gratton, 1998). For example, an experimenter may set a rejection criterion of 50 μV, whereby any deflection on the VEOG or HEOG channels greater than 50 μV is automatically rejected from the analysis (Croft & Barry, 2000; Gratton, 1998). Although this approach removes all ocular artefacts exceeding a set amplitude from the recording, it can result in an unacceptable amount of data loss, rendering the recording unusable. Correction techniques on the other hand attempt to remove the EOG artefact from the

recording, without the need to reject whole segments of the EEG. This tends to involve estimating the amount of EOG contamination at an electrode and subtracting this from the EEG recording (Croft & Barry, 2000). As these techniques are based on estimations, which may not always be reliable, rejection techniques may be preferable as they completely remove the artefacts from the recording (Srinivasan, 2007). When the rejection approach results in too much data loss however (e.g., over a third of trials), correction techniques may be more suitable (Picton et al., 2000).

2.3.2 – Attaching the electrodes

Once all the electrode sites of interest have been measured, they are marked on the scalp using a chinagraph pencil. Before attaching the electrodes, the skin should be gently abraded with a cotton bud and abrasive paste. The purpose of this is to remove the surface epidermal layer (Ferree, Luu, Russell, & Tucker, 2001) in order to lower the electrical impedance (resistance to electrical current) and allow a clearer electrical signal to be received by the electrodes. Various methods for skin abrasion have been discussed in the literature. Picton and Hillyard (1972) proposed a method whereby the skin should be abraded or punctured with a blunt needle until a small amount of blood is drawn from the scalp. The authors proposed that drawing blood eliminated electrodermal potentials at the electrode site, which may contaminate the EEG signal with artefacts. Whilst this approach may eliminate such electrodermal potentials, puncturing the skin brings the electrodes into contact with blood, thus increasing the risk of passing on blood-borne infections such as Human Immunodeficiency Virus or Creutzfeldt-Jacob Disease between patients and participants (Ferree et al., 2001). Puncturing the skin is therefore no longer a desirable option but, according to Ferree et al. (2001), it is no longer necessary with modern recording and analysing systems. As such, it has become rare for researchers to

puncture or abrade the skin to the extent where blood is drawn. Excessive skin abrasion can introduce bodily fluids onto the scalp, which increase the occurrence of potentials generated at the electrode site between the electrode and any fluid beneath it. These potentials, known as half-cell potentials, can distort the EEG signal. Gentle scalp abrasion that causes a slight reddening of the skin without introducing bodily fluids onto the scalp is therefore the preferred option. Although this approach reduces the risk of passing on infections between participants, Ferree et al. recommended that electrodes should be sterilised after each use to eliminate any risk. Researchers may also use the abrasive paste to part the participant's hair at the site of interest to ensure the electrode can be applied directly on to the scalp. Careful abrasion and parting of the hair is important as scalp oils, dead skin cells, and hair can all contribute to higher impedance between the scalp and the electrodes (Degabriele & Lagopoulos, 2008).

Following the skin abrasion the electrodes are attached to the scalp. This can be done in a number of ways. For example, researchers using a large electrode montage may opt to use a cap with the electrodes embedded into it in the designated 10-20 or 10-10 locations. Researchers using smaller electrode montages may however choose to apply the electrodes to the scalp individually. One such technique is to glue the electrode directly on to the scalp and inject a conductive gel into the electrode cup using a blunt syringe. This results in the electrode being securely held in place, but removing the glue from the scalp can result in a lengthy de-prep and cause irritation and discomfort to the participant. An alternative technique is to fill the electrode cup with an adhesive and conductive paste to attach the electrode onto the scalp. The electrode can then be secured in place using tape smeared with glue if necessary. As this method does not involve gluing directly on to the scalp, it reduces the length of time taken to de-prep the

participant, whilst still resulting in a firm hold on the scalp. Once all the electrodes have been applied, the experimenter should then check the impedance at each electrode. High impedances will distort the EEG signal and so it is desirable to obtain homogenously low impedance values across the montage. Andreassi (2007) suggests that the impedance at each electrode site should be less than 5 kΩ if there is a good contact between the electrodes and the scalp tissue. If the impedance at an electrode exceeds this value, or impedance values across sites are not homogenous, the electrode should be removed and the scalp cleaned, before re-attaching the electrode following the above procedure.

2.3.3 – Selecting appropriate electrodes and gels

A wide variety of electrodes, abrasive skin preparation pastes, and conductive gels are commercially available for EEG recordings. Appropriate selection of this equipment is crucial if valid results are to be obtained, particularly when recording direct current (DC) EEG. Electrodes made from silver, chlorided silver, gold, platinum, tin and stainless steel are available from various suppliers of EEG equipment. Similarly, conductive gels with varying concentrations of sodium chloride (NaCl) are on the market. Some gels are strongly hypertonic, whilst other gels are advertised as being chloride free (Butler, 1993). Butler pointed out that these commercially available gels may also contain differing amounts of gums, cellulose derivatives, preservatives, colourings, or abrasives; all of which may affect the stability of the DC EEG signal. To produce stable EEG recordings, the most suitable combination of electrodes and gels is thought to be the use of silver/silver chloride (Ag/AgCl) electrodes with a high NaCl content conductive gel (Bauer, Korunka, & Leodolter, 1989; Butler, 1993). Tallgren, Vanhatalo, Kaila, and Voipio (2005) confirmed this in their comparison of a number of commercially available electrodes and gels for recording DC slow potentials. They compared 12 brands of electrodes made of either

Ag/AgCl, gold, tin, silver, sintered Ag/AgCl, platinum, and stainless steel, and 9 brands of electrode gels of various NaCl concentrations (ranging from 0.01 to 2.1 mol/l). They reported that Ag/AgCl electrodes and gels with the highest NaCl concentrations produced the most stable signals, with the lowest amount of signal drift. Conversely, the other types of electrodes and gels with a low NaCl content brought about unstable signals. This led the authors to conclude that sufficient signal stability for DC EEG recordings can only be achieved when using Ag/AgCl electrodes and an electrode gel with a high NaCl content. Butler suggests that the reason a high NaCl content gel is required is that its composition is almost equivalent to extra-cellular tissue fluid, and as such allows the electrode to conduct without polarising. For these reasons, all EEG recordings reported in this thesis were conducted using Ag/AgCl electrodes and a conductive gel with a high NaCl content.

2.3.4 – Minimising signal drift

When recording DC EEG, once all the electrodes have been attached to the scalp, a 'settling' period is required before the experiment can begin. If this rule is not adhered to, it can result in the EEG signal drifting away from its baseline level, making it impossible to obtain valid results. This drifting is thought to be caused by a slow, spontaneous change in electrode polarisation (Tallgren et al., 2005). Although the selection of appropriate electrodes and gels can minimise the amount of drift, some drifting is unavoidable. Whenever something is placed on the skin that is not in ionic balance with the contents of the skin, a settling period is always required (Bauer, 1993). Bauer et al. (1989) suggested that a 30 minute settling period is usually sufficient to record a stable EEG signal with minimal signal drift. Although 30 minutes may be adequate in most cases, pilot testing for the first study in this thesis revealed that it may be more appropriate to

wait for 45 minutes before beginning the experiment (see Appendix A). Following this settling period, the impedance values should be re-checked to ensure they are still homogenously below 5 kΩ.

2.4 – Analysis of slow potentials

Birbaumer et al. (1990) stated that slow potential shifts recorded in a laboratory typically range from 5-30 μV in amplitude. Spontaneous variations in the background EEG on the other hand may reach amplitudes within the range of 10-100 μV. In addition, spontaneous shifts in the background EEG also occur at a higher frequency than slow potential shifts. As a result, these background EEG signals conceal the slow potential shifts, rendering them rarely visible in the raw EEG trace. In order to extract any meaningful slow potential activity (such as a MRCP), multiple recordings of the same trials must be taken and averaged across these trials (Birbaumer et al., 1990). The rationale behind this approach is that the EEG data recorded from a single trial consists of both the MRCP waveform, as well as random, spontaneous noise (Luck, 2005). When multiple trials are averaged, the background noise in each trial will cancel itself out, leaving only the MRCP waveform. Gerbrandt (1978) calculated that at least 64 trials per participant are required to obtain an acceptable signal-to-noise ratio when averaging slow potential data. Whilst this may be the minimum number required, researchers will generally record a minimum of 100 identical trials for averaging slow potential data.

In order to obtain an accurate representation of the averaged slow potential activity, a number of sequential steps must be taken before averaging the data. First, the onset of movement must be marked on to the EEG recording. It is essential that this is marked accurately as the various components of the MRCP are time-locked to movement onset. Typically, electromyography (EMG) is recorded alongside the EEG, with the onset

of EMG activity used to determine movement onset. An alternative technique for marking movement onset includes feeding a button trigger into a spare EEG channel. When the button is pressed (movement onset), a marker is inserted on the EEG channel and can be identified on the EEG trace. This can then be used as a marker to average the data either forward or backwards. After movement onset has been determined, it is important to remove/correct any ocular artefacts (detected by EOG) from the recording to ensure only true EEG activity is included in the averaged waveform. This is typically done by using either the EOG correction or rejection techniques mentioned earlier in section 2.3.1 of this chapter.

Once movement onset has been determined and ocular artefacts have been removed or corrected, the data must be filtered offline to remove the higher frequency components from the recording. As slow potential shifts, such as the MRCP, occur at low frequencies researchers typically apply a filter of 0-5 or 0-10 Hz to the data. This removes most of the background noise in the signal, leaving only the low frequency EEG activity for averaging. If the EEG has been recorded continuously throughout the experiment epoching is required before the trials can be averaged. This process involves splitting the data into the individual trials. As early components of the MRCP occur approximately 1.5 – 2 seconds before movement onset and the later components occur several milliseconds after movement onset (Jahanshahi & Hallett, 2003; Shibasaki & Hallett, 2006), it is important that these time periods are included in the epochs. One or two seconds prior to the expected onset time of the early MRCP components are also included to provide a measure of the baseline EEG activity. Once the epochs have been created the data is averaged to produce the MRCP waveform. Further details and examples of how the MRCP is extracted from the EEG trace can be seen in Appendix B.

2.5 – Limitations of EEG

Although a wealth of research has used EEG to investigate human brain function it is not a technique without limitations. The purpose of this section of the thesis is to summarise some of the key limitations of EEG, so as to provide a more rounded understanding of the technique. One of the key limitations of EEG is that whilst it has an excellent temporal resolution, it has a poor spatial resolution (Luck, 2005; Pinel, 2009). This means that whilst researchers who use EEG are able to identify changes in cortical activity with millisecond accuracy, it is more difficult for them to locate exactly where in the brain any changes occurred. Using a combination of dense electrode montages (consistent with parts of the 10-10 or 10-5 systems of electrode placement) and modern analysing techniques can enhance the spatial resolution of EEG (Pinel, 2009), although it is still not as accurate as can be obtained using brain imaging techniques such as functional magnetic resonance imaging (fMRI). A second major limitation with EEG is that it is not possible to record neural activity from all areas of the brain as EEG is unable to detect the activity at sub-cortical levels (Hatfield et al., 2006). It is therefore not possible to study neural activity within numerous brain regions including the basal ganglia, cerebellum or hippocampus with EEG. Furthermore, EEG only records the electrical activity of neurons that are aligned in a perpendicular direction to the scalp, meaning that activity from any neurons aligned in a different direction or from neurons located within the sulci of the cortex are not detected.

From a practical viewpoint it is also important to acknowledge some of the limitations associated with conducting EEG experiments using movement-based tasks. As discussed in section 2.3.1, eye-movement artefacts can contaminate and distort the EEG recording, and the same is true of muscle activity, sweat, electrode movement, and

electrical interference from other equipment (Thompson, Steffert, Ros, Leach, & Gruzelier, 2008). Researchers can control for some of these factors, for example by conducting experiments in an air conditioned room to lower body temperature and prevent participants sweating, or by conducting experiments in electrically shielded rooms to eliminate electrical interference. Even if researchers are able to effectively control for these issues however, artefacts caused by muscle activity or electrode movements are likely to pose the greatest challenge to researchers using EEG to study movement-based tasks (Thompson et al., 2008). As these issues are difficult to control for, and attaching the electrodes to a participant's scalp and connecting them to an EEG amplifier severely limits the mobility of the participant, using EEG to study movement-based tasks is currently limited to simple motor actions that require little whole body movements. Despite these shortcomings, EEG is still a useful technique for probing human brain functioning. The temporal resolution of EEG is better than that provided by the majority of neuroscientific techniques and it is also much less invasive and cheaper to run than neuroimaging techniques such as fMRI or positron emission tomography.

This chapter has summarised technical and methodological issues regarding EEG data collection, as well as explained some of the limitations of the technique. The overview of the issues covered in this chapter was necessary in order to understand and interpret the published EEG research that is explored throughout this thesis. In the next chapter, the literature that has used EEG to study the cortical processes involved in motor skill learning is reviewed extensively.

Chapter 3

Literature review – Electroencephalography and motor skill learning

This literature review examines published research in the area of neuroscience and motor skill learning; mainly focusing on research that recorded the MRCP, as this is the EEG component examined in the studies described in Chapters 4 – 10. The review first discusses critically the research that has used the MRCP to study motor skill learning, both through within-participant and between-group designs. The review then draws upon relevant research in the field of motor skill learning that has recorded background EEG activity, or that has used other neuroscientific techniques, in order to support or contrast with the MRCP findings. Limitations of and omissions in the currently published research are highlighted, and methods to address these limitations are proposed.

3.1 – The MRCP and motor skill learning

To date there has been some, although not extensive, research into the MRCP and how it is influenced by skill learning. According to Poldrack (2000), there are two fundamental strategies for assessing changes in cortical activity associated with skill learning or training; (i) the longitudinal approach and (ii) the cross-sectional approach. Poldrack explains that using a longitudinal approach involves measuring participants' cortical activity on multiple occasions over the course of the learning or developmental process. For example, a longitudinal study investigating changes in cortical activity over a 12 week training programme may measure participants' cortical activity before any training in the skill has occurred, mid-way through the training programme, and upon completion of the training. Any changes in cortical activity that occur from pre- to post-test are attributed to the training. Alternatively, with the cross-sectional approach,

participants of differing skill levels are compared against each other and researchers identify differences in their neuronal function or structure related to their skill level (Poldrack, 2000). There are advantages and disadvantages to both the longitudinal and cross-sectional approaches. Poldrack explains that cross-sectional approaches may suffer from between-participant variability and cohort effects, whereby characteristics of participants in the groups may differ in factors other than the factor of interest (e.g., the age of the participants), which may confound the results. Longitudinal approaches, in contrast, have less variability and do not suffer from cohort effects as the same participants are tested throughout. A limitation of the longitudinal approach however is that studies may suffer from greater experimental mortality as the same participants are required to attend testing sessions over a longer period.

3.1.1 – Investigating skill learning using within-participant designs

The majority of studies that have assessed changes in the MRCP as a result of skill learning using within-participant designs have been conducted over the course of a single testing session (e.g., Dirnberger, Duregger, Lindinger, & Lang, 2004; Lang, Beisteiner, Lindinger, & Deecke, 1992; Niemann, Winker, Gerling, Landwehrmeyer, & Jung, 1991; Taylor, 1978). One of the earliest studies to examine changes in the MRCP as a result of skill acquisition was conducted by Taylor (1978). This study investigated changes in the BP that were associated with learning to perform a button pressing sequence with the right index finger. Participants performed 45 trials of a six button sequence. Each trial had to be performed as quickly as possible whilst EEG was recorded from electrodes positioned over the frontal lobe and motor cortex (sites Fz, Cz, C3”, and C4”). To assess changes in cortical activity associated with learning the motor task, the 45 trials were split into nine blocks, each containing five trials. Performance was measured in terms of response time,

which was found to decrease (indicating an improved performance) until approximately the 4th block of trials. The amplitude of the BP increased at all electrode sites whilst performance improved. Once the response time reached a plateau, Taylor suggested that the participants had learnt the movement task as no further improvements in performance were observed. After this point the amplitude of the BP in the subsequent blocks either decreased (Fz and C4") or remained constant (Cz and C3"). Taylor concluded that the size and distribution of the BP is linked to the level of proficiency at the motor task. As the amplitude of the MRCP is often taken as an indicator of the cortical effort required to perform a task, this finding indicates that individuals require greater cortical effort when learning to use a skill, compared to when they have become competent at the skill.

Taylor's (1978) research is supported by a study conducted by Lang et al. (1992). In this experiment participants were trained to perform a repetitive motor sequence involving flexion and extension of the index finger and wrist. Following 40 practice trials, participants performed between 80 and 100 repetitions of the task. The amplitude of the MRCP recorded in the first third of the trials was compared with the amplitude of the MRCP recorded in the final third of the trials. There was no change in performance between early and late trials, as measured by duration of each sequence. Despite this, the amplitudes of the MRCPs at locations over the motor cortex (C3, Cz, and C4) were significantly smaller in the late trials compared to the early trials. This may indicate that as participants become more familiar with an action, the activity required to plan and perform that action is reduced at certain locations over the motor cortex. The results of a study by Dirnberger et al. (2004) support this finding. Dirnberger et al. investigated changes in the amplitude of the MRCP that were associated with habituation to a

repetitive index finger flexion button pressing movement over 100 trials. To assess changes in cortical activity across the testing session, the 100 trials were split into five blocks of 20 trials. Similar to the findings of Lang et al., the amplitude of the MRCP was found to decrease significantly from the first block of trials to the last block. As Lang et al. suggested that a change in the amplitude of the MRCP may reflect a change in the amount of effort involved in the task, this reduced activity in the late trials could be interpreted as indicating that as experience in the task increases, reduced cortical effort is required to plan the task. Although this is an interesting finding, all these studies examined changes in cortical activity associated with performance of simple motor sequences, as opposed to complex motor tasks such as playing a musical instrument. It would therefore be informative to study changes in cortical activity associated with the practice of real-world motor tasks.

These findings are partially supported by a study conducted by Niemann et al. (1991). They investigated the negativity in the low frequency EEG signal *during* performance of a motor task, as opposed to immediately *prior to* the task, as is the case in traditional MRCP studies. They compared a complex task, which involved moving a match stick between the index and little fingers without visual guidance, and a simple task, which involved pressing a sequence of four buttons. Participants performed 60 repetitions of each task. The mean negativity during performance of the first 15 trials was compared with the mean negativity during the last 15 trials. The purpose of this was to identify any changes in the EEG negativity as a result of practising the motor task. A significantly reduced negativity was reported in the last 15 trials compared to the first 15 trials, but only for the complex task. As a decrease was reported at Cz, Niemann et al. suggested that the contribution of the supplementary motor area (SMA) may become

reduced as movements become automatic and the participant becomes more skilled at the task. It is possible that participants' familiarity with the two tasks could explain why a reduction in negativity was only found for the complex task. The button pressing action required to perform the simple task probably already existed in the participants' motor repertoire, and so the lack of change in the negativity may have been due to the fact that the participants were already competent at the task. A reduction in the negativity was found in the complex task however, which was unlikely to previously exist within the participants' motor repertoire. This indicates that the more competent the participants became in the skill, the fewer cortical resources were required to perform it. It is therefore possible that a reduction in the EEG negativity could provide an objective marker of motor skill learning.

Taken together, the results of the studies by Taylor (1978), Lang et al. (1992), Dirnberger et al. (2004), and Niemann et al. (1991) appear to indicate that following practice, the negativity in the EEG decreases prior to, and during, performance of a motor task. Negativity in the EEG has been related to increased synaptic activity (Deecke, 1996). The reduced negativity at the end of the learning period in these studies therefore indicates that following a period of skill learning, the task is able to be performed with reduced activity in areas of the motor cortex. Although providing interesting results, these studies only assessed changes in cortical activity associated with practising simple tasks over the course of a single testing session. These results may therefore reflect the effect of short-term repetitive practice, rather than actual learning. At present, there is a lack of research investigating the cortical processes involved in the learning of complex, real world skills over a period of weeks or months, and so further research is necessary to address this issue (Nakata et al., 2010).

3.1.2 – Investigating skill learning using between-group designs

In recent years, it has become more common for researchers to investigate skill-related differences in the MRCP using the cross-sectional approach outlined in section 3.1. Where this has been done, researchers have typically selected a group of expert or experienced performers in a specific skill and compared their MRCP to that of a group of novices who have little or no previous experience of performing that skill (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001). Rather than using the exact skill in which their performers are experts however, all these studies have used simple tasks that require reduced body movement compared to the task under investigation. Researchers have then extrapolated the results to the more complex motor tasks in which their participants are experienced. For example, button pressing actions have been used when studying pistol (Fattapposta et al., 1996) or clay target shooting (Di Russo, Pitzalis, et al., 2005), whilst wrist flexion-extension or hand gripping actions have been used when studying kendo or gymnastics (Hatta et al., 2009; Kita et al., 2001). Although this reductionist approach is far from ideal, as the exact skills under scrutiny have not been examined directly, these studies have still yielded some interesting results.

The first study that examined cross-sectional differences in the MRCP was conducted by Fattapposta et al. (1996). They recorded the BP during performance of a skilled bi-manual button pressing task, and compared differences in the amplitude and onset latency of the BP between a group of national standard Italian modern pentathletes and a group of non-athlete control participants. The results were then applied to the sport of precision pistol shooting, an event which used to form part of the modern pentathalon. The participants in the athlete group had a minimum of ten years' pistol shooting experience, whilst the control group reported that they had no experience in

pistol shooting. The task, performed whilst seated, involved participants pressing a button with the left index finger to start a sweep trace on an oscilloscope. A second button was then pressed with the right index finger to stop the sweep in a predefined area. This task was chosen as the authors considered the action required to stop the sweep to be similar to that required to pull the trigger of a gun in the pistol shooting event of the modern pentathalon. The trained shooters performed the task to a significantly higher standard than the control participants, with a mean of 50.2% successful trials, compared to only 37.6% in the control group. In addition to the superior performance, the amplitude of the BP was significantly smaller over the supplementary motor area (electrode site Cz) in the group of trained athletes. There was no difference in the onset time of the BP between the two groups. As a larger amplitude negativity in the EEG may reflect greater synaptic activity, a larger amplitude BP may indicate a higher level of preparation to perform a voluntary movement. Fattapposta et al. therefore concluded that following long-term practice in a similar task, the athlete group required a reduced amount of "mental effort" (p. 505) to plan and prepare to perform the button pressing task.

Although this is an interesting finding, there are concerns with the task used in the Fattapposta et al. (1996) study. Whilst the mechanical action required to stop the oscilloscope trace may be the same action as pulling the trigger of a gun, the cortical activity involved in planning and performing the two tasks may differ. Precision pistol shooting is a self-paced skill, performed in a standing position, whereas in the Fattapposta et al. experiment an externally-paced reactive skill, performed whilst seated, was used. It is likely that the planning and preparation for the seated reactive task would require different timing and postural considerations than those normally faced by precision pistol shooters. It is possible that these other considerations may have resulted in a different

cortical processing than when performing precision pistol shooting. As the experiment investigated cortical differences as a result of long-term pistol training, a standing, self-paced aiming task may have been more suitable.

These results have been replicated by Di Russo, Pitzalis, et al. (2005), who investigated differences in the MRCP amplitudes and onset latencies of expert and novice clay target shooters. They recorded the MRCP prior to, and during, performance of a self-paced, index finger flexion button pressing task, performed with either the left or right hand. This action was chosen as it is a similar action to that required to pull the trigger of a gun. The expert group comprised ten professional clay target shooters, with a mean of ten years' experience in the sport, all of whom had competed in the Olympics. The novice group was made up of twelve individuals with no prior shooting experience. The authors reported that the amplitude of both the BP and NS' components of the MRCP were significantly smaller in the expert group compared to the novice group. This was accompanied by onset latencies that were significantly closer to movement onset in the expert group. These differences were observed over the motor cortex (electrode sites C3, Cz, and C4), but were only present for right-handed index finger movements. As the expert group often performed similar movements with their right hand as part of their sport, the authors suggested that the differences were the result of specific motor practice. As the MRCP is thought to reflect the synaptic cortical activity involved in planning and preparing to perform an action, the authors proposed that sport experience facilitates the planning and selection of a specific movement. Also, as the differences in the expert MRCP indicated a reduced cortical activity, this could be interpreted as requiring less cortical effort, leading Di Russo, Pitzalis, et al. to conclude that following practice, a motor task is able to be performed "at a lower metabolic cost" (p. 1591).

As with the Fattapposta et al. (1996) study, whilst the button press task used in the study by Di Russo, Pitzalis, et al. (2005) may have been a similar action to that used to pull a trigger in clay target shooting, the cortical processing involved in the two tasks is unlikely to be the same. Clay target shooting is a complex, interceptive skill that involves aiming to shoot at one or more targets several meters away that are moving quickly through the air. As such, a clay target shooter has to predict the target direction, distance, and velocity, as well as align the gun barrel with the moving target before pulling the trigger (Abernethy & Neal, 1999). By only focusing on the trigger pull element of the skill, much of the cortical activity involved in holding, steadying and aiming the gun is excluded. If these elements had been included in the task, the magnitude of the reported differences may have been greater.

A similar study comparing expert-novice differences in the pre-movement components of the MRCP was conducted by Kita et al. (2001). In this study the expert group comprised four male kendo performers and two male gymnasts, whilst the novice group was made up of nine non-athletes (six female, three male). The authors stated that all the athletes were top ranked athletes in Japan. The movement task was a self-paced wrist extension action, and was chosen because the athletes used wrist extension movements extensively as part of their daily training. The mean amplitudes of the BP over the motor cortex (electrode sites C3, Cz and C4) were significantly smaller in the athlete group than in the control group. The amplitude of the NS' was smaller in the athlete group at these sites but the difference was not significant. There was also a difference in the onset times of the MRCP between the groups, with the athlete group exhibiting a significantly later MRCP onset compared to the control participants (approximately 400 ms prior to movement onset in the athletes, compared to approximately 1500 ms prior to

movement onset in the control participants). These results illustrate that the MRCP of athletes differ to those of non-athletes when performing a task with which the athletes have extensive experience. Long-term potentiation is a relatively long lasting increase in synaptic activity (Martinez & Derrick, 1996) that leads to enhanced 'communication' between two or more neurons. The authors concluded that long-term training of a certain task brings about the process of long-term potentiation, causing the neural circuits of athletes to become specific, resulting in the reduced amplitude and later onset of the MRCP.

A recent study that assessed MRCP differences between expert and novice performers was conducted by Hatta et al. (2009). As with the Kita et al. (2001) study, the MRCP recorded from the motor cortex of elite male kendo athletes was compared to a group of control participants. The kendo athletes had a mean of 16.4 years' experience in the sport, whilst the control group rarely engaged in physical exercise. The movement task was a self-paced, handgrip action using the non-dominant hand. Participants had to squeeze at 20% of their maximum voluntary contraction (MVC) to reach a predefined target on an oscilloscope. This task was chosen as the kendo athletes regularly performed gripping actions with their non-dominant hand as part of their martial art training. In contrast to previous studies that have adopted this paradigm, no significant differences were reported between groups in the amplitude of either the BP or NS'. Consistent with previous research however the BP onset time was significantly later in the kendo athlete group than in the control group. The authors suggested that the shorter BP onset time for the kendo athletes shows that they performed a non-dominant handgrip task "more smoothly" (p. 107) than the control group. Given that the kendo athletes were used to non-dominant hand gripping in their daily training, and the control participants were not,

Hatta et al. proposed that central motor control of hand grip movements becomes specifically developed and more efficient through long-term motor practice. Furthermore, the authors proposed that the lack of amplitude differences in their study may have been due to the fact that they regulated the force of the movement (20% MVC), whereas other studies did not (e.g., Kita et al., 2001). They suggested that unless force is regulated, the athletes may be able to perform the task easily, resulting in smaller amplitude MRCPs than the control group.

In summary, previous research that has compared skill-related differences in the MRCP between expert and novice performers has yielded two consistent findings. First, the pre-movement components of the MRCP have been reported to be of significantly smaller amplitude in the expert performers, compared to the novices. This indicates that expert performers require less activity in areas of the motor cortex when planning and preparing to perform an action. In turn, this reduced activity has been interpreted to indicate reduced effort expenditure in the motor cortex of the expert performers during the planning and preparation phase of a movement (Di Russo, Pitzalis, et al., 2005). Second, the onset time of the MRCP has been reported to be significantly later (i.e., closer to movement onset) in the expert group compared to the novices. A later onset of the MRCP may indicate more efficient motor preparation (Hatta et al., 2009). Typically, authors have proposed the long-term practice or training undertaken by the expert performers as the reason for these differences. Taken together, the results of these experiments indicate that following long-term training, the motor cortex of the expert performer exerts 'less effort' and is more efficient when planning and preparing to perform a skilled action. In the only MRCP study to also include a performance measure in addition to the MRCP measure, Fattapposta et al. (1996) showed that this reduced

cortical activity in the expert group was also accompanied by superior performance compared to the novices. This concept has been termed *neural efficiency* (Del Percio et al., 2008). According to this concept, individuals who perform a skill to a high standard are likely to have more efficient cortical functioning when performing that skill, compared to individuals who perform to a lower standard (Babiloni et al., 2010). The common assumption that neural efficiency underlies the acquisition of motor skills is challenged by the research reported in the present thesis.

It is important to remember that, whilst the interpretation of this cross-sectional data seems sensible, EEG can only provide data about the activity of the cortex directly beneath the electrode. Using EEG it is not possible to obtain a measure of activity from all the motor regions of the brain. By using solely EEG data it is not possible to make claims about neural efficiency of the motor areas, as the technique is unable to detect the activity at sub-cortical levels (Hatfield et al., 2006). It is possible that, as a result of skill learning, the reduced activity in the motor cortex may be accompanied by an increase in activity at other motor regions of the brain such as the basal ganglia or the cerebellum. Recent evidence from research using brain imaging techniques such as fMRI may provide a clearer indication of whether neural efficiency of motor areas occurs following motor skill learning. This will be discussed further in section 3.3.

3.2 – Supporting evidence from background EEG studies

Background EEG research tends to focus on changes in the frequency of the EEG signal. Much of the research examining changes in background EEG related to skilled movement and movement preparation has examined changes in the alpha rhythm (e.g., Crews & Landers, 1993; Haufler, Spalding, Santa Maria, & Hatfield, 2000; Janelle et al.,

2000). The alpha rhythm occurs in the 8-13 Hz frequency band and originates at the back of the head before becoming widely distributed over the scalp (Niedermeyer, 2005). Historically, activity within a participant's alpha frequency band has been associated with a relaxed state of mind, and is disrupted with any form of mental activity (Andreassi, 2007). Alpha is produced when an individual is inactive, for example, when sitting quietly, but its amplitude is reduced, or even completely blocked, with physical or mental activity (Andreassi, 2007). When investigating alpha in relation to movement, researchers often study event-related desynchronisation (ERD) of the alpha rhythm. ERD describes the short duration and regionally localised attenuation or blocking of the alpha power band that is directly related to an event (Pfurtscheller, 1992). In relation to movement production, alpha rhythm ERD tends to occur around two seconds prior to movement onset over the contralateral Rolandic region, before becoming bi-laterally symmetrically distributed immediately prior to movement execution (Pfurtscheller & Lopes da Silva, 1999a). The magnitude and size of the ERD may reflect the mass of neural networks involved in the performance of a task at a specific time (Pfurtscheller, Stancak, & Neuper, 1996). ERD may therefore be a correlate of an activated cortical area, whilst the opposite phenomenon, event-related synchronisation may be a correlate of an inactive or resting cortical area (Pfurtscheller, 2001). The magnitude of alpha rhythm ERD prior to movement production could therefore provide an indication of the level of cortical activity involved in planning and preparing to perform a movement.

Several studies have investigated differences in alpha activity over the motor cortex between groups of expert and novice performers prior to movement onset in skilled motor tasks (e.g., Haufler et al., 2000; Janelle et al., 2000). For example, Janelle et al. (2000) examined expertise differences in cortical activity during rifle shooting. In this

study, a group of expert shooters were compared with a group of experienced shooters. Both groups had participated in shooting for around 17 years, but the expert group had been involved in competitive shooting for 14 years, compared to only 4 years competitive experience in the experienced shooter group. The expert shooters performed significantly better on the shooting task. While both groups showed increased alpha activity in the left hemisphere compared to the right, this increase was significantly greater in the expert shooters compared to the experienced group. As mentioned above, an increase in alpha power prior to movement may reflect a resting or inactive cortical area. These results could therefore be interpreted as indicating that, as there was greater alpha power in the expert group prior to shooting performance, the expert shooters were able to prepare their shots with reduced cortical activity compared to the experienced group.

A similar study was conducted by Haufler et al. (2000) who compared the EEG profiles of expert and novice shooters during shooting performance and during dot localisation and word finding comparative tasks. By using one task that the expert group had considerably greater experience in, and two tasks that neither group had a greater experience of performing, the authors aimed to determine whether any differences between groups were specific to their field of expertise. The expert shooters performed significantly better than the novices at the shooting task, whilst performance was similar between groups on the verbal and spatial tasks. During the aiming process prior to the trigger pull, the expert shooters showed a cortical profile of higher background alpha power than the novice shooters at all electrodes sites. This difference was more evident in the left hemisphere at central, parietal and temporal regions (C3, P3 and T3). The experts and novices showed similar cortical profiles during both comparative tasks. These findings could be interpreted to indicate a more efficient cortical processing prior to

shooting performance in the expert group. As similar cortical activity was reported between groups on the comparative tasks that both groups had equal prior experience of, it appears that any neural efficiency that occurs is experience dependent.

Although numerous studies of background EEG offer support for the findings of cross-sectional MRCP studies (i.e., reduced cortical activity prior to task performance in expert performers compared to novices), it is important to note that the two approaches do not measure the same thing. Pfurtscheller and Lopes da Silva (1999b) proposed that the waves and oscillations of the ongoing background EEG may be common activity of a large number of neurons, whilst the event-related low frequency potentials may depend on synchronous activity of neurons in a relatively small area of the cortex. Babiloni et al. (1999) reiterated this, suggesting that alpha ERD may be associated with a "functional alerting of wider cortical populations" (p. 662) such as the SMA, posterior parietal areas and bi-lateral primary sensorimotor areas. They suggested that MRCPs on the other hand are principally associated with increased excitability of cortical areas such as the SMA and contralateral sensorimotor areas, which are specifically involved in the selection, planning and running of motor commands. Changes in the alpha rhythm (ERD) prior to movement production may therefore reflect a general decrease in cortical activity in a wide range of cortical areas, whilst the MRCP may reflect specific changes in activity in cortical areas associated with movement production. Based on this it may be more suitable to examine changes or differences in the MRCP, as opposed to alpha, when investigating skill-specific changes in cortical functioning. Despite this, the consistent findings from background EEG research of increased alpha (i.e., reduced activity) in experts, compared to novices, prior to movement production partially corroborate the results reported in the cross-sectional MRCP studies discussed in section 3.1.2.

3.3 – Supporting evidence from fMRI studies

In addition to the EEG and skill learning literature much research has investigated human motor area functioning in relation to skill learning using brain imaging techniques, such as fMRI. The most common use of fMRI is to study the blood oxygen level dependent (BOLD) signal (Amaro & Barker, 2006; Arthurs & Boniface, 2002). This method exploits differences in the magnetic properties of oxygenated and deoxygenated blood flow to provide an indication of the level of cortical activity (Casey, Davidson, & Rosen, 2002). When parts of the brain are activated, a localised increase in blood flow increases blood oxygenation in that part of the brain, causing the fMRI BOLD signal to increase (Casey et al., 2002). The BOLD signal therefore measures changes in neuronal activity via its assumed haemodynamic correlate, and as such provides an indirect measure of neuronal activity (Arthurs & Boniface, 2002). A stronger BOLD signal is generally thought to reflect a greater amount of blood flow to a certain part of the brain, which could be interpreted as indicating an increase in activity in that area of the brain.

In relation to skill learning, Krings et al. (2000) investigated whether the degree of BOLD activation during performance of a motor task was influenced by the motor experience of the participants. A group of professional pianists and a group of non-musician control participants performed a complex, uni-manual, finger-thumb opposition task whilst inside the fMRI scanner. The pianists had a greater reduction in BOLD activation than the control participants in movement-related cortical sub-systems such as the pre-motor areas, primary sensory motor areas and the SMA. This reduced BOLD activity was accompanied by superior performance at the task, as measured by the increased frequency of the finger tapping in the group of professional pianists. Krings et al. interpreted this to mean that the pianist group recruited a smaller subset of neurons

to perform the task. As such, the authors concluded that following long-term practice, a use-dependent change in cortical activation occurs, allowing fewer neurons needing to be activated to perform the same task.

Further experiments have since extended the research to bi-manual finger tapping tasks and reported similar results in numerous movement-related cortical areas (e.g., Haslinger et al., 2004; Jancke, Shah, & Peters, 2000; Koeneke, Lutz, Wustenberg, & Jancke, 2004). For example, Jancke et al. (2000) compared activity in motor areas of the brain between two professional classical pianists and two non-musician control participants during performance of bi-manual and uni-manual finger tapping movements. In the bi-manual task, one hand tapped a slow rhythm whilst the other hand tapped a faster rhythm at twice the speed of the slow hand. In the uni-manual tasks, one hand tapped a rhythm at either a fast or slow pace. For all types of movement task, there was less activity in the primary and secondary motor areas in the professional pianists, compared to the control participants. This led the authors to conclude that following long-term training, professional pianists were able to use smaller neural networks within the primary motor cortex, SMA and pre-supplementary motor areas, in order to control bi-manual hand movements. Jancke et al. speculated that this could indicate a more efficient control of their hand movements. In similar experiments, Haslinger et al. (2004) and Koeneke et al. (2004) have also reported that the cerebellum and the right basal ganglia are less active in experienced musicians, compared to novices, during performance of finger tapping movements. In line with the study by Jancke et al., these researchers also concluded that long-term motor practice may bring about increased efficiency of the cortical systems responsible for bi-manual movement.

Taken together, the results of the above fMRI studies seem to indicate that experienced musicians exhibit less BOLD activity in cortical areas associated with movement during both uni-manual and bi-manual tasks, compared to non-musician control participants. This has consistently been interpreted to indicate that as a result of the long-term practice or training undertaken by the musician group, the movement task is able to be performed more efficiently, with reduced cortical activity. Although based on differences in haemodynamic, rather than synaptic activity, these conclusions from fMRI studies offer support for the findings reported in cross-sectional EEG studies, which have compared the amplitude and onset latency of the MRCP in expert and novice performers. Furthermore, as these experiments reported a global decrease in activity in motor areas, the results provide support for the idea of neural efficiency associated with motor skill learning.

3.4 – Limitations of previous research

The above research has provided useful insights into the cortical processes that may be involved in motor skill learning, however the body of research is not without its limitations. One limitation is that there is a lack of ecological validity within the literature. Ecological validity is defined by McBurney and White (2010) as "the extent to which an experimental situation mimics a real world situation" (p. 177). For a study to have ecological validity however does not simply mean that the experimental setting is the same as the real-world setting the task is usually performed in. Furthermore, it should not be interpreted that the more realistic the experimental setting is, the greater the ecological validity of a study (see Coolican, 2009). Rather, from a skill learning perspective, the movement task used in the laboratory setting should be as similar as possible, if not identical, to the skill the experiment is investigating. For a study to have

ecological validity, the task employed in the experimental setting must bear a close resemblance to how the task is performed in a real world environment. This is important if the purpose of the research is to describe or demonstrate a particular phenomenon (Brewer, 2000). If a researcher aims to demonstrate the differences in cortical processing between a group of experts and a group of novices as a result of long-term skill learning, it is therefore important that the movement task used in the experiment is the same as the task one group has long-term experience of performing.

In the cross-sectional MRCP comparison studies described in section 3.1.2, there was a lack of ecological validity due to the reductionist approaches employed. Typically, the tasks used in the experimental setting are far removed from and simpler than the skills the expert groups have long-term experience of performing. For example, both Di Russo, Pitzalis, et al. (2005) and Fattapposta et al. (1996) used button pressing tasks and applied the results to the sports of clay target and pistol shooting, respectively. The rationale for this was that the action required to press the button was similar to that required to pull the trigger of a gun. Similarly, wrist extension and hand gripping tasks were used by Kita et al. (2001) and Hatta et al. (2009) respectively, and applied to the sport of kendo based on the fact that these actions are regularly used by these athletes in their daily training. Finally, finger tapping tasks have been applied regularly to piano playing (e.g., Haslinger et al., 2004; Jancke et al., 2000; Koeneke et al., 2004; Krings et al., 2000), on the basis that the action required when tapping the fingers is similar to that required to press the keys of a piano. Although the movement tasks used in these experiments were selected on the basis that the action was similar to the task in which the performers had expertise, the tasks only focused on the mechanical actions required to perform the movement. The result of this is that the cortical processing involved in

other aspects of the task performance were not accounted for. For example, in the shooting studies, the cortical activity involved in holding, steadying and aiming the gun were excluded. Similarly, in the studies that required pianists to perform finger tapping tasks, aspects of musicality related to timing and the tone of the notes were excluded. The fact that these experiments reported differences in cortical activity between the experts and the novice participants indicates that, although the experimental tasks lacked ecological validity, there may have been positive transfer between the tasks. Positive transfer is defined by Magill (2011) as "the beneficial effect of previous experience on the learning or performance of a new skill, or on the performance of a skill in a new context" (p. 291). The evidence presented in the MRCP studies could indicate that positive transfer had occurred at a cortical level, resulting in reduced amplitude MRCPs in the experts when performing a task related to their area of expertise. Had the experiments studied the skills as a whole, and in an ecologically valid way, rather than adopting a more reductionist approach, the magnitude of the cortical differences between the groups may have been greater. This would provide a clearer picture of the cortical differences associated with motor task performance between experts and novices.

Equipment constraints are possibly responsible for the lack of ecological validity within the studies mentioned above. In order to obtain EEG data sufficiently accurate to be usable it is essential that participants keep their head and body as still as possible, as minimal head, body, or electrode wire movements can cause artefacts in the EEG recording (Degabriele & Lagopoulos, 2008). As such, in many cases it is difficult to record EEG during ecologically valid movement-based tasks. Previous studies however have been successful in recording EEG during the movement preparation period prior to ecologically valid tasks such as simple piano playing (e.g., Kristeva, 1984), violin playing (e.g., Kristeva,

Chakarov, Schulte-Monting, & Spreer, 2003), rifle and pistol shooting (e.g., Hung, Haufler, Lo, Mayer-Kress, & Hatfield, 2008; Kerick, Hatfield, & Allender, 2007; Konttinen & Lyytinen, 1992, 1993; Loze, Collins, & Holmes, 2001), archery (e.g., Salazar et al., 1990) and golf putting (e.g., Crews & Landers, 1993). It is therefore possible to record EEG in some ecologically valid movement-based settings. As such, further studies should attempt to replicate the results of cross-sectional MRCP studies using an ecologically valid motor task (Nakata et al., 2010).

A further limitation to the body of research regarding skill learning-related changes in motor cortex functioning is the lack of longitudinal research. Most MRCP studies have adopted a cross-sectional approach and compared activity within the motor cortex of expert performers with that of a group of novices (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001). Differences found between the two groups have then been attributed to the long-term training undertaken by the expert group. This is problematic as it is possible that the differences between groups are due to an innate predisposition in the expert performers. For example, individuals who become skilled musicians or athletes may start out with a different cerebral structure to those who do not attain a high level of performance (Poldrack, 2000). Studies investigating motor learning using within-participant designs would help address this issue. Where MRCP studies have assessed learning using a within-participant design, this has typically taken place over the course of a single testing session (e.g., Dirnberger et al., 2004; Lang et al., 1992; Niemann et al., 1991; Taylor, 1978). In order to establish whether the differences reported in studies using a cross-sectional design are the result of the long-term training undertaken by the expert group, further research into

the MRCP is needed employing a longitudinal approach over a period of months and using ecologically valid motor tasks (Nakata et al., 2010).

Using musicians and an ecologically valid musical skill may be a suitable way to address these issues. Musical performance demands complex motor operations, involving precise timing and co-ordination of both hands (Norton et al., 2005). It therefore requires a high degree of motor control for musicians to perform accurately and expressively (Watson, 2006). Experienced musicians have typically spent many years learning to perform complex motor skills (Munte, Altenmuller, & Jancke, 2002). Such individuals therefore provide an ideal participant group for researchers wishing to study both structural and functional adaptations in the human brain resulting from the long-term practice of motor skills (Jancke, 2002). Experienced musicians and a musical skill would therefore make a suitable participant group and task for future experiments investigating the cortical processes involved in motor skill learning.

3.5 – Summary and conclusions

This section will summarise and conclude the literature review, before the aims of the thesis are stated in the following section. The movement-related cortical potential is thought to reflect the cortical activity involved in the planning and preparation of voluntary movement production. There has been some, although not extensive, research examining the MRCP in an attempt to identify possible changes in cortical function as a result of motor skill learning. This has typically adopted a cross-sectional approach by comparing the MRCP of expert performers with the MRCP of a group of novices. Expert performers generally produce MRCPs of a smaller amplitude that begin later (closer to movement onset), compared to novice control participants. The research discussed in this

literature review has claimed that this smaller amplitude and later onset time reflects a reduced amount of cortical activity required by the experts to plan and prepare to perform the task, resulting in a more efficient motor preparation. These differences are usually attributed to the long-term training undertaken by the expert group. Support for these findings has been provided by additional research investigating changes in background EEG and research using fMRI.

Although this body of research has provided interesting insights into the changes in cortical activity that may be associated with motor skill learning, there are two significant omissions in the previously published literature. First, the movement tasks used generally lack ecological validity, in that the tasks differ as to the skills that the expert groups have long-term experience of using. Second, any differences reported in these cross-sectional studies are proposed to be the result of the long-term training undertaken by the expert group, yet there is a lack of longitudinal evidence to support this claim. This thesis addressed these issues, using a musical task to provide a more complete understanding of the cortical processes involved in motor skill learning.

3.6 – Aims of the research programme

This thesis investigated the cortical processes involved in motor skill learning, by using EEG to record the MRCP. Section 3.4 of the literature review summarised the key limitations of and omissions in the published literature on the cognitive and behavioural neuroscience of motor skill learning, which are addressed in this thesis. The lack of ecological validity in cross-sectional studies and the lack of longitudinal research were highlighted as key areas requiring further investigation. The following chapters of this thesis address these concerns as follows:

- An ecologically valid scale-playing motor task on the guitar from which it was possible to record the MRCP was identified in Study 1.

- In Study 2, the lack of ecological validity in cross-sectional studies was addressed by comparing differences in the MRCP, recorded during a scale-playing task on the guitar, between a group of experienced guitarists and a group of non-musicians. For the purposes of these experiments, non-musicians were classified as individuals with no prior experience of playing any musical instrument.

- To verify whether differences reported in cross-sectional studies are the result of the practice or training undertaken by the experienced performers, changes in the MRCP associated with short-term motor skill practice of the scale-playing task were examined in Study 3.

- To address the lack of longitudinal work into the neuroscience of motor skill learning, changes in the MRCP that were brought about by learning to play the guitar over a sixteen-week training and de-training period were explored in Study 4.

- To complete the thesis, within-session changes in the MRCP that were associated with learning to play the guitar over a longitudinal period were investigated in Study 5.

Chapter 4

Study 1: Recording the movement-related cortical potential prior to performance of an ecologically valid motor task

4.1 – Introduction

As discussed in the literature review (see Chapter 3), some cross-sectional neuroscientific research has focused on the cortical processes involved in motor skill learning. This research has consistently reported that skilled performers require reduced cortical activity, compared to novices, during motor skill preparation and performance (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Haslinger et al., 2004; Hatta et al., 2009; Jancke et al., 2000; Kita et al., 2001; Koeneke et al., 2004; Krings et al., 2000).

Although this body of research has produced some interesting findings, and has provided a useful insight into the cortical process that may be involved in motor skill learning, some limitations to this research were highlighted in section 3.4 of the literature review. One limitation is that the research lacks ecological validity; the movement tasks used in these experiments are far removed from the motor skills being studied. To rectify this limitation it was recommended by Nakata et al. (2010), and reiterated in section 3.4 of the literature review, that future research into the neuroscience of motor skill learning should attempt to replicate the above studies in a more ecologically valid way. It was first necessary however to establish an ecologically valid motor task from which it was possible to record the MRCP.

4.2 – Aims of the investigation

This study aimed to establish the efficacy of recording MRCPs prior to performance of an ecologically valid motor task.

4.3 – Hypothesis

It was hypothesised that it would be possible to record MRCP waveforms that showed similar features to the schematic MRCP shown in Figure 2.1, prior to performance of an ecologically valid motor task.

4.4 – Method

4.4.1 – Selecting the movement task

Originally, it was planned to use a pistol-shooting task during all the studies in this research programme. The rationale for this was that, in the proposed cross-sectional study, the 'expert' group would comprise the Great Britain 10 metre air pistol shooting squad. Due to funding constraints however the squad disbanded during the early stages of this research programme. This resulted in access to any elite shooters being severely restricted, and so another task and expert group were sought.

A guitar-playing task was chosen for three reasons. First, as discussed in section 3.4, experienced musicians have typically had long-term exposure to complex motor skill learning (Munte et al., 2002). As a result, they are an ideal participant group to use when investigating changes in cortical activity as a result of motor learning (Jancke, 2002). A group of experienced musicians would therefore provide a suitable participant group for the proposed cross-sectional study in this thesis. Second, it was essential to find a motor task that required minimal whole body movements either prior to, or during,

performance of the task. This was important as if performance of the task involved excessive movement, movement artefacts would contaminate the EEG recording rendering it impossible to obtain valid MRCPs. It was expected that a guitar-playing task performed in a seated position would meet this criterion. Third, in anticipation that the chosen task would be used in a cross-sectional study, it was also important to find a motor task for which it was possible to access a sample of 10-15 experienced or expert performers. Whilst it may have been possible to record the MRCP from certain sporting tasks that require little movement to perform, for example archery or rifle shooting, it was easier to locate a sample of experienced performers if a musical task was used. Although not in the context of skill learning, the MRCP has been recorded previously during ecologically valid musical performance on the piano (Kristeva, 1984) and violin (Kristeva et al., 2003). As such, either of these musical tasks could have been suitable, however access to a sample of experienced pianists or violinists was not possible. After consultation with staff members from the university's music department, it was decided that a guitar playing task would provide the best opportunity to access a sample of experienced musicians from a pool of guitarists either studying or teaching guitar at the university, and from local music schools. A guitar-playing task was therefore trialled in this study.

The nature of the guitar playing task that the participants would perform was then addressed. The MRCP could have been recorded during a variety of guitar playing tasks, including playing a scale, a sequence of chords, or a song. To determine what task to use, an assessor from the Rockschool rock and pop music examination board was consulted. After explaining the nature of the proposed experiments to the assessor, it was decided that a scale-playing task may be the most suitable, as it would require little movement to

perform and it would be easy to assess its performance. The Rockschool Guitar Syllabus consists of eight grades, in ascending order of difficulty (Rockschool, 2006). It seemed logical that the scale-playing task used in this research programme should correspond to a particular grade in the Rockschool Syllabus. The assessor suggested that the G Major scale, played in time with a metronome at a tempo of 100 beats per minute (bpm), would be a suitable task. This is a Rockschool Grade 2 assessment piece (Rockschool, 2008), which the assessor predicted would be easy for experienced guitarists to play, whilst still achievable for non-musicians with some practice. As such, this scale-playing task was trialled in this study.

4.4.2 – Participants

Three male participants (mean age 22.67 years ± 1.73) volunteered to take part in this study. All participants were right handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971; see Appendix C). All participants were non-musicians, with no prior experience of playing the guitar or any other musical instrument. Prior to commencing the experiment the participants provided their written informed consent to take part in the study (see Appendix E), which had been granted ethical approval by the Exercise and Sport Science departmental ethics committee at the Manchester Metropolitan University.

4.4.3 – Electrophysiological recording

Electroencephalography (EEG) was recorded continuously throughout the testing session from six, 6 mm diameter, silver/silver-chloride electrodes positioned at sites FC3, FCz, FC4, C3, Cz, and C4 (see Figure 4.1), according to the 10-10 system of electrode placement (Nuwer et al., 1998). These sites corresponded to the cortical areas overlying

the hand representations of the left (FC3 and C3) and right (FC4 and C4) motor cortex, as well as over the supplementary motor area (FCz and Cz). EOG was also recorded from below and adjacent to the left eye to monitor both vertical (VEOG) and horizontal (HEOG) eye movements. All electrodes were referenced to linked mastoids and a ground electrode was placed at the centre of the forehead. Prior to electrode attachment, the recording sites were gently abraded with NuPrep skin preparation paste (DO Weaver, Aurora, CO, USA). Electrodes were then attached to the scalp using Ten20 conductive EEG paste (DO Weaver, Aurora, CO, USA). This paste was selected as research by Tallgren et al. (2005) recommended it was the best conductive gel to provide stable DC-EEG recordings with minimal signal drift, due to its high NaCl concentration (see section 2.3.3). This was subsequently confirmed during early pilot testing for this study. Electrode impedances were kept homogenously low at, or below 5 kΩ throughout the experiment. Based on the results of pilot testing (see Appendix A), data collection commenced 45 minutes after the electrodes were attached to the scalp to minimise signal drift. After 45 minutes, the electrode impedances were re-checked to confirm that the impedance values remained homogenously below 5 kΩ. The EEG and EOG were recorded using a NeuroScan Synamps amplifier and Scan 4.3 software (Compumedics Neuroscan, Charlotte, NC, USA) with a gain of 1000 and an A/D sampling rate of 1000 Hz. The bandpass filter for the cortical channels was set at 0 – 30 Hz, whilst the bandpass filter for the EOG channels was set at 0.15 – 30 Hz. The default notch filter at 50 Hz was turned on, but given the online filter settings this was irrelevant to the data capture.

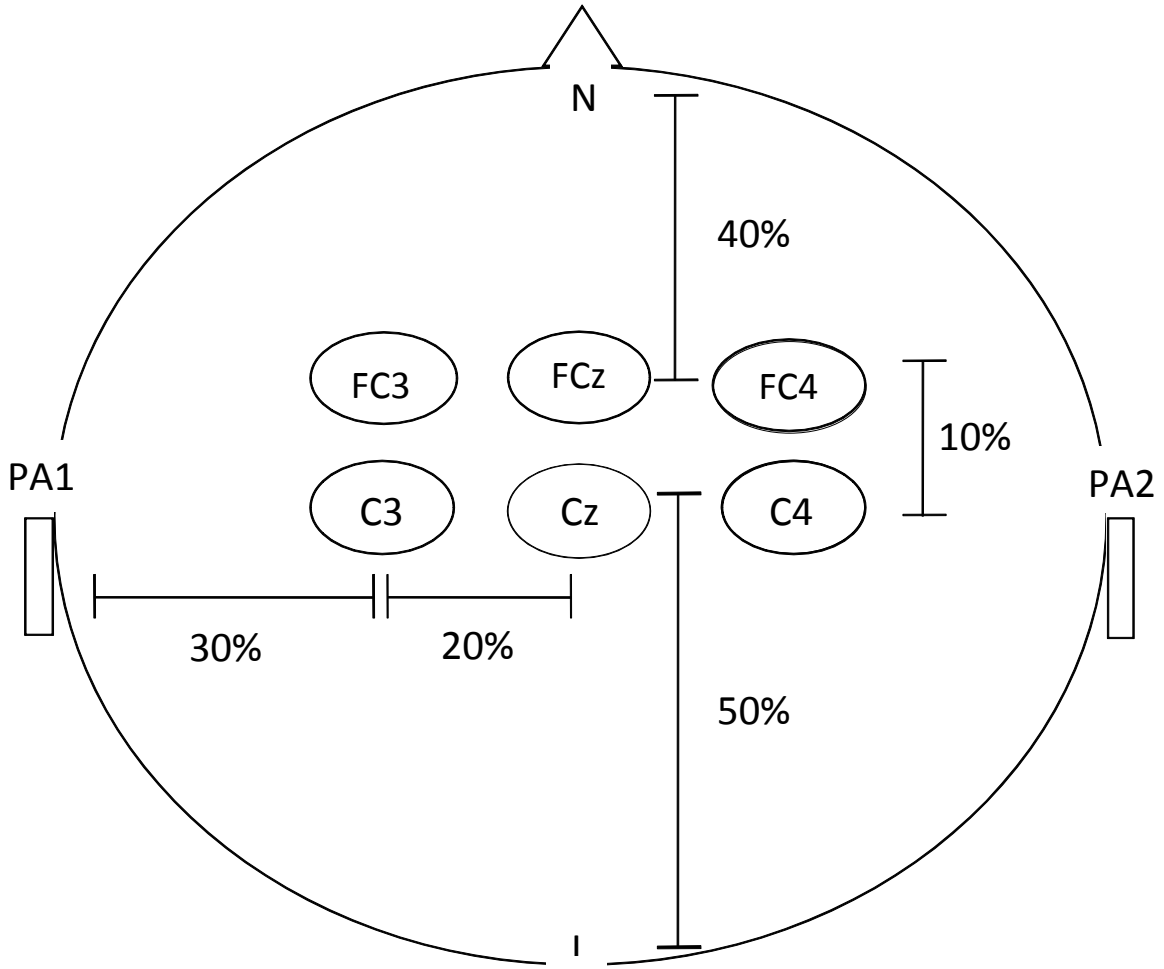

Figure 4.1: A schematic representation of the electrode locations used in Study 1. According to the 10-10 system (Nuwer et al., 1998), all electrodes are located at 10% deviations from each other. The nasion (N), inion (I), and the left (PA1) and right (PA2) pre-auricular points are also shown.

4.4.4 – Experimental procedure

Participants performed 100 repetitions of the first seven notes of the G Major scale (see Figures 4.2 and 4.3) on a Yamaha Pacifica 112V electric guitar. This number of repetitions was chosen as it is greater than the 64 trials Gerbrandt (1978) stated were required to obtain an acceptable signal-to-noise ratio. It is also consistent with, or greater than, the number of trials generally recorded in MRCP skill learning experiments (e.g., Dirnberger et al., 2004; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001; Lang et al., 1992). The scale-playing task was performed acoustically, as connecting the electric guitar into an amplifier introduced electrical interference into the EEG recording (see Appendix D). The participants were seated and, in accordance with the Rockschool Grade 2 guitar examination procedures (Rockschool, 2008), were instructed to play in time with an auditory metronome set at 100 bpm. The metronome ran continuously throughout the experiment and participants were free to initiate each performance of the scale when ready. Participants were however instructed to leave approximately ten seconds in between each repetition of the scale. To minimise movement artefacts and enhance the quality of the EEG recording, participants were asked to keep as still as possible and to refrain from tapping their feet or nodding their head in time with the metronome. Participants were also instructed to avoid blinking immediately prior to and during performance of the task in order to reduce the occurrence of eye-movement artefacts on the EEG trace (see section 2.3.1).

4.4.4.1 – De-prep procedure

At the end of the testing session the electrodes were removed from the participants' scalp. The scalp was then cleaned using warm water to remove any

remaining conductive paste from the head. The electrodes were cleaned using warm water and a soft toothbrush to remove any conductive gel from the electrodes. Based on the recommendation by Ferree et al. (2001), the electrodes were then sterilised, using Milton sterilising fluid (Ceuta Healthcare Ltd, Dorset, UK), to eliminate the risk of passing on blood-borne infections between participants. This de-prep procedure was consistent across all studies reported in this thesis.

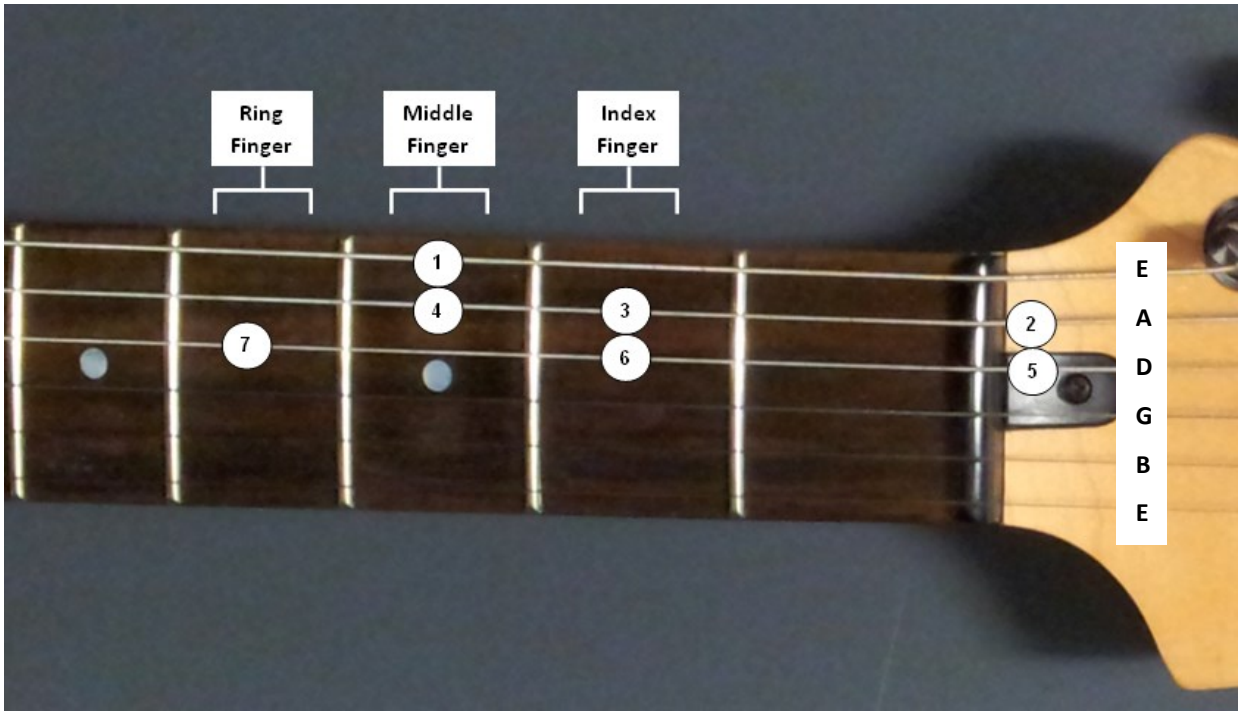

Figure 4.2: The first seven notes of the G Major scale as played on the guitar. The circled numbers show where the participants had to press the strings with their left hand to play the notes, in the ascending order in which the notes were played. Notes where the circled numbers are not located on the fret board (2 and 5) indicate open notes, where no string is pressed with the left hand to play the note. Participants were advised to play notes on the second fret with their index finger, third fret with their middle finger and fourth fret with their ring finger. The letters on the right of the figure show the names of each string.

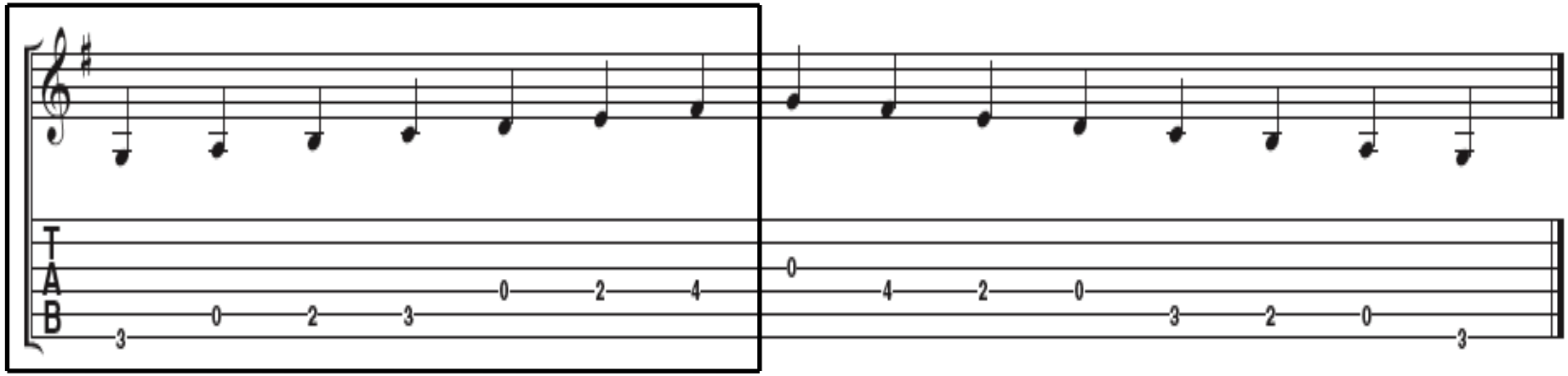

Figure 4.3: Treble clef and tab versions of the G Major scale as played on the guitar. Participants played the first seven notes, highlighted within the black box, at a tempo of 100 beats per minute. In tab format, the horizontal lines represent each of the six strings on the guitar. The bottom line represents the bottom E string (the thickest string) and the top line represents the top E string (the thinnest string). The numbers depict which fret the string should be pressed down at to successfully play the note. Figure adapted from Rockschool (2008).

4.4.5 – Marking movement onset on the EEG recording

As the MRCP is time-locked to movement onset, it was important to devise a method for accurately marking movement onset on the EEG trace. Traditionally this is determined by recording EMG from the muscles involved in the movement, alongside the EEG recording (e.g., Del Percio et al., 2008; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001; Tarkka, 1994). In the study by Tarkka (1994), the MRCP was recorded whilst participants performed index finger abduction movements. Concurrent to the EEG recording, EMG was recorded from the first dorsal interosseus muscle, the prime mover in index finger abduction movements. Movement onset was taken at the point on the EEG recording where a sharp increase in EMG activity occurred, and the MRCP was averaged around this EMG onset. This is a common method for marking movement onset in MRCP studies. As a key focus of this research programme was to record the MRCP during guitar playing in an ecologically valid way, this method was deemed inappropriate for use in this study. Following a discussion with an assessor from the Rockschool examination board, it was decided that attaching EMG electrodes onto the participants' hand as they played the guitar would be unnatural for the guitarists and would interfere with their ability to move their fingers freely. This would result in them being unable to play the guitar properly and as such would interfere with the ecological validity of the study. It was therefore necessary to establish an alternative method for marking movement onset on the EEG trace.

An alternative method is to use a microphone to detect the sound generated by the onset of the movement. This has typically been used during tasks such as pistol or rifle shooting, where movement onset is accompanied by an auditory output (e.g., Deeny, Hillman, Janelle, & Hatfield, 2003; Holmes, Collins, & Calmels, 2006; Loze et al., 2001). For

example, when investigating changes in alpha activity associated with air pistol shooting, Loze et al. (2001) used a microphone, positioned to the side of the shooter, to detect the moment of trigger release. When the microphone detected the sound of the shot being fired, a signal was sent into the EEG amplifier and served as a marker of movement onset. A similar system may have been possible in the current series of studies. Unlike a shooting task however, the guitar-playing task used in this study was performed in time with an auditory metronome, which ran continuously throughout the data collection period. The presence of the metronome meant that using a microphone to mark movement onset was not a viable option, as it would not have been possible to determine which signals detected by the microphone were from the guitar-playing task and which were from the metronome.

Another technique that has been used to mark movement onset on the EEG trace, in studies in which the movement task has involved pressing a button, has been to send a marker onto the EEG at the time the button is pressed (e.g., Di Russo, Pitzalis, et al., 2005; Domingues et al., 2008). The first movement when playing the G Major scale on the guitar, before plucking a string, is to press down the bottom E string at the third fret, using the middle finger of the left hand (see Figure 4.2). Using the string pressing action required to play the first note of the scale as a marker of movement onset seemed a possibility. Attaching a button or sensor onto the string itself however would alter the sound generated when playing the note, and would interfere with the ecological validity of the study. Following discussions with the technical team at the university, it was decided that a thin electrode could be attached on to the neck of the guitar behind the strings at the third fret, and connected into a spare channel on the EEG amplifier. When the string was pressed to play the first note of the scale, it made contact with the

electrode and sent a digital marker onto the EEG trace, which was then used as the point of movement onset. Pilot testing found this method effective for marking movement onset. Figures 4.4 and 4.5 show the electrode attached to the neck of the guitar and a screen shot of the EEG trace, indicating the sharp deflection caused by the string making contact with the electrode.

Figure 4.4: The method used to mark movement onset onto the EEG trace. When the first note of the scale was played, the string made contact with the thin electrode that was taped to the neck of the guitar, causing a digital signal to appear on the EEG trace.

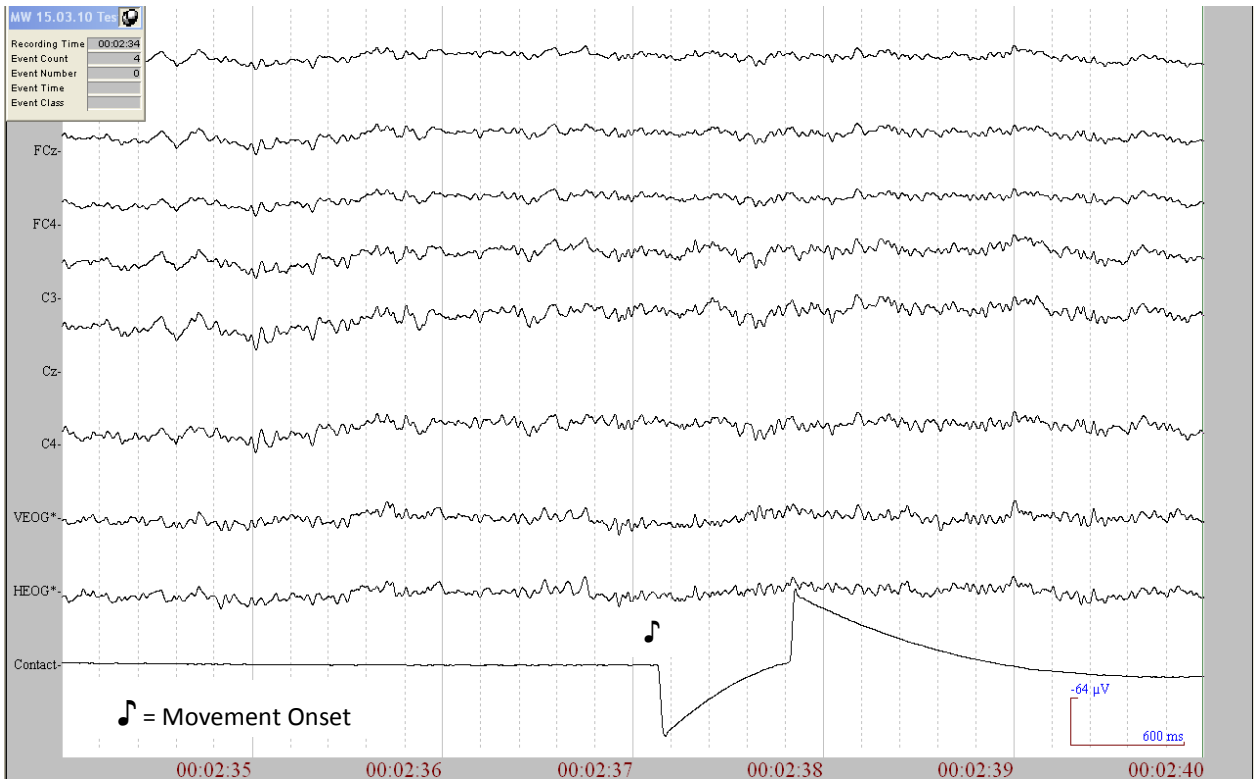

Figure 4.5: Screen shot of EEG data highlighting the point of movement onset during scale-playing on the guitar. When the first note was played a digital marker was inserted on the EEG trace causing a 100 µV step to appear on the 'movement onset' channel, indicated by the musical note (♪). This was used as the point of movement onset.

4.4.6 – Data analysis

Digital markers were inserted into the EEG recording at the points where the sharp deflection caused by the first note being played exceeded 50 µV in amplitude on the 'movement onset' channel. An offline computerised eye-movement rejection was then run on the raw data, to remove any segments of the EEG that contained artefacts in excess of 50 µV in either the VEOG or HEOG channels. As discussed in section 2.3.1, this was the same criteria outlined by both Croft and Barry (2000) and Gratton (1998). This approach is also used widely in the MRCP skill learning literature (e.g., Di Russo, Pitzalis,

et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001). An average of 10 trials per participant was removed for this reason. Following the automated EOG rejection, the data were visually scanned and additional artefacts in the recording were removed. Movement artefacts were rare since only the pre-movement components of the EEG were analysed. Using Scan 4.3 software, the EEG recording was then filtered offline with a 0–5 Hz bandpass to remove the higher frequency signals. Following this, the EEG was split into epochs of 3 seconds around the movement onset marker (2500 ms prior to and 500 ms after movement onset). The epochs were then averaged to produce the MRCP. The process of filtering, epoching, and averaging the data can be seen in more detail in Appendix B. Finally, prior to analysis, the microvolt values were converted into *z*-scores referenced to a baseline period from -2500 ms to -2000 ms. The purpose of this was to normalise the data and remove any variability in the baseline data between participants. This procedure has been used previously in MRCP studies (e.g., Rossi et al., 2000).

4.5 – Results

MRCPs in which the BP, NS', and MP components were present prior to movement onset were recorded in all participants (see Figure 4.6). The MRCP waveform shown here is similar to that shown schematically in Figure 2.1. This shows that the MRCP recorded prior to the ecologically valid guitar-playing task does not differ greatly from the 'textbook' MRCP waveform. MRCP component onset times were similar in all participants. The BP, characterised by a gradual increase in negativity, initiated around 2000 ms prior to movement onset. This rise continued until just after 1000 ms prior to movement, when the steeper gradient NS' component occurred. The NS' continued to rise until peaking with the MP in the final 200 ms prior to movement onset.

Figure 4.7 shows the data recorded at individual electrode sites from one of the three participants in this study. Similar data to those shown in Figure 4.7 were also found in the other two participants who took part in this study. As can be seen in Figure 4.7, MRCP waveforms were recorded at all six electrode sites.

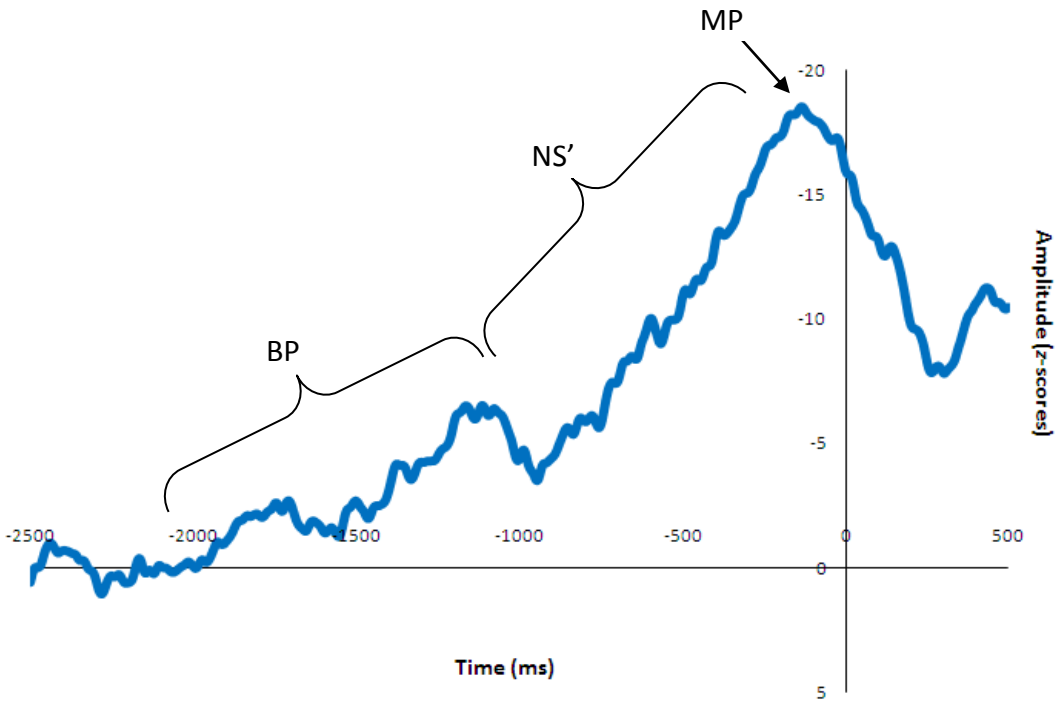

Figure 4.6: Movement-related cortical potential grand average from three non-musicians, recorded prior to the scale-playing task. Data from electrode sites FC3, FCz, FC4, C3, Cz, and C4 are included in this grand average.

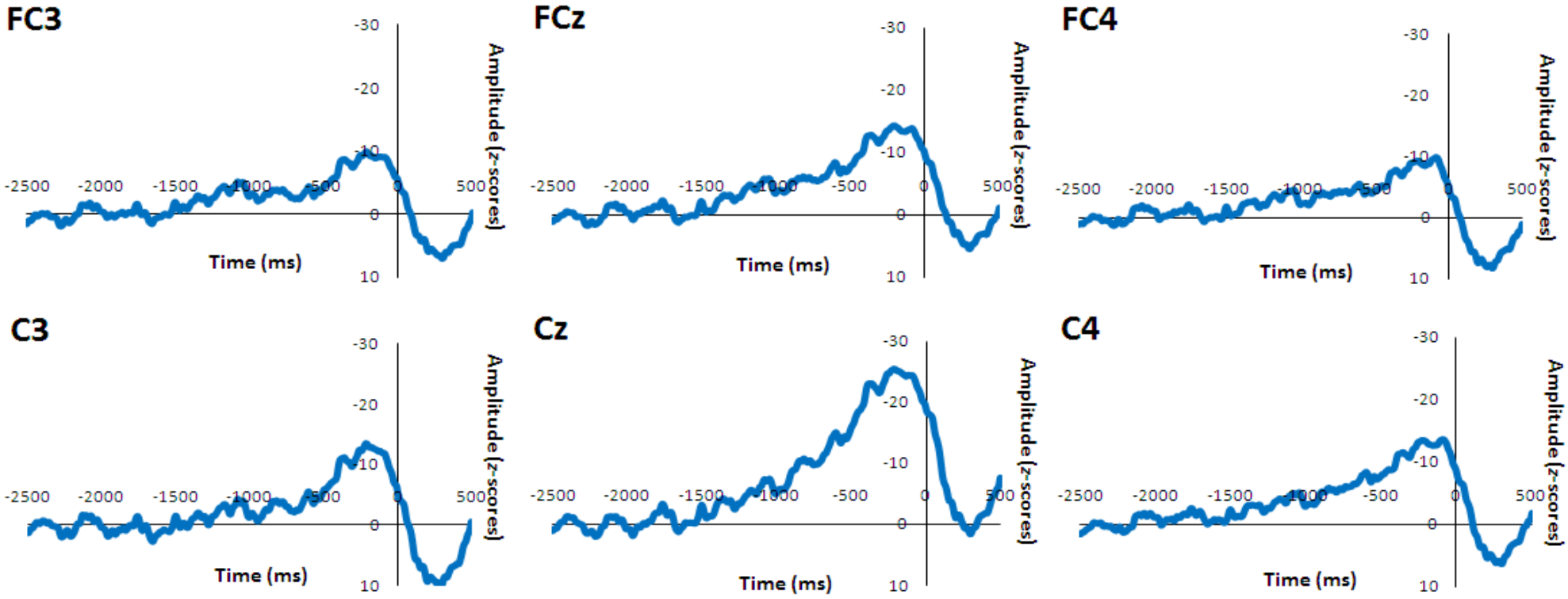

Figure 4.7: Example of typical movement-related cortical potentials recorded in Study 1. Data from one participant are presented here, recorded from electrode sites FC3, FCz, FC4, C3, Cz and C4 prior to performance of the scale-playing task on the guitar.

4.6 – Discussion

The aim of this study was to establish whether it was possible to record the MRCP from an ecologically valid scale-playing task on the guitar. Figures 4.6 and 4.7 illustrate that this was achievable, with the MRCPs recorded from all participants at all electrode sites showing a similar profile to the schematic MRCP in Figure 2.1. This confirmed the hypothesis for the study.

It is worth noting that the amplitude of the MRCP was maximal at electrode site Cz (see Figure 4.7). It is well established that the early components of the MRCP are generated in the supplementary motor area (Cui & Deecke, 1999; Deecke, 1990; Ikeda, Luders, Burgess, & Shibasaki, 1992; Shibasaki & Hallett, 2006), and as such the amplitude of the MRCP is typically largest at electrode site Cz (Shibasaki & Hallett, 2006). This finding is consistent with literature regarding the MRCP, providing face validity to the results.

The results had important implications for this research programme. As this study was successful in recording the MRCP during an ecologically valid guitar playing task, the remaining studies reported in this thesis used the same task and method. In Study 2, a cross-sectional design was used to compare differences in the MRCP between a group of experienced guitarists and a group of non-musicians as they performed the scale on the guitar. The aim of this study was to replicate and extend the findings of previous cross-sectional studies that have recorded the MRCP to investigate the cortical processes involved in motor skill learning (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001), using an ecologically valid motor task. In Studies 3, 4, and 5, within-participant designs were used to explore changes in the MRCP resulting from short-term practice on the guitar over a single testing session, and longer-term practice over periods of five, ten, and sixteen weeks. The purpose of these studies

were to verify the claims made in cross-sectional studies, that differences in the MRCP between experts and novices are the result of the long-term learning undertaken by the expert group.

Chapter 5

Study 2: Movement-related cortical potential differences between experienced guitarists and non-musicians

5.1 – Introduction

As mentioned in the literature review section of this thesis (Chapter 3), several researchers have compared differences in the MRCP between a group of experts and a group of novices in a skill, to investigate the cortical processes involved motor skill learning (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001). These studies have reported MRCPs of smaller amplitude and later onset in the expert group, compared to the novices. Such findings have been interpreted to indicate that, as a result of long-term training, the expert performers require reduced cortical activity to plan and perform a motor skill.

Whilst these studies have provided a useful insight into learning-related changes in motor cortex activity, they were criticised in the literature review for using simple, laboratory-based tasks that lack ecological validity and extrapolating the results to more complex motor skills. This led Nakata et al. (2010) to call for future studies to assess differences in the MRCP of expert and novice performers using more ecologically valid motor skills. Ideally, this would be achieved by measuring cortical activity whilst participants perform the task being investigated, as opposed to whilst participants perform a task that requires similar actions to perform as the task being studied. In Study 1 an ecologically valid scale-playing task on the guitar, from which it was possible to accurately record the MRCP, was identified. As such, the same scale-playing task was used in this study.

5.2 – Aims of the investigation

The aim of this study was to attempt to replicate and extend the findings of previous cross-sectional MRCP studies, using an ecologically valid motor task. As Study 1 showed it was possible to accurately record the MRCP during an ecologically valid scale-playing task on the guitar, the same task was used in this study.

5.3 – Hypothesis

Based on the literature discussed in Chapter 3 it was predicted that, compared to non-musicians, experienced guitarists would require less cortical activity to plan their movements prior to playing a scale on the guitar. It was therefore hypothesised that experienced guitarists would exhibit smaller amplitude MRCPs that would begin closer to movement onset than non-musicians.

5.4 – Method

5.4.1 – Participants

Ten experienced guitar players (all male, mean age 36.5 years ± 13.73) and twelve non-musicians (6 male, 6 female; mean age 25.14 years ± 7.97) participated in the study. The experienced guitarists had between 8 and 40 years (mean 18.8 years ± 11.23) of guitar playing experience and reported that they spent approximately 12.8 (± 7.35) hours per week practicing their instrument. The non-musicians had received no musical training and had no prior experience of playing the guitar or any other musical instrument. All participants were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971; see Appendix C). After reading an information sheet detailing the aims and procedures involved, all participants gave their written informed consent to take part in the study (see Appendix E). The experiment was conducted in accordance with the

Declaration of Helsinki and the experimental procedures were granted ethical approval by the Exercise and Sport Science departmental ethics committee at the Manchester Metropolitan University.

5.4.2 – Electrophysiological recording

The EEG recording procedure was identical to that described in Study 1.

5.4.3 – Experimental procedure

The experimental task and procedure were identical to those described in Study 1, with one addition. Following the 100 repetitions performed alongside the EEG recording, the guitar was connected to an Apple Mac Mini computer (Apple, Cupertino, CA, USA) and participants performed a further 20 repetitions of the scale, in time with the metronome, whilst guitar performance was recorded using Logic Express version 9 software (Apple, Cupertino, CA, USA). This allowed each participant's performance to be assessed offline. Task performance was measured by how closely the participants' played in time with the metronome. It was not to possible record the guitar performance and the EEG concurrently, as connecting the guitar to the computer introduced electrical interference into the EEG trace (see Appendix D).

5.4.4 – Data analysis

The MRCP was extracted using the same procedure described in Study 1. Data from two non-musicians were removed from the study as their EEG recordings were contaminated with ocular artefacts due to numerous eye-movements throughout the recording process. Using EOG rejection techniques would have resulted in an unacceptable amount of data loss (around 90% of trials) and correction techniques were not suitable as almost the entire recording would have needed to be corrected. This was

not desirable and so the whole data sets from these two participants were removed from the study. Data from ten non-musicians and ten experienced guitarists were therefore submitted to statistical analysis. During the EOG artefact rejection phase, an average of 17 trials per participant was rejected due to the presence of eye-movement artefacts. As highlighted in section 2.4, Gerbrandt (1978) calculated that at least 64 trials were required to obtain an acceptable signal-to-noise ration when averaging slow potential data. The mean of 83 trials per participant after EOG rejection was above this value, indicating that an adequate number of trials were included in the analysis.

For statistical analysis the mean amplitudes and onset times of the BP and NS', together with the peak amplitude of the MP, were extracted from the averaged EEG prior to movement onset at electrode sites FCz, C3, Cz and C4. MRCPs were not present in all participants at FC3 and FC4 and so therefore these sites were excluded from analysis. Following the method used in numerous MRCP experiments (e.g., Fattapposta et al., 1996; Kita et al., 2001), the BP and NS' onset times were established by visual inspection. Using Scan 4.3 software it was possible to place a cursor marker at the points of BP and NS' onset, and obtain an exact millisecond value at each cursor placement. These values were then subsequently confirmed by a member of staff independent of the supervisory team. Mean amplitude values for the BP and the NS' components were based around their respective onset times. The BP amplitude was taken as the mean amplitude from the time of the BP onset to the time of NS' onset. Similarly, the NS' amplitude was taken as the mean amplitude from the time of NS' onset to the peak of the MRCP. The MP amplitude was taken as the maximum negative peak amplitude immediately prior to movement onset. Statistical analysis was performed using SPSS for Windows 16.0 statistical package. The mean amplitudes and onset times of the BP and NS' and the peak

amplitude of the MP were submitted to separate 2 group (guitarists, non-musicians) x 4 electrodes (FCz, C3, Cz, C4) analyses of variance (ANOVA). This analysis was used as opposed to a multivariate analysis of variance, as the different electrode sites were not considered to be separate dependant variables. Furthermore, previous researchers have typically used the ANOVA technique when analysing the MRCP in skill learning experiments (e.g., Di Russo, Pitzalis, et al., 2005; Dirnberger et al., 2004; Hatta et al., 2009). Where Mauchly's test indicated that sphericity had been violated, the degrees of freedom were corrected using the Huynh-Feldt method. This statement is consistent across all studies reported in this thesis. Significant effects were reported at an alpha level of .05 and post-hoc interpretations were made using Duncan's multiple range tests. Although this is a more liberal post-hoc test, which may increase the likelihood of making a type 1 error, it was an appropriate test to use given the inherent variability in psychophysiological data. Furthermore, this choice of post-hoc test has been used in previous studies investigating the MRCP (e.g., Del Percio et al., 2008; Di Russo, Pitzalis, et al., 2005). Effect sizes are reported as partial eta squared (η^2_p).

The participants' scale-playing performance was measured using Logic Express software. By measuring the difference in milliseconds between the beat of the metronome and the notes of the scale being played, it was possible to establish synchronicity with the metronome. This performance measure was then submitted to the appropriate parametric or non-parametric test.

5.5 - Results

5.5.1 – Electrophysiological data

MRCPs in which the BP, NS', and MP components were evident were found in both groups, peaking at electrode site Cz. Waveforms of the MRCP recorded from both

groups at all electrode sites are shown in Figure 5.1. Mean amplitudes and onset times of the MRCP components are shown in Figure 5.2 and Table 5.1.

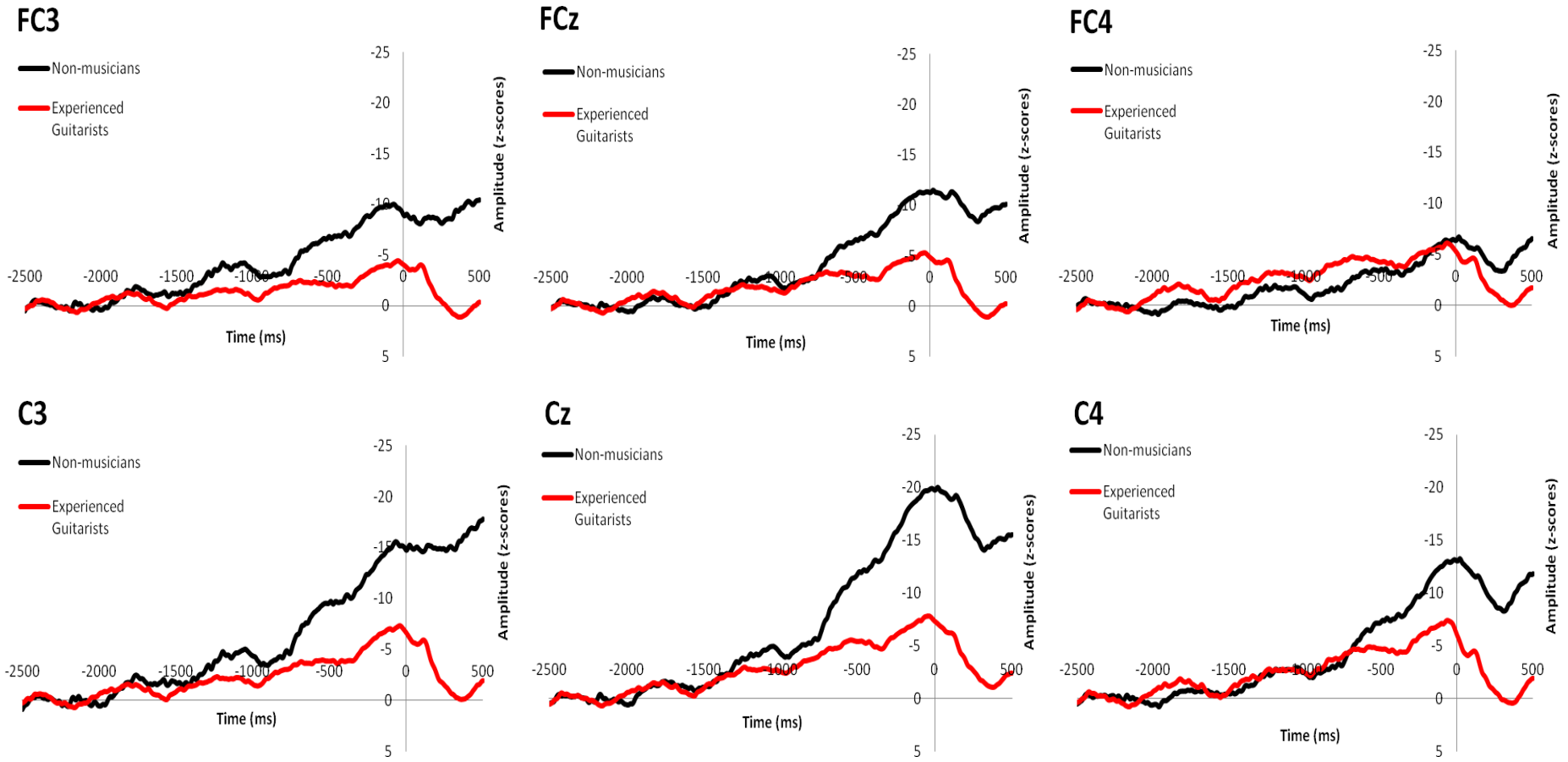

Figure 5.1: Movement-related cortical potential waveforms recorded from experienced guitarists (red) and non-musicians (black), prior to performance of the G Major scale on the guitar.

5.5.1.1 – Bereitschaftspotential (BP)

The BP initiated around 1900 ms prior to movement onset and was of similar amplitude in both groups until around -700 ms, when the waveform became more negative in the non-musicians. The onset times of the BP component in both groups are shown in Table 5.1. The ANOVA for BP onset time revealed no main effect of group ($F_{1, 18} = 1.63$, $p = .22$, $\eta^2_\rho = .08$), or electrode ($F_{2.4, 43.1} = 0.82$, $p = .46$ $\eta^2_\rho = .04$). There was however a significant group x electrode interaction for BP onset ($F_{2.4, 43.1} = 3.77$, $p = .02$, $\eta^2_\rho = .17$). The post-hoc analysis indicated that the BP onset times at Cz and C4 occurred later in the non-musicians than in the experienced guitarists.

The amplitude of the BP was taken as the mean amplitude from the point of BP onset to the point of NS' onset. The mean *z*-score for the BP amplitude in the experienced guitarist group was -2.34 (± 2.56) compared to -2.44 (± 2.29) in the non-musicians. The ANOVA revealed no significant main effect of group ($F_{1, 18} = .01$, $p = .92$, $\eta^2_\rho = .001$), or electrode ($F_{3, 54} = 2.64$, $p = .06$, $\eta^2_\rho = .13$). Similarly, there was no group x electrode interaction ($F_{3, 54} = 1.45$, $p = .24$, $\eta^2_\rho = .07$).

5.5.1.2 – Negative Slope (NS')

The onset times of the NS' component in both groups are shown in Table 5.1. The ANOVA revealed a significant main effect of group, with a significantly later NS' onset in the experienced guitarists compared to the non-musicians ($F_{1, 18} = 9.78$, $p = .006$, $\eta^2_\rho = .35$). There was no significant main effect of electrode ($F_{1.9, 34.3} = 1.18$, $p = .32$, $\eta^2_\rho = .06$), and no significant group x electrode interaction ($F_{1.9, 34.3} = 1.54$, $p = .23$, $\eta^2_\rho = .08$).

The amplitude of the NS' was taken as the mean amplitude from the point of NS' onset to the MRCP peak. The mean *z*-score amplitude for the NS' was -5.41 (± 5.02) in the experienced guitarists, compared to -10.45 (± 6.22) in the non-musicians. The ANOVA revealed a significant main effect of group, with a significantly lower amplitude NS'

component in the experienced guitarists compared to the non-musicians ($F_{1, 18} = 5.43$, $p = .03$, $\eta^2_\rho = .23$). There was also a significant main effect of electrode ($F_{3, 54} = 6.26$, $p = .001$, $\eta^2_\rho = .26$). The post-hoc analysis indicated that the NS' amplitude at Cz was significantly larger than at FCz. Finally, there was no significant group x electrode interaction ($F_{3, 54} = 2.2$, $p = .10$, $\eta^2_\rho = .11$).

5.5.1.3 – Motor Potential (MP)

The amplitude of the MP was taken as the maximum negative peak immediately prior to movement onset. The mean *z*-score amplitude for the MP peak was -7.48 (± 5.28) in the experienced guitarists, compared to -16.17 (± 8.36) in the non-musicians. The ANOVA found a main effect of group, with a significantly lower amplitude MP in the experienced guitarists compared to the non-musicians ($F_{1, 18} = 10.85$, $p = .004$, $\eta^2_\rho = .38$). There was also a significant main effect of electrode ($F_{3, 54} = 7.02$, $p < .001$, $\eta^2_\rho = .28$). The post-hoc analysis indicated that, as with the NS', the amplitude of the MP peak was significantly larger at Cz than at FCz. Finally, there was a significant group x electrode interaction ($F_{3, 54} = 2.97$, $p = .04$, $\eta^2_\rho = .14$). The post-hoc analysis indicated that the MP amplitude was smaller in the experienced guitarists, compared to the non-musicians, at all electrode sites.

Table 5.1: Mean onset times (ms) for BP and NS' components of the MRCP in the experienced guitarists and non-musicians, together with *p* values from the ANOVA analysis. A separate ANOVA was conducted for each component of the MRCP.

	Experienced Guitarists	Non-musicians	Significance
BP Onset (ms)	-1917 (± 226)	-1794 (± 281)	$p = .22$
NS' Onset (ms)	-462 (± 168)	-721 (± 209)	$p = .006$

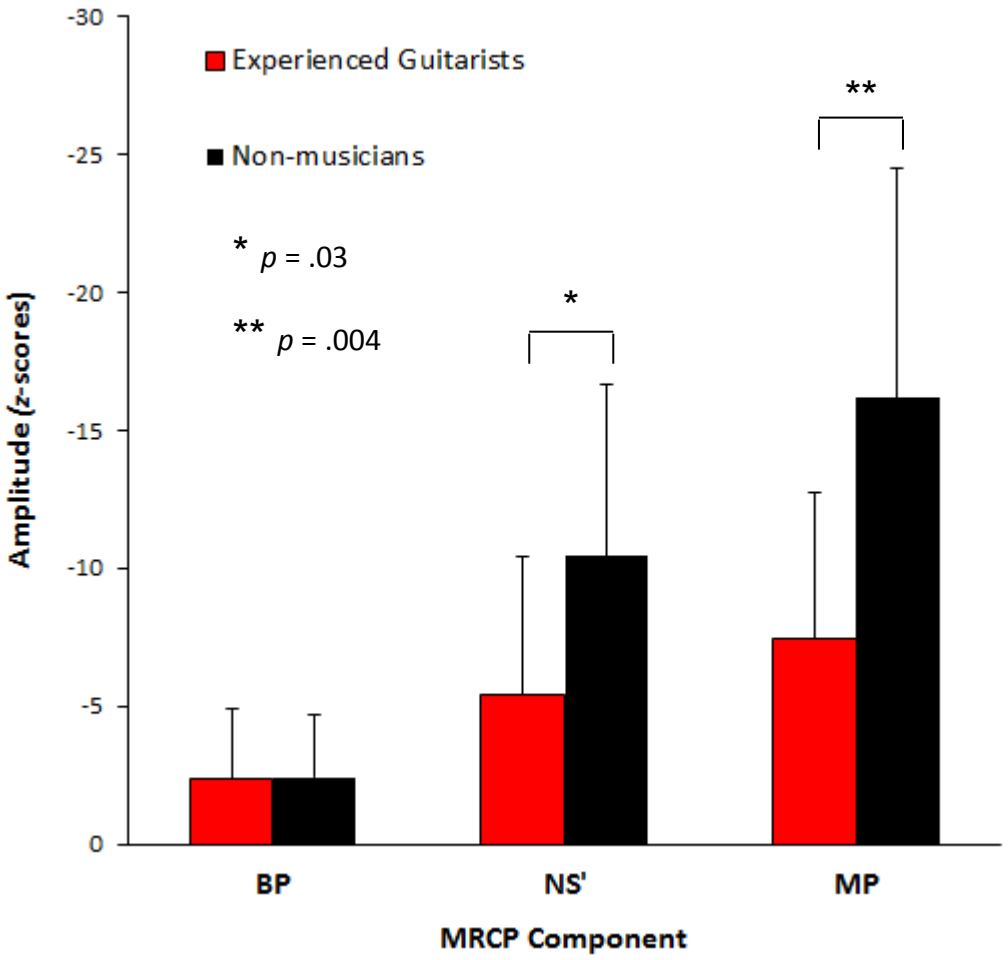

Figure 5.2: Mean amplitude values of the BP, NS', and MP components of the MRCP for experienced guitarists (red) and non-musicians (black). This figure contains data recorded from electrode sites FCz, C3, Cz and C4, prior to performance of the G Major scale on the guitar. Significant differences between the groups are indicated by asterisks.

5.5.2 – Performance data

The experienced guitarists were able to play the scale in time with the metronome with an average of 46 ms (±77) error between the beat of the metronome and the note being played, compared to 573 ms (±1084) error in the non-musician group. Due to the large variability in performance by the non-musician group (see the high standard deviation value), the assumption of homogeneity of variance was violated. Given this violation, these data were analysed using a non-parametric Mann-Whitney U test. The results of this test indicated that the experienced guitarists were able to play the scale more closely in time with the metronome than the non-musicians (U = 11, p = .002).

5.6 - Discussion

The aim of this study was to investigate possible differences in the pre-movement components of the MRCP between experienced guitarists and non-musicians in an ecologically valid guitar-playing task. This study provides the first account of skill-related differences in the MRCP between groups prior to performance of an ecologically valid motor task. There were no differences between the two groups in the amplitude of the BP component, although the BP was found to start later in the non-musicians at Cz and C4. The amplitude of the NS' component was significantly smaller and began significantly later in the experienced guitarists compared to the non-musicians. Also, the amplitude of the MP was significantly smaller in the experienced players, compared to the non-musicians. Previous research has reported smaller amplitudes in the BP, NS', and MP components of the MRCP, that also began later in elite performers compared to novices (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001). Only the NS' and MP findings in this study therefore support those of previous research.

Deecke (1996) suggested that negativity in the EEG indicates increased activity in the area of the cortex beneath the electrode. Based on this suggestion, the reduced negativity in areas of the motor cortex prior to movement production in the experienced guitarists, compared to the non-musicians, may indicate less activity involved in cortical motor preparation. Furthermore, the later onset of this activity provides evidence to support the idea of a greater efficiency during motor preparation in the experienced guitarists. The long-term training undertaken by the experienced guitarists may have been a major contributing factor to this reduced electrical activity. In addition, this reduced activity during movement preparation may 'free up' neurons, allowing the guitarists to allocate more cortical activity to other aspects of performance that could be described as more advanced, relating to creativity, artistic expressivity, or improvisation (Gruber, Jansen, Marienhagen, & Altenmuller, 2010). Without a larger electrode montage however it is not possible to speculate further on this issue.

As predicted, the reduced cortical activity during motor preparation in the experienced guitarists was accompanied by superior performance in the task. The experienced guitarists were able to play the scale more closely in time with the metronome than the non-musicians. This finding supports the concept of neural efficiency following motor skill learning (Babiloni et al., 2010; Del Percio et al., 2008), as superior performance by the experienced musicians was accompanied by a reduced cortical activity during motor preparation. This finding is consistent with the study by Fattapposta et al. (1996), who reported that expert pistol shooters produced smaller amplitude MRCPs than a novice control group, and performed better in a shooting-based task. These performance data strengthen the claim that lower amplitude MRCPs in experienced performers are skill-related.

As highlighted in section 3.4 of the literature review, previous research in this area

has tended to use relatively simple motor tasks and extrapolated the findings to more complex motor skills, leading Nakata et al. (2010) to call for researchers to use tasks with a greater ecological validity in future experiments. The current study addressed this need as it investigated the MRCP prior to performance of an ecologically valid motor task on a guitar, as opposed to more simple motor tasks. The results indicate that the experienced guitarists required less cortical activity to plan and perform the task. This can be seen by the smaller amplitude NS' and MP components, and the later onset of the NS' in the experienced guitarists, compared to the non-musicians. This finding is consistent with the research reporting that experienced athletes (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001) and musicians (e.g., Haslinger et al., 2004; Jancke et al., 2000; Koeneke et al., 2004; Krings et al., 2000) require reduced cortical activity, compared to novices, during motor planning and preparation. The fact that these findings have been replicated using an ecologically valid motor skill extends the current literature base and adds support to the claims that the reported differences are due to long-term training in a motor skill.

No differences were found between the two groups in the amplitude of the BP component, and the onset time of the BP occurred later in the non-musicians, compared to the experienced guitarists at sites Cz and C4. This finding contrasts with previous research that has reported smaller amplitude and later onset BP components in expert, compared to novice performers (e.g., Di Russo, Pitzalis, et al,. 2005; Fattapposta et al., 1996; Kita et al., 2001). The contradictory BP evidence presented here could be due to the sound generated by the metronome, which ran continuously throughout the experiment at 100 bpm. Although participants were free to initiate each repetition of the scale when ready, they were also instructed to play in time with the metronome. This may have resulted in the decision to begin each repetition of the scale being governed by the

metronome, rather than being self-initiated. A study by Di Russo, Incoccia, Formisano, Sabatini, and Zoccolotti (2005) compared components of the MRCP prior to index finger flexion actions that were either self-initiated or externally triggered by a tone. These authors reported that the BP component was present prior to self-initiated movements, but absent prior to externally triggered movements. It could be argued that the presence of the metronome in this experiment may have acted as an external trigger for the participants to begin playing the scale. In this experiment the decision to begin a repetition of the scale may therefore have been partially internally triggered and partially externally triggered. The external trigger element may have reduced the BP amplitude and contributed to the lack of differences between the groups. As such, it is not possible to speculate as to the cause of the later BP onset at Cz and C4 in the non-musician group. The presence of the metronome however was vital. Measuring performance differences between the groups would have been difficult and more subjective without the presence of the metronome. It is possible that, consistent with previous research, the amplitude of the BP may have been smaller and begun later in the experienced players, compared to the non-musicians, if no metronome had been used.

Alternative explanations for the NS' and MP differences reported in this study could be the age and/or sex differences between the groups, rather than the differences in the skill level of the participants. The non-musician sample contained five males and five females with a mean age of 24.1 (± 6.57) years. The sample of experienced guitarists contained ten males with a mean age of 36.5 years (± 13.73). Differences between these samples are a limitation to this study, yet it is unlikely that they had a confounding effect on the results. Regarding age differences, a study by Singh, Knight, Woods, Beckley, and Clayworth (1990) compared amplitude and onset time differences in the MRCP between young (20-40 years) and older (54-78 years) participants, prior to uni-manual and bi-

manual button pressing tasks. The authors reported that there were no differences between the groups in either the amplitude or onset times for any components of the MRCP. Furthermore, the younger group was sub-divided into two groups; one with an age range of 20-29 years, and one with an age range of 30-40 years. Again, no differences were reported between these groups for any components of the MRCP. Where age effects have previously been reported to influence the MRCP, it has typically only been an issue in older populations. For example, in an earlier study by Deecke, Englitz, and Schmitt (1978), age was reported to be associated with a decline in MRCP amplitude, but only after the fourth decade of life. It is therefore unlikely that the differences reported here are age-related.

There are no published data regarding sex differences in the MRCP. Comparison of the MRCP of the five male non-musicians with the five female non-musicians in this study however revealed that there were no differences in the MRCP in terms of sex[1]. As such, whilst not matching participants for age and sex are limitations to the study, it does not appear that these factors have caused the differences between the two groups. Despite this, if the study were to be replicated, it would be desirable to match participants for age and sex in future.

The differences reported in this study indicate that less cortical activity is required by the motor cortex during movement preparation in a group of experienced guitarists, compared to a group of non-musicians. It is likely that practice and long-term training by the experienced guitarists brought about these differences. It is not possible to verify this claim however using cross-sectional designs. To establish if the differences that have

[1] Sex differences in the MRCP of the non-musicians were compared using separate 2 sex (male, female) x 4 electrode (FCz, C3, Cz, C4) independent measures ANOVAs. No differences were found between sex for the onset times of the BP (p = .10) or NS' (p = .89) components. Similarly, no differences were found between sex for the amplitudes of the BP (p = .08), NS' (p = .67), or MP (p = .93) components.

consistently been reported between experienced and novice performers are due to the long-term training undertaken by the expert group, future studies should adopt a longitudinal design (Nakata et al. 2010). This would involve examining participants' cortical activity on numerous occasions over the course of a learning period (Poldrack, 2000). A reduction in cortical activity at the end of the learning period, compared to the beginning, would provide a stronger indication that the differences reported here are due to long-term training. The following studies in this research programme were designed to address this issue. In the next chapter an investigation into changes in the MRCP that were associated with short-term practice of the scale-playing task over the course of a single testing session is described in Study 3. In Studies 4 and 5 changes in the MRCP that were associated with training on the guitar over a longer period are reported[2].

[2] The following five chapters in this thesis report the findings from one major data collection period with three different research questions. A group of non-musicians undertook a sixteen-week training period learning to play a scale on the guitar. In Study 3, changes in the MRCP that were associated with short-term practice of the scale over a single testing session were investigated and these findings are presented in Chapter 6. Following this the results of Study 4, a three-part extended training study, are presented in Chapters 7, 8, and 9. Chapter 10 then presents a re-analysis of the data reported in the previous chapters in an attempt to resolve some of the contrasting explanations for findings provided in Study 3. As the data presented came from the same data collection with the same participants, methodological issues regarding participant details and ethics procedures are presented only once in Chapter 6, but are consistent across the remaining studies presented in this thesis.

Chapter 6

Study 3: The effect of short term practice on the guitar on the movement-related cortical potential

6.1 – Introduction

As highlighted in section 3.1.2 of the literature review, most research that has investigated the cortical processes involved in motor skill learning has used cross-sectional comparison designs (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001). Where experimenters have used within-participant designs to study the cortical processes involved in motor skill learning, they have tended to study changes in the MRCP associated with short-term practice over the course of a single testing session (e.g., Dirnberger et al., 2004; Lang et al., 1992; Taylor, 1978). Collectively, these authors have reported that short-term motor skill practice causes a reduction in the amplitude of the MRCP, which may indicate a reduction in the amount effort involved in motor preparation (Lang et al., 1992). The results of these studies therefore indicate that as the participant becomes more familiar with a skill through short-term practice, less activity is required by the motor cortex during the planning and performance of that skill.

These results provide an interesting insight into the effects of motor practice on activity within the motor cortex. Similar to the cross-sectional studies discussed in Study 2 however, a problem exists with these studies in that the motor tasks have lacked ecological validity. To date, no research has investigated changes in the MRCP associated with short-term practice of a complex, ecologically valid motor task, such as playing a musical instrument.

6.2 – Aims of the investigation

This study aimed to establish whether short-term practice of a motor task, in this

case practising a scale on the guitar, would bring about a change in the amplitude and onset time of the MRCP. The purpose of this study was to replicate and extend the findings of previous studies that have examined the effect of short-term motor practice on cortical activity (e.g., Dirnberger et al., 2004; Lang et al., 1992), using an ecologically valid motor task.

6.3 – Hypothesis

It was hypothesised that short-term practice in a motor task would result in reduced activity in the motor cortex during motor preparation. A smaller amplitude and later onset of MRCP components in late trials, compared to early trials, would provide evidence in support of this hypothesis.

6.4 – Method

6.4.1 – Participants

Ten non-musicians (5 male, 5 female; mean age = 26 years ± 9.35) participated in this study. All participants were right handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971; see Appendix C) and reported that they had no prior experience of playing the guitar or any other musical instruments. After reading an information sheet detailing the aims and procedures involved, all participants gave their written informed consent to take part in the study, which had been granted ethical approval by the Exercise and Sport Science departmental ethics committee at the Manchester Metropolitan University (see Appendix F).

6.4.2 – Electrophysiological recording

The EEG recording procedure was identical to that described in Study 1.

6.4.3 – Experimental procedure

The experimental procedure was identical to that described in Study 2. Following the methods employed by Dirnberger et al. (2004) and Lang et al. (1992), who studied changes in cortical activity associated with short-term practice of simple motor actions, 100 trials were deemed an appropriate number for this type of experiment. No performance data were recorded for this study as it was not possible to record performance alongside the EEG.

6.4.4 – Data analysis

Movement onset was marked on to the EEG recording in the same way as described in section 4.4.5 of Study 1. Extracting the MRCP from the EEG recording was done using the same procedure as described in Study 1. The only exception to this was that instead of averaging all 100 trials to produce one MRCP, using the same procedure as Lang et al. (1992), two MRCPs were extracted from the EEG recording of each participant. The first 30 artefact-free trials were averaged to produce a MRCP of the early trials, and the final 30 artefact-free trials were averaged to produce a second MRCP of the late trials. Differences between the early and late trials were compared to show the effects of short-term practice on the MRCP.

For statistical analysis, the mean amplitudes of the BP and NS', together with the peak amplitude of the MP were extracted from the averaged EEG prior to movement onset at all six electrode sites. As each MRCP was based on the average of only thirty trials, individual participants' MRCPs were noisier than in Studies 1 and 2, where the MRCPs were based on the average of 100 trials. Consequently, it was not possible to identify the onset times of the BP and NS' accurately in this study. As such, only

amplitude values of the BP, NS', and MP were analysed. As it was not possible to base amplitude values for the BP and the NS' around their onset times, the amplitude of the BP was taken as the mean amplitude from -2000 to -500 ms and the amplitude of the NS' was taken as the mean amplitude from -500 to 0 ms. These time points are consistent with previously published studies that analysed MRCP amplitude values in this way (e.g., Di Russo, Pitzalis, et al., 2005). The MP amplitude was taken at the MRCP peak, immediately prior to movement onset. Statistical analyses were performed using the SPSS for Windows 16.0 statistical package. The mean amplitudes of the BP and NS' components of the MRCP, together with the peak MP values, were submitted to separate 2 time (early, late) x 6 electrode (FC3, FCz, FC4, C3, Cz, C4) repeated measures analyses of variance (ANOVAs). Significant effects were reported at an alpha level of .05 and post-hoc interpretations were made using Duncan's multiple range tests. Effect sizes were reported as partial eta squared (η^2_ρ).

6.5 – Results

6.5.1 – Electrophysiological data

MRCPs were evident in all participants, in both the early and the late block of trials, at all six electrode sites. The MRCP waveforms for the early and late blocks of trials from each electrode are displayed in Figure 6.1. The mean amplitudes of the individual components of the MRCP are shown in Figure 6.2.

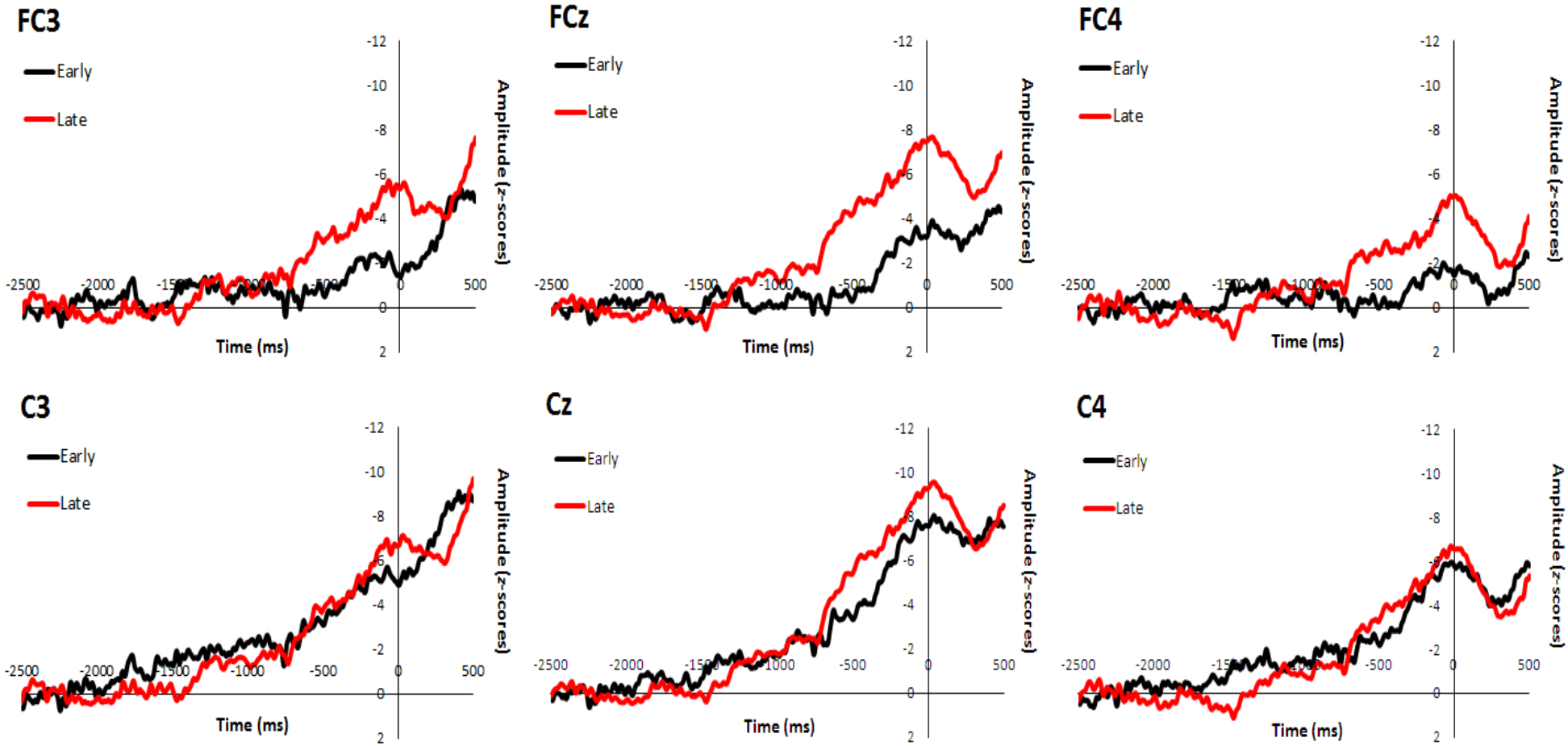

Figure 6.1: Movement-related cortical potential waveforms recorded from the motor cortex of non-musicians, during early (black) and late (red) blocks of trials.

6.5.1.1 – Bereitschaftspotential (BP)

For both early and late blocks of trials, the BP appeared to initiate around 1600 ms prior to movement onset. In the early trials, the BP continued to increase gradually until around 400 ms prior to movement onset, before the gradient of the negativity increased sharply. In the late trials however, the negative increase of the BP stopped at around 700 ms prior to movement onset, when the steeper gradient increase of the NS' occurred.

The amplitude of the BP was taken as the mean value from -2000 to -500 ms. The mean *z*-score amplitude of the BP in the early trials was -1.05 (± 1.7), compared to -1.49 (± 2.12) in the later trials. The repeated measures ANOVA revealed no significant main effect of time ($F_{1,9} = .26$, $p = .62$, $\eta^2_\rho = .03$), and no significant main effect of electrode ($F_{5, 45} = 2.05$, $p = .09$, $\eta^2_\rho = .19$). In addition, there was no significant time x electrode interaction ($F_{5, 45} = 1.75$, $p = .14$, $\eta^2_\rho = .16$).

6.5.1.2 – Negative Slope (NS')

The NS' initiated at around 400 ms prior to movement onset in the early trials, compared to around 700 ms prior to movement onset in the late trials. Due to the low number of trials comprising the MRCP waveforms however, it was not possible to determine exact onset values.

The amplitude of the NS' was taken as the mean value between -500 to 0 ms. The mean *z*-score amplitude of the NS' in the early trials was -3.22 (± 3.48), compared to -5.13 (± 4.03) in the late trials. The repeated measures ANOVA for the NS' amplitude revealed no significant main effect of time ($F_{1,9} = 1.48$, $p = .25$, $\eta^2_\rho = .14$). There was however a significant main effect of electrode ($F_{5, 45} = 7.59$, $p < .001$, $\eta^2_\rho = .46$). The post-hoc analysis revealed that the amplitude of the NS' at Cz was significantly larger than at FC3, FCz and FC4, whilst the amplitude at C3 was significantly larger than at FC4. There was also a significant time x electrode interaction ($F_{3.1, 28.3} = 2.92$, $p = .05$, $\eta^2_\rho = .25$). The

post-hoc analysis indicated that the amplitude of the NS' was larger in late, compared to early, trials at FC3, FCz, and FC4.

6.5.1.3 – Motor Potential (MP)

The amplitude of the MP was taken as the peak value immediately prior to movement onset. The mean *z*-score amplitude for the MP peak was -5.85 (± 3.91) in the early block of trials, compared to -7.65 (± 4.67) in the late block of trials. The repeated measures ANOVA for MP amplitude revealed no significant main effect of time ($F_{1,9} = .99$, $p = .35$, $\eta^2_\rho = .10$). There was however a significant main effect of electrode ($F_{5, 45} = 8.23$, $p < .001$, $\eta^2_\rho = .48$). The post-hoc analysis revealed that the amplitude of the MP at Cz was significantly larger than at FC3, FCz, and FC4. Additionally, there was no significant time x electrode interaction ($F_{2.8, 25.3} = 2.29$, $p = .06$, $\eta^2_\rho = .20$).

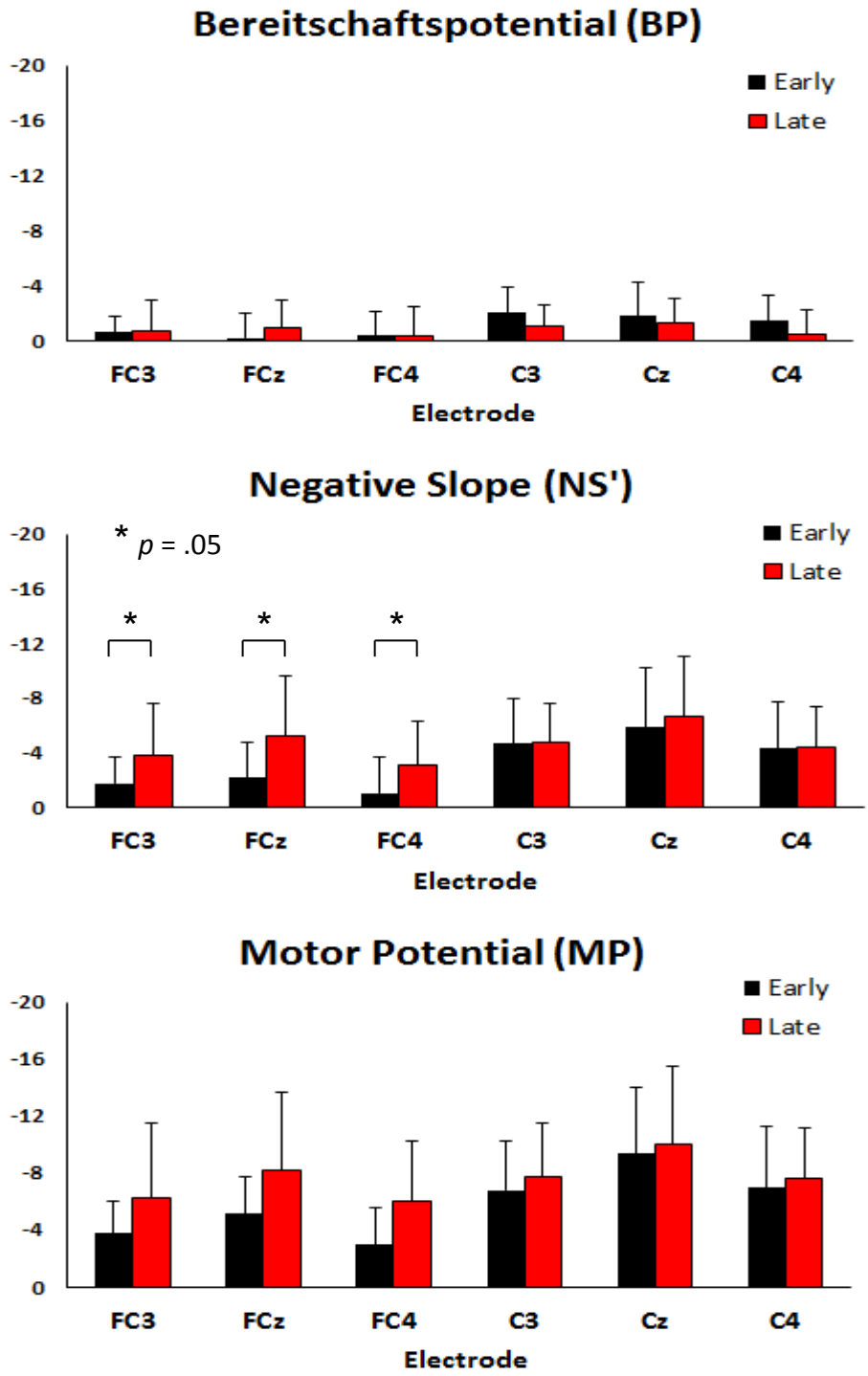

Figure 6.2: Mean amplitude values of the BP, NS', and MP components of the MRCP recorded from non-musicians during early (black) and late (red) blocks of trials. Data were recorded from electrode sites overlying the motor cortex (FC3, FCz, FC4, C3, Cz, C4), prior to performance of a section of the G Major scale on the guitar. Significant effects are indicated by asterisks.

6.6 – Discussion

The aim of this study was to investigate the effects of short-term motor task practice on the amplitude of the MRCP, using a more ecologically valid motor task than had been used in previous research. The purpose of this was to replicate and extend the results of previous studies that have investigated the effects of short-term motor practice on cortical activity, by recording the MRCP during performance of a scale-playing task on the guitar. As with Study 2, this was the first time this had been investigated during the practice of an ecologically valid motor skill, as opposed to during the practice of more simple laboratory-based motor actions. It was predicted that short-term practice on the guitar would cause a reduction in the amplitude of the MRCP. The results of this study showed that there was no change in the amplitude of the BP or the MP as a result of short-term practice on the guitar. There was however a significant increase in the amplitude of the NS' component from early to late trials at sites FC3, FCz, and FC4. Although this was not analysed, it is worth noting that the NS' appeared to begin earlier in the late block of trials, compared to the early block (see Figure 6.1).

These results are in contrast with the experimental hypothesis and previous research in this area. Both Dirnberger et al. (2004) and Lang et al. (1992) reported that practice or habituation in a repetitive task, caused a reduction in the amplitude of the MRCP at motor cortex electrode sites such as C3, Cz and C4. The results of these studies indicated that short-term motor practice modulates activity within the motor cortex, bringing about a reduced level of cortical activity involved in motor task preparation. The results of the current study challenge this proposal as the amplitude of the NS' was larger at sites FC3, FCz, and FC4 in late trials, compared to early trials. Lang et al. suggest that a change in the amplitude of the MRCP reflects a change in the amount of cortical effort involved in motor planning and performance. The results of this study therefore indicate

that more cortical activity may have been required during motor planning following a period of practice in the guitar-playing task.

There are two possible explanations for this finding. First, it is possible that during the early phases of learning a motor task, there is an increase in the cortical activity involved in motor planning and performance, as the participants have difficulty learning and performing the motor task. Once the participants become more familiar with the motor task however, a reduction in the amount of cortical activity involved in motor planning may become evident. This hypothesis is consistent with the study by Taylor (1978) described in section 3.1.1, where a similar increase in cortical activity was reported during the early stages of motor practice. This led Taylor to conclude that the size of the MRCP is systematically related to the performers' level of proficiency at the motor task. Similarly, in an fMRI study by Toni, Krams, Turner, and Passingham (1998), participants learnt a motor sequence of eight button presses by trial and error. In early blocks of trials, performance errors in the sequence were common. After ten blocks however, participants' performance errors were either non-existent or infrequent. The authors reported that large increases in cortical activity occurred during the early learning stages in a variety of movement-related cortical areas, including areas of the pre-frontal, pre-motor and anterior cingulate cortices. In later trials however, after the sequence had been learnt (i.e., no further performance errors), activity in these areas decreased back to, or close to, baseline. Further evidence indicating that early motor task learning is characterised by an increase, followed by a later decrease, in cortical activity is presented by Pascual-Leone, Grafman, and Hallett (1994). This study used transcranial magnetic stimulation (TMS) to map changes in the size of participants' motor cortex representation for various finger muscles that were associated with practice of a button pressing serial reaction time task. They reported that in early blocks of trials, the size of the cortical

representation for the finger muscles involved in the task increased. Once participants had gained explicit knowledge of the task however, the size of the cortical representation of the finger muscles decreased back to baseline. Although this study plotted structural, rather than functional, changes in the motor cortex, the pattern of an increase in cortical representation during early learning followed by a decrease in cortical representation in later learning, mirrors the pattern reported by Taylor and Toni et al. (1998).

It should be reiterated however that the motor tasks used by Taylor (1978) and Toni et al. (1998) involved the practice or learning of simple button pressing sequences. The actions required to press the buttons may have already existed within the participants' motor repertoire. In these studies therefore the participants probably only had to learn the order in which to press the buttons, which was likely to be an easy task for the participants to learn. As such, it is not surprising that the participants were able to learn the task and reach a high standard of performance within a single testing session. The guitar-playing task used in this study was a more complex task than that used by Taylor and Toni et al. It is therefore possible that in this study, the participants were still learning and finding it difficult to perform the task successfully during the late block of trials. If this were the case, based on the findings reported by Taylor and Toni et al., this could explain why the amplitude of the NS' was larger in the late trials, compared to the early trials, at certain electrode sites in the current study. Additionally, the fact that this study used a more complex motor task than the relatively simple motor tasks used by Dirnberger et al. (2004) and Lang et al. (1992) could explain why a reduction in MRCP amplitude was reported in their experiments, but not in this study. If a longer practice period were employed it is possible that the initial increase in amplitude may have been followed by a decrease once participants became more competent at the task.

A second explanation for the larger amplitude of the NS' in the late block of trials,

compared to the early block, could be the effect of fatigue. Several studies have reported the effects of fatigue on the MRCP (e.g., Falvo, Sirevaag, Rohrbaugh, & Earhart, 2011; Freude & Ullsperger, 1987; Johnston, Rearick, & Slobounov, 2001; Schillings et al., 2006). The majority of these studies have recorded the MRCP during the performance of repetitive, high intensity, grasping actions, and compared the amplitude of the MRCP in early blocks of trials to late blocks of trials. For example, Schillings et al. (2006) reported that the area under the MRCP curve almost doubled at site Cz and increased four-fold at modified sites C3" and C4", within a 30-minute period of repetitive grasping at 70% maximum voluntary contraction (MVC). Additionally, in a similar right-handed grasping task at 70% MVC, Johnston et al. (2001) reported significant increases in the amplitude of both the BP (Cz and FCz) and MP (C3, Cz and FCz) over three blocks of forty trials. Recently Falvo et al. (2011) replicated these findings in young (aged 22-25 years, mean 24.1 years) but not older (aged 59-78 years, mean 68.8 years) participants. The amplitude of the MRCP has therefore consistently been shown to increase as a result of fatiguing, high intensity muscular activity. It has been proposed that this is a central adaptation that occurs to compensate for fatigue at a peripheral level (e.g., Johnston et al., 2001).

Whilst the effects of muscular fatigue on the MRCP are well established, it should be noted that the above-mentioned studies involved repetitive grasping at high intensity, whereas the scale-playing task used in this study was performed at a lower intensity. A study by Freude and Ullsperger (1987) investigated the effect of grasping at various intensities on the MRCP. They reported that repetitive grasping at both high (80% MVC) and low (20% MVC) intensities produced an increase in MRCP amplitude over time. The finding of an increase in MRCP amplitude at 20% MVC is particularly interesting as this intensity was unlikely to have caused peripheral fatigue at a muscular level. The authors reported that the high level of concentration and intentional involvement required to

perform the task at such a low intensity may have been the reason for their findings. The high levels of concentration and attention involved in the repetitive performance of a complex motor task at low intensity levels, such as playing a scale on the guitar, may therefore have induced fatigue at a central level and brought about an increase in the amplitude of the MRCP.

At present, it is not possible to determine which of the two proposed explanations for the current findings is the more valid. Study 5 in this research programme addressed this issue by repeating the same procedures used in this study with EEG data recorded after five and ten weeks of practice on the guitar. Before presenting these findings, the following studies report changes in the MRCP associated with an extended training period on the guitar.

Chapter 7

Study 4a: Changes in the movement-related cortical potential associated with a five-week training period on the guitar

7.1 – Introduction

As discussed in the literature review section of this thesis (Chapter 3), most of the research that has investigated the cortical processes involved in motor skill learning has used a cross-sectional design and reported MRCPs of smaller amplitude and later onset in expert performers compared to novices (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001). This was confirmed using an ecologically valid, bi-manual, scale-playing task on the guitar in Study 2. In these studies, researchers have attributed the differences between the groups to the long-term training undertaken by the expert group. Although this seems to be a plausible explanation, it is problematic to claim that the reported differences are due to long-term learning based solely on cross-sectional evidence. To adequately demonstrate that learning has occurred, a relatively permanent change in performance or activity must be observed over a period of time, and as a result of practice or training (Schmidt & Lee, 2011). Longitudinal studies that assess possible changes in cortical activity within the same participants over the course of a training programme are therefore required to support the claims made in cross-sectional studies (Nakata et al., 2010).

Several attempts have been made to study the effects of learning on cortical activity by investigating changes in the MRCP that are associated with repetitive practice of a movement, but only over the course of a single testing session (e.g., Dirnberger et al., 2004; Lang et al., 1992; Taylor, 1978). These changes are therefore likely to reflect the effects of short-term practice, rather than actual learning. No study has yet investigated

changes in the MRCP using an ecologically valid motor task over an extended training period.

7.2 – Aims of the investigation

This study aimed to investigate whether training in a motor task, such as playing the guitar over an extended period, would bring about a change in the amplitude and onset times of the MRCP. The purpose of this was to verify the claims made in previous cross-sectional studies, that the between-group differences were the result of the long-term training undertaken by the experts.

7.3 – Hypothesis

It was hypothesised that following a period of extended training in a motor task, the amplitude of the MRCP components would decrease, and the onset time of the components would occur later. This finding would offer support to the claims made in cross-sectional studies that long-term motor task training causes a reduction in the cortical activity involved in movement planning and preparation.

7.4 – Method

7.4.1 – Participants

Participant details for this experiment were identical to those provided in Study 3.

7.4.2 – Electrophysiological recording

The EEG recording procedure was identical to that described in Study 1.

7.4.3 – Experimental procedure

Participants took part in a five-week training programme learning to play a section of the G Major scale on the guitar. During this period, they were required to attend one testing session per week. At week 1, EEG was recorded whilst participants performed 100 repetitions of the first seven notes of the G Major scale, in time with a metronome running at 100 bpm. Following the EEG recording participants performed an additional 20 repetitions of the scale whilst their performance was recorded using Logic Express software, allowing their performances to be assessed offline. At weeks 2 – 4 participants received an individual one hour guitar lesson. Each lesson was split into three parts. First, participants spent 15 minutes practising the G Major scale in time with the metronome at 100 bpm. Second, participants spent 30 minutes learning songs on the guitar. The purpose of this section was to make the lessons more enjoyable for the participants and keep them motivated, in an attempt to reduce participant dropout. Third, participants spent the final 15 minutes of the lesson practising the scale in time with the metronome. During each 15-minute practice period, participants performed 75 repetitions of the scale, resulting in a total of 150 repetitions per lesson. By the end of the lesson at week 4, all participants had performed the scale a total of 570 times (120 repetitions at week 1 and 150 repetitions at weeks 2 – 4). At week 5 participants returned for a final EEG testing session with the same procedure as week 1. The duration of the training study was set at five weeks as consultation with members of staff from the university's music department indicated that this would be sufficient time to bring about improvements in performance of the scale-playing task. In addition, research from the sports sciences have shown improvements in performance of sporting tasks within a similar time frame (e.g., Smith,

Wright, Allsopp, & Westhead, 2007; Smith, Wright, & Cantwell, 2008). The protocol for this experiment is shown in Figure 7.1.

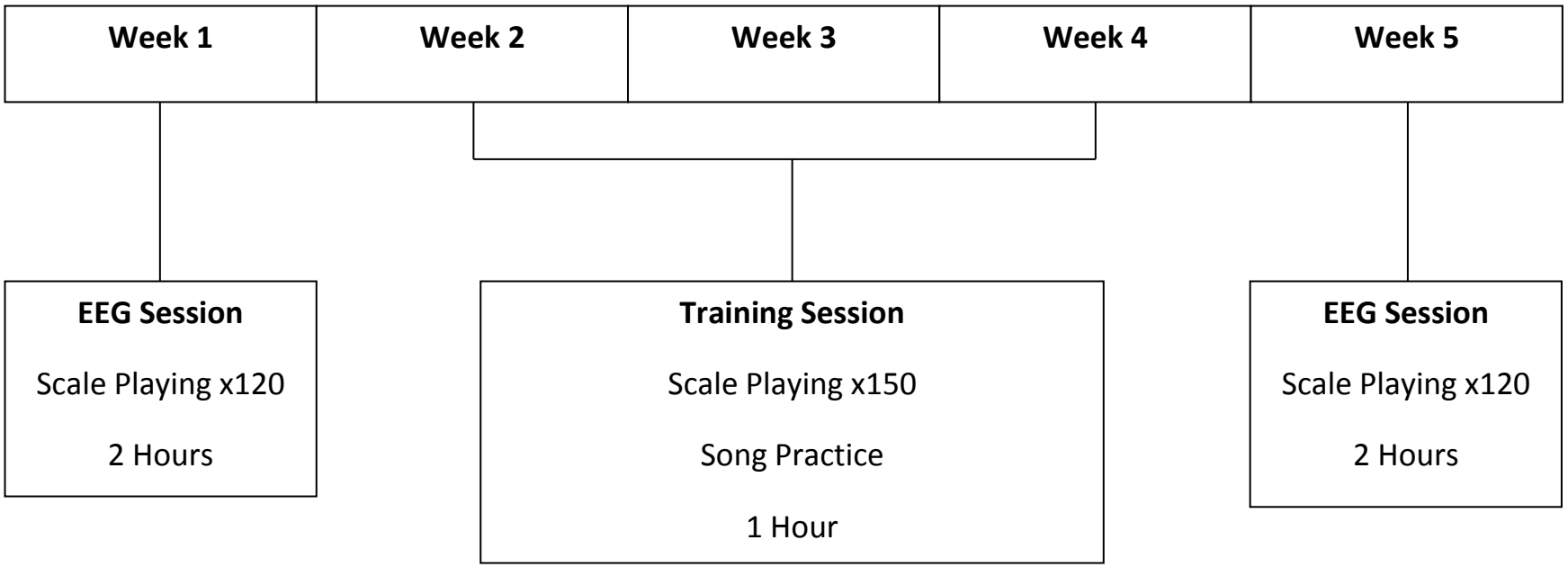

Figure 7.1: Protocol for the training study.

7.4.4 – Data analysis

The MRCP was extracted from the raw EEG data using the same procedure described in Study 1. During the EOG artefact rejection phase, an average of 16.5 trials per participant was rejected as they contained eye-movement artefacts. Rejection of this many artefacts still resulted in an acceptable number of trials for averaging, based on Gerbrandt's (1978) recommendation.

For statistical analysis, the mean amplitudes and onset times of the BP and NS', together with the peak amplitude of the MP, were extracted from the averaged EEG prior to movement onset at all six electrode sites. Onset time and amplitude values for the pre-movement components of the MRCP were established using the same procedure described in section 5.4.4 of Study 2. Statistical analyses were performed using the SPSS for Windows 16.0 statistical package. The mean amplitudes and onset times of the BP and NS' components of the MRCP, together with the peak MP values, were submitted to separate 2 time (week 1, week 5) x 6 electrode (FC3, FCz, FC4, C3, Cz, C4) repeated measures analyses of variance (ANOVA). Significant effects were reported at an alpha level of .05 and post-hoc interpretations were made using Duncan's multiple range tests. Effect sizes were reported as partial eta squared (η^2_p).

Performance was assessed over the course of the training programme in terms of how closely participants played the scale in time with the metronome. This was assessed using the same procedure described in Study 2. These performance data were then submitted to a paired samples *t* test.

7.5 - Results

7.5.1 – Electrophysiological data

MRCPs were evident in all participants, at all six electrodes sites, at both week 1 and week 5. The MRCP waveforms from each electrode, recorded at week 1 and week 5, are displayed in Figure 7.2. The mean amplitudes and onset times of the individual components of the MRCP are shown in Table 7.1 and Figure 7.3, respectively.

7.5.1.1 – Bereitschaftspotential (BP)

At both week 1 and week 5, the BP initiated around 1800 ms prior to movement onset and increased gradually until around 700 ms prior to movement onset. The onset times of the BP at week 1 and week 5 are shown in Table 7.1. The repeated measures ANOVA for the BP onset time revealed no significant main effect of time ($F_{1, 9} = 0.24$, $p = .64$, $\eta^2_\rho = .03$), or electrode ($F_{5, 45} = 0.292$, $p = .79$, $\eta^2_\rho = .031$). In addition, there was no significant time x electrode interaction ($F_{5, 45} = 0.77$, $p = .54$, $\eta^2_\rho = .08$).

The amplitude of the BP was taken as the mean amplitude between BP onset and NS' onset. The mean *z*-score amplitude for the BP was -1.36 (± 1.91) at week 1, compared to -1.1 (± 3.25) at week 5. The repeated measures ANOVA revealed no significant main effect of time ($F_{1, 9} = 0.053$, $p = .82$, $\eta^2_\rho = .006$), or electrode ($F_{5, 45} = 2.15$, $p = .08$, $\eta^2_\rho = .19$). Additionally, for the BP amplitude, there was no significant time x electrode interaction ($F_{5, 45} = 1.73$, $p = .15$, $\eta^2_\rho = .16$).

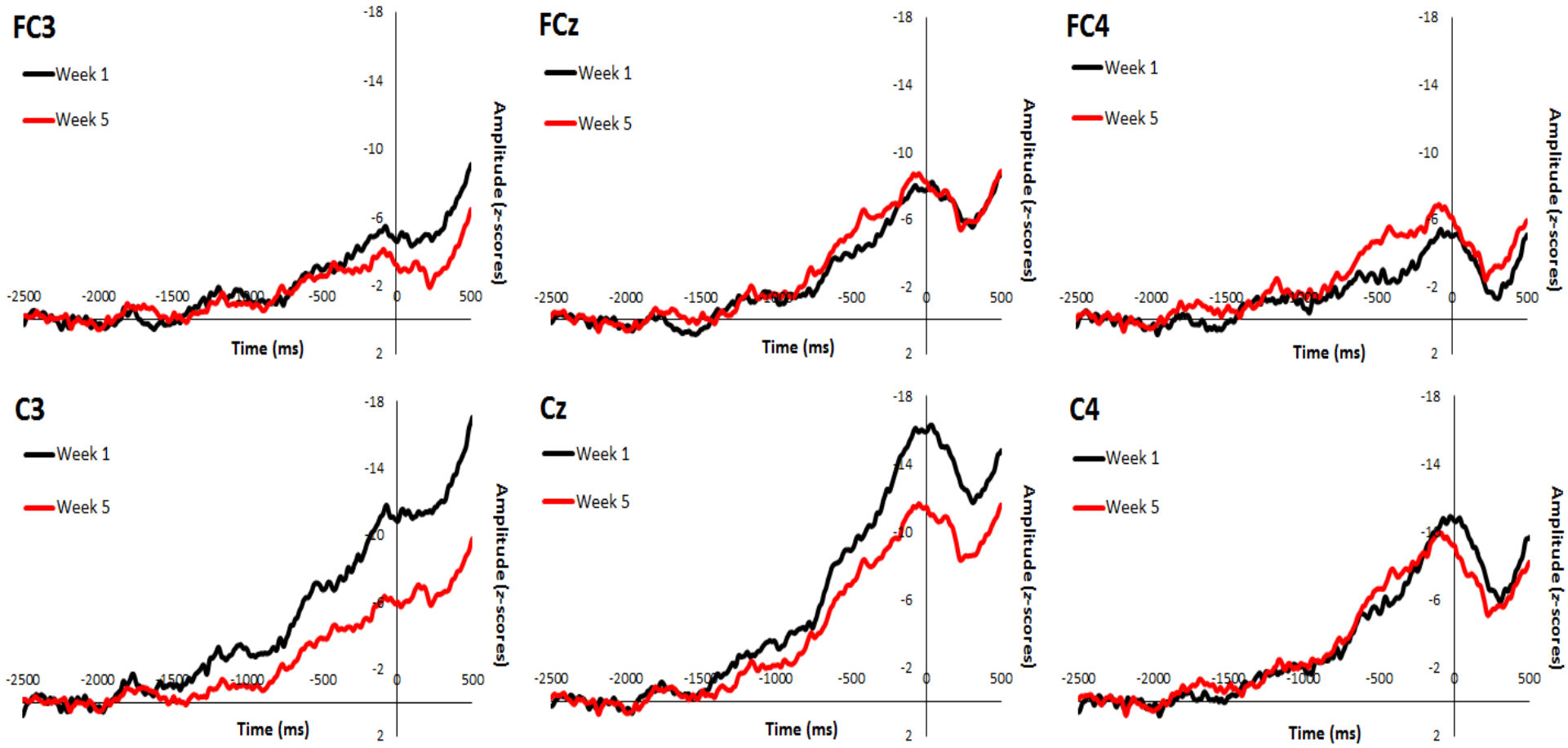

Figure 7.2: Movement-related cortical potential waveforms recorded from the motor cortex of non-musicians, at week 1 (black) and week 5 (red).

7.5.1.2 – Negative Slope (NS')

The onset times of the NS' at week 1 and week 5 are shown in Table 7.1. The repeated measures ANOVA for the NS' onset time indicated that there was no significant main effect of time ($F_{1, 9} = 0.25$, $p = .63$, $\eta^2_\rho = .03$), or electrode ($F_{5, 45} = 0.38$, $p = .79$, $\eta^2_\rho = .041$). In addition, there was no significant time x electrode interaction ($F_{5, 45} = 0.64$, $p = .67$, $\eta^2_\rho = .07$).

The amplitude of the NS' was taken as the mean amplitude from NS' onset to the peak of the MP. The mean *z*-score amplitude for the NS' was -6.5 (± 4.88) at week 1, compared to -5.62 (± 6.86) at week 5. The repeated measures ANOVA revealed no significant main effect of time ($F_{1, 9} = 0.2$, $p = .67$, $\eta^2_\rho = .022$). There was however a significant main effect of electrode ($F_{5, 45} = 8.31$, $p < .001$, $\eta^2_\rho = .48$). The post-hoc comparison revealed that the NS' amplitude at Cz was larger than at FC3 and FC4, whilst the amplitude at C4 was larger than at FC3. In addition, there was a significant time x electrode interaction ($F_{4.8, 43.3} = 2.93$, $p = .02$, $\eta^2_\rho = .25$). The post-hoc analysis indicated that the amplitude of the NS' was smaller at week 5, compared to week 1, at sites C3 and Cz.

7.5.1.3 – Motor Potential (MP)

The amplitude of the MP was taken as the peak of the MRCP, corresponding to the maximum negative peak immediately prior to movement onset. The mean *z*-score amplitude for the MP at week 1 was -10.58 (± 6.49), compared to -9.25 (± 8.28) at week 5. The repeated measures ANOVA revealed that there was no significant main effect of time ($F_{1, 9} = 0.419$, $p = .54$, $\eta^2_\rho = .049$). There was however a significant main effect of electrode ($F_{5, 45} = 10.49$, $p = < .001$, $\eta^2_\rho = .54$). The post-hoc comparison showed that the amplitude of the MP at Cz was significantly larger than at FC3, FCz, FC4, and C3. Similarly, the

amplitude of the MP at C4 was larger than at FC3. In addition, there was a significant time x electrode interaction ($F_{4, 36.2} = 2.98$, $p = .03$, $\eta^2_p = .25$). The post-hoc analysis indicated that the amplitude of the MP was smaller at week 5, compared to week 1, at sites C3 and Cz.

Table 7.1: Mean onset times (ms) for BP and NS' components of the MRCP at week 1 and week 5, together with *p* values from the ANOVA analysis. A separate ANOVA was conducted for each component of the MRCP.

	Week 1	Week 5	Significance
BP Onset (ms)	-1804 (± 245)	-1856 (± 297)	$p = .64$
NS' Onset (ms)	-691 (± 193)	-737 (± 195)	$p = .63$

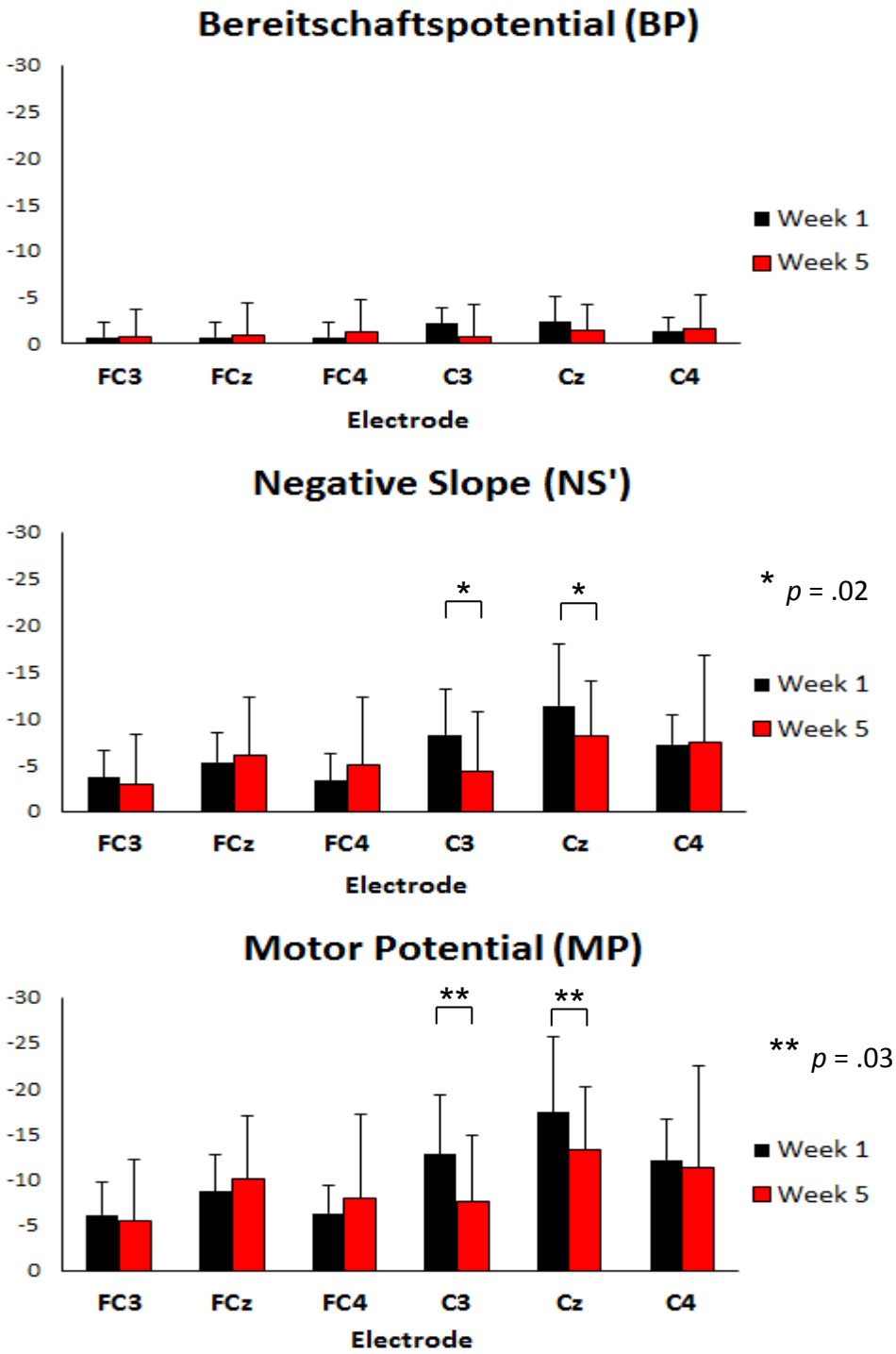

Figure 7.3: Mean amplitude values of the BP, NS', and MP components of the MRCP recorded from non-musicians at week 1 (black) and week 5 (red). Data were recorded from electrode sites overlying the motor cortex (FC3, FCz, FC4, C3, Cz, C4), prior to performance of a section of the G Major scale on the guitar. Significant effects are indicated by asterisks.

7.5.2 – Performance data

At week 1, participants performed the scale with a mean of 749 ms (± 1074) error between the beat of the metronome and the note being played. At week 5, participants performed the scale with a mean of 273 ms (± 582) error between the beat of the metronome and the note being played. A paired samples *t* test confirmed that participants' performance had significantly improved over the course of the training programme, as they played the scale more closely in time with the metronome at week 5 compared to week 1 ($t = 2.219$, $df = 9$, $p = .05$).

7.6 – Discussion

The aim of this study was to investigate changes in the pre-movement components of the MRCP as a result of learning to play a scale on the guitar over a period of five weeks. The objective of this experiment was to verify the claims made in Study 2 and in previous cross-sectional MRCP studies (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001), that following a period of learning, reduced activity is required by the pre-motor and primary motor cortices to plan and prepare to perform a skilled action. This experiment represents the first attempt to explore changes in the MRCP associated with the learning of an ecologically valid motor task over an extended period. No change in the onset times of the BP and NS' components were found as a result of the training programme. In relation to the amplitude values, there was no change in the BP. There was however a significant reduction in the amplitude of both the NS' and MP components at electrode sites C3 and Cz as a result of the training.

According to Lang et al. (1992), a change in the amplitude of the MRCP is thought to reflect a change in the amount of effort involved in movement preparation. The reduced NS' and MP amplitude over the course of the training programme at sites C3 and Cz (see Figure 7.2) may therefore indicate that less cortical activity was required during motor preparation by certain areas of the primary motor cortex, as a result of learning the task. This finding is consistent with the experimental hypothesis and the claims made in cross-sectional MRCP (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001) and fMRI (e.g., Haslinger et al., 2004; Jancke et al., 2000; Koeneke et al., 2004; Krings et al., 2000) studies, that fewer cortical resources are required to plan and perform a skill following training. The results also support the findings of several studies that have shown a reduced amplitude MRCP following short-term repetitive practice of motor actions during a single testing session (e.g., Dirnberger et al., 2004; Lang et al., 1992; Taylor, 1978).

The reduction in the amplitude of the NS' and MP components at C3 and Cz over the course of the training programme was accompanied by a significant improvement in performance. This may indicate that, as an individual becomes more competent in a motor skill, fewer cortical resources are required to be devoted to its planning and performance. This finding is consistent with the concept of neural efficiency following motor skill learning. Babiloni et al. (2010) explained that, according to the concept of neural efficiency, individuals who perform a skill to a high standard are likely to have a more efficient cortical functioning when performing that skill, compared to individuals who perform to a lower standard. This proposal was based on the results of cross-sectional experiments. This study therefore makes an important contribution to the literature. It represents the first longitudinal evidence in support of the concept of neural

efficiency, as improvements in performance over time were accompanied by a reduced cortical processing in certain areas of the motor cortex. As discussed in the final paragraph of section 3.1.2, it is not possible to obtain data from sub-cortical regions using EEG. It is therefore not possible to make firm claims about neural efficiency of all motor areas using EEG. Reduced activity in areas of the motor cortex may be accompanied by increased activity in other movement-related brain areas, such as the cerebellum and basal ganglia. Although this finding supports the neural efficiency literature, the term neural efficiency may be too simplistic without fMRI data recorded from other movement-related brain areas. It may be more suitable to discuss the results of this study in terms of a *motor cortex efficiency* following skill learning, as opposed to a *global neural efficiency*.

The reduction in the amplitude of the NS' and MP occurred at electrode sites C3 and Cz following the five-week training programme. Electrode site Cz is approximately located over the supplementary motor area; a medial frontal area of the brain involved in motor planning and bi-manual control (Cunnington, Bradshaw, & Iansek, 1996). It is also the area of the brain where the early components of the MRCP are generated and of maximal amplitude (Shibasaki & Hallett, 2006). Due to the bi-manual nature of the task, it is likely that the SMA was involved in both the planning and the performance of the task across all weeks. The reduction in the amplitude of the NS' and the MP shown at Cz was therefore expected. The reduction in amplitude found at C3, but not C4, could be due in part to the different hemispheric contribution to the bi-manual task. Electrode site C3 is located over the motor representation for the right hand, whilst C4 is located over the motor representation for the left hand. When playing the scale, the right-hand movement is arguably simpler to perform, for most individuals, than the left-hand movement. As

such, participants may have learnt the right hand part of the task more easily than the left, promoting the reduction in amplitude at C3, but not C4. With the small number of electrodes used in this study however, it is not possible to speculate further on this issue. Future research, using a more dense electrode montage, could provide a better explanation as to the topography and the typography of the learning process.

Based on cross-sectional skill learning MRCP studies (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Kita et al., 2001), a reduction in the amplitude of the BP was hypothesised, yet no change was found. As discussed in section 5.6 of Study 2 this could be due to the presence of the metronome, used in this study to control movement tempo. Based on the research by Di Russo, Incoccia et al. (2005), the presence of the metronome may have resulted in the decision to perform a movement being externally triggered, as opposed to self-initiated. This may have reduced the amplitude of the BP and contributed to the lack of change in the BP over the five-week training programme.

In relation to the onset times of the MRCP components, previous cross-sectional studies have reported later onset times for both the BP and NS' in expert performers compared to novices (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001). This finding was replicated in Study 2, but only for the NS' component (see section 5.5.1.2). This has been interpreted as an indication of a more efficient motor preparation, brought about by the long-term training undertaken by the expert group (Hatta et al., 2009). Consequently, it was predicted that there may have been a change in the BP and NS' onset times across the five-week training programme, with onset times at week 5 predicted to occur later than at week 1. Contrary to this prediction, no significant differences in the onset times of either the BP or NS' components were found between week 1 and week 5. The time-scale required to bring

about changes in MRCP component onset times may be longer than five weeks. Generally, in cross-sectional studies, participants of either national or international standard, with many years of training in a particular skill, are compared to a group of novices with no prior experience in that skill. Similarly, in Study 2, guitarists with a mean of 18.8 (± 11.23) years' guitar playing experience were compared to non-musicians who had never previously played any musical instrument. As such, the differences reported in cross-sectional studies may be the result of long-term learning that may take longer than five weeks to occur. If the training programme were extended further, significant changes in MRCP onset time may have been found.

To conclude, as an individual becomes more competent in performing a task following a period of training, there is a reduction in the amount of cortical activity required during motor planning of that task, in specific areas of the primary motor cortex. This is in line with the concept of neural efficiency following motor skill learning. This is the first study to demonstrate this effect during the learning of an ecologically valid motor task over a training period. It is hypothesised that with further training a reduction in MRCP amplitude may occur at other electrode sites, whilst the onset time of these components may occur later. In the following chapter, Study 4b extended the training period for a further five weeks to investigate this proposal.

Chapter 8

Study 4b: Changes in the movement-related cortical potential associated with a ten-week practice period on the guitar: The extended training study

8.1 – Introduction

Study 4a was influential as it represented the first experiment to explore skill learning-related changes in the MRCP over a training period of five weeks. The results of Study 4a indicated a reduced amplitude of the NS' and MP components of the MRCP at electrode sites C3 and Cz, following a five-week learning period. This finding provided initial support for the claims made in Study 2, and in the published cross-sectional MRCP studies (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001), that the differences between expert and novice participants are the result of the long-term training undertaken by the experts. This effect offered the first longitudinal evidence in support of the concept of neural efficiency. It is unclear however why the reduced amplitude was only found at electrode sites C3 and Cz, and why no changes in the MRCP component onset times occurred as a result of the training. The relatively short duration of the training period was proposed as one explanation for these results, and so the training study was extended to ten weeks.

8.2 – Aims of the investigation

The aim of this study was to investigate whether longitudinal training in a motor task would produce a reduction in amplitude and/or a change in onset time of the pre-movement components of the MRCP. As Study 4a only reported a reduced NS' and MP amplitude at electrode sites C3 and Cz after five-weeks, Study 4b was extended to a ten-week training study.

8.3 – Hypothesis

It was hypothesised that further training on the guitar would bring about a significant reduction in the amplitude of the pre-movement MRCP components at other electrode sites, and may produce a later onset of various pre-movement MRCP components.

8.4 – Method

8.4.1 – Participants

All ten participants who took part in Study 4a agreed to remain involved in the extended study for a further five weeks. It was explained to them that this would involve a further four weeks of guitar training, followed by a final EEG testing session. All participants agreed to this as they were keen to continue learning to play the guitar.

8.4.2 – Electrophysiological recording

The EEG recording procedure was identical to that used in the previous studies.

8.4.3 – Experimental procedure

Following week 5 in Study 4a, all participants attended a further four weeks of individual guitar lessons. The guitar lessons took the same format as in Study 4a, whereby the participants spent half the lesson practising the scale-playing task in time with a metronome, and half the lesson learning to play songs on the guitar. As with Study 4a, the participants performed a total of 150 repetitions of the scale during each lesson. By the end of the final guitar lesson at week 9, all participants had played the scale a total of 1290 times (120 repetitions at week 1, 150 repetitions at weeks 2-4, 120 repetitions at week 5, and 150 repetitions at weeks 6-9). The participants then returned for a final EEG

testing session, following the same procedure as weeks 1 and 5. The protocol for the extended training study can be seen in Figure 8.1.

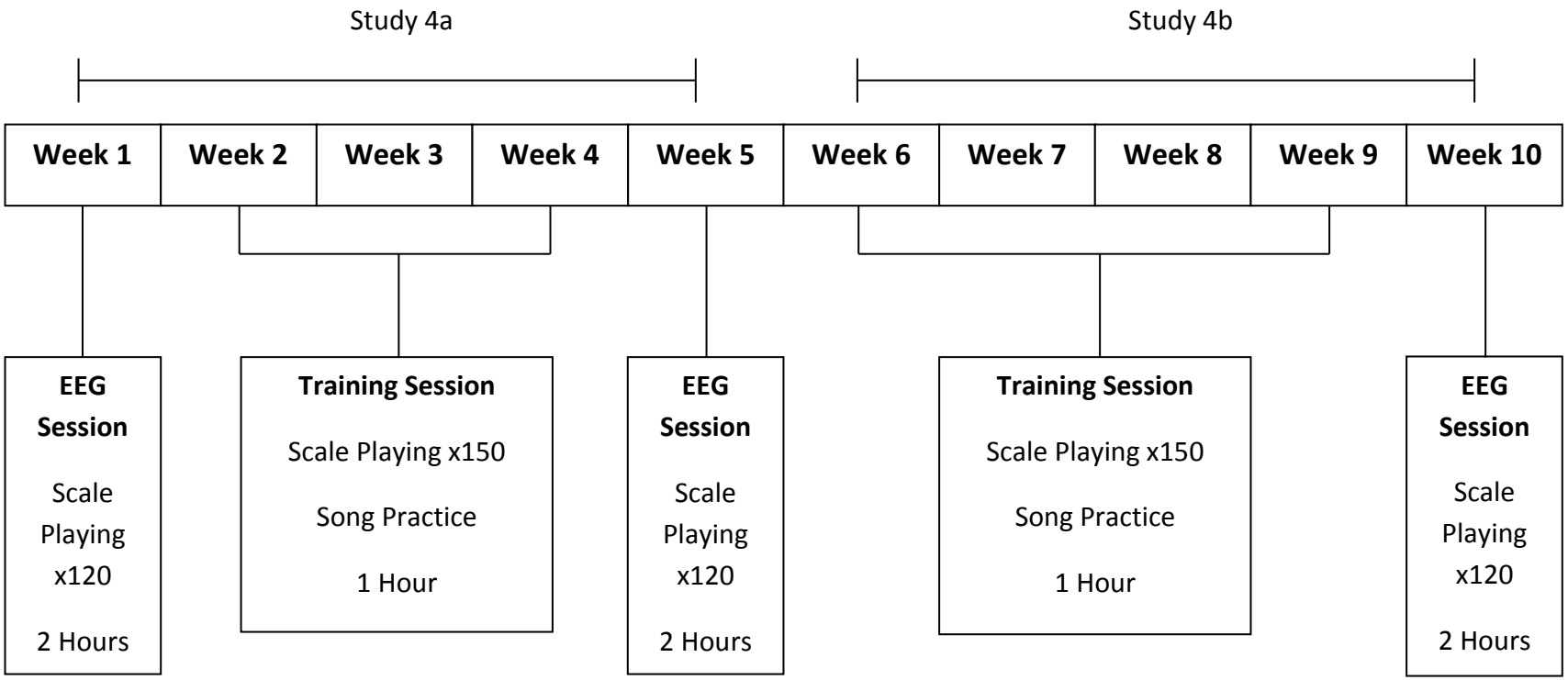

Figure 8.1: Protocol for the extended training study.

8.4.4 – Data analysis

The procedure used to extract the MRCP from the EEG trace was the same as that described in Study 1. During the EOG rejection phase of the analysis, an average of 15.6 trials per participant was rejected as they contained eye-movement artefacts.

For statistical analysis, the amplitudes and onset times of the BP, NS', and MP components of the MRCP were identified and extracted in the same was as described in Study 4a. The onset times of the BP and NS', and the amplitudes of the BP, NS' and MP were submitted to separate 3 time (week 1, week 5, week 10) x 6 electrode (FC3, FCz, FC4, C3, Cz, C4) repeated measures ANOVAs. Significant effects were reported at an alpha level of .05 and post-hoc interpretations were made using Duncan's multiple range tests. Effect sizes were reported as partial eta squared (η^2_ρ).

Performance was assessed over the course of the training programme in terms of how closely the participants played the scale in time with the metronome. This performance measure was recorded in the same way as in Study 2. The performance data were submitted to a one-way repeated measures ANOVA, with post-hoc paired samples *t* tests used to interpret the results.

8.5 – Results

8.5.1 – Electrophysiological data

MRCPs were recorded in all participants, at all six electrode sites, during all testing sessions. The waveform at week 10 however was very different to that at recorded in previous weeks. Specifically, the BP and NS' components of the MRCP were not distinguishable at week 10, rather the MRCP appeared as one continuous negative increase. The MRCP waveforms from each electrode, recorded at week 1, week 5, and

week 10 are displayed in Figure 8.2. The mean amplitudes and onset times of the individual components of the MRCP are shown in Figure 8.3 and Table 8.1, respectively.

8.5.1.1 – Bereitschaftspotential (BP)

At all weeks, the BP initiated between 1800 and 1900 ms prior to movement onset, and continued to increase gradually until around 700 ms prior to movement onset. The onset times for the BP at weeks 1, 5, and 10 are shown in Table 8.1. The repeated measures ANOVA for BP onset time revealed no significant main effect of time ($F_{2, 18}$ = 0.45, p = .65, η^2_ρ =.05) and no significant main effect of electrode ($F_{2.2, 20.1}$ = 2.04, p = .15, η^2_ρ =.19). There was however a significant time x electrode interaction ($F_{10, 90}$ = 2.06, p = .04, η^2_ρ =.19). The post-hoc analysis indicated that the BP onset occurred significantly earlier at week 10, compared to weeks 1 and 5, at electrode sites FC3 and FC4.

The amplitude of the BP was taken as the mean amplitude from the point of BP onset, to the point of NS' onset. The mean *z*-score amplitude for the BP at week 1 was -1.36 (± 1.91), compared to -1.1 (± 3.25) at week 5, and -2.65 (± 2.37) at week 10. The repeated measures ANOVA revealed that there was no significant main effect of time ($F_{2, 18}$ = 1.34, p = .29, η^2_ρ =.13) and no significant main effect of electrode ($F_{5, 45}$ = 1.53, p = .20, η^2_ρ =.15) for BP amplitude. Also, there was no significant time x electrode interaction ($F_{10, 90}$ = 1.6, p = .12, η^2_ρ =.15).

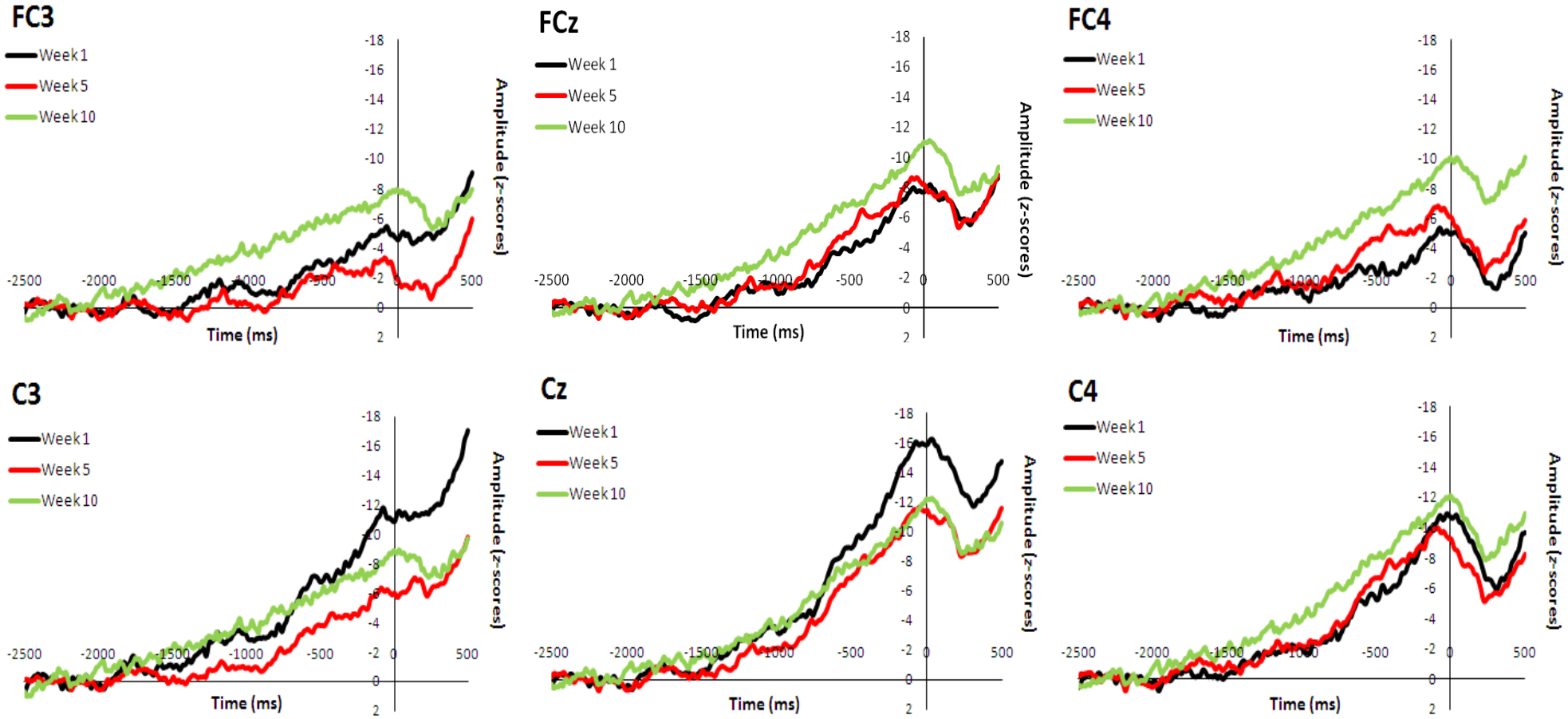

Figure 8.2: Movement-related cortical potential waveforms recorded from the motor cortex of non-musicians, at week 1 (black), week 5 (red), and week 10 (green), prior to performance of the G Major scale on the guitar.

8.5.1.2 – Negative Slope (NS')

The onset times for the NS' components at weeks 1, 5, and 10 are shown in Table 8.1. At weeks 1 and 5 the sharp, negative increase corresponding to NS' onset was clearly distinguishable from the BP. At week 10 however it was not possible to distinguish the NS' onset, as the whole MRCP appeared as a continuous negative increase, rather than a gradual negative increase (BP), followed by an increase of a much steeper gradient (NS'). As it was not possible to identify NS' onset at week 10, the mean NS' onset time at weeks 1 and 5 was calculated. This value was used as the week 10 onset time value in the NS' onset time analysis, and as the time point from which to calculate NS' amplitude. This was appropriate, as there had been no significant change in NS' onset from weeks 1 to 5.

The repeated measures ANOVA for the NS' onset found no significant main effect of time ($F_{2, 18} = 0.25$, $p = .78$, $\eta^2_\rho = .03$) and no significant main effect of electrode ($F_{3.4, 30.7} = 0.38$, $p = .79$, $\eta^2_\rho = .04$). In addition, there was no significant time x electrode interaction ($F_{10, 90} = 0.64$, $p = .78$, $\eta^2_\rho = .07$). These findings were expected given the lack of difference in NS' onset between weeks 1 and 5, and the fact that the NS' onset value at week 10 was taken as the mean of weeks 1 and 5.

The amplitude of the NS' was taken as the mean amplitude from the point of NS' onset to the peak of the MP. The mean *z*-score amplitude for the NS' at week 1 was -6.5 (± 4.88), compared to -5.62 (± 6.86) at week 5, and -7.62 (± 5.52) at week 10. The repeated measures ANOVA for NS' amplitude revealed no significant main effect of time ($F_{2, 18} = .45$, $p = .65$, $\eta^2_\rho = .05$). There was however a significant main effect of electrode ($F_{5, 45} = 7.66$, $p < .001$, $\eta^2_\rho = .46$). The post-hoc analysis indicated that the NS' amplitude at Cz was significantly larger than at FC3. There were also a significant time x electrode interaction ($F_{10, 90} = 3.15$, $p = .002$, $\eta^2_\rho = .26$). The post-hoc analysis indicated that, as with

Study 4a, the amplitude of the NS' was significantly smaller at week 5, compared to week 1, at electrode sites C3 and Cz. This significant difference was also present at Cz at week 10, compared to week 1, but not at C3. The post-hoc analysis also indicated that the amplitude of the NS' was significantly larger at week 10 at FC3, compared to weeks 1 and 5, and significantly larger at week 10 at FC4, compared to week 1.

8.5.1.3 – Motor Potential (MP)

The amplitude of the MP was taken at the peak of the MRCP, corresponding to the maximum negative peak immediately prior to movement onset. The mean *z*-score amplitude for the MP at week 1 was -10.58 (± 6.49), compared to -9.25 (± 8.28) at week 5, and -10.96 (± 6.69) at week 10. The repeated measures ANOVA revealed that there was no significant main effect of time for MP amplitude ($F_{2, 18} = 0.25$, $p = .78$, $\eta^2_\rho = .03$). There was however a significant main effect of electrode ($F_{5, 45} = 10.45$, $p < .001$, $\eta^2_\rho = .54$). The post-hoc analysis indicated that the amplitude of the MP at Cz was significantly larger than at FC3 and FC4, whilst the MP amplitude at C4 was significantly larger than at FC3. There were also a significant time x electrode interaction ($F_{10, 90} = 3.48$, $p = .001$, $\eta^2_\rho = .28$). The post-hoc analysis indicated that, as with Study 4a, the amplitude of the MP was significantly smaller at week 5, compared to week 1, at electrode sites C3 and Cz. This significant difference was also present at Cz at week 10, compared to week 1, but not at C3. The post-hoc analysis also indicated that the amplitude of the MP was significantly larger at week 10, compared to week 1 at FC4, and compared to week 5 at FC3.

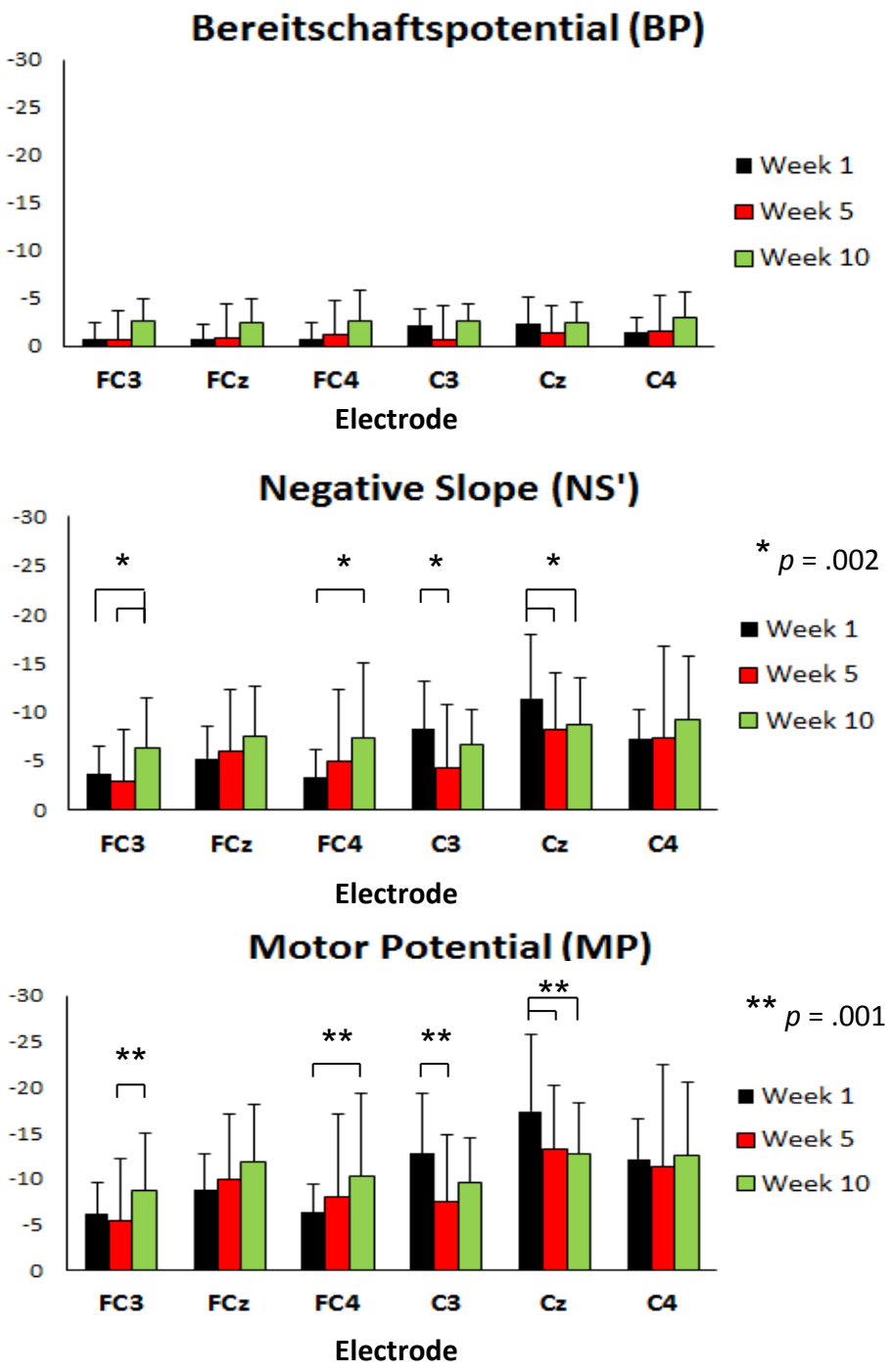

Figure 8.3: Mean amplitude values of the BP, NS', and MP recorded from non-musicians at week 1 (black), week 5 (red), and week 10 (green). Data was recorded from electrode sites overlying the motor cortex (FC3, FCz, FC4, C3, Cz, C4), prior to performance of a section of the G Major scale on the guitar. Significant effects are indicated by asterisks.

Table 8.1: Mean onset times (ms) for BP and NS' components of the MRCP at week 1, week 5, and week 10.

	Week 1	Week 5	Week 10	Significance
BP Onset (ms)	-1804 (± 245)	-1856 (± 297)	-1915 (± 410)	p = .65
NS' Onset (ms)	-691 (± 193)	-737 (± 195)	-714 (± 120)	p = .78

8.5.2 – Performance data

The mean millisecond difference between the beat of the metronome and the note being played decreased throughout the training programme (see Table 8.2). A one-way repeated measures ANOVA revealed a significant change in performance over time ($F_{2, 18} = 4.4$, $p = .05$, $\eta^2_\rho = .33$). Post-hoc paired samples t tests indicated that there was a significant improvement in performance from week 1 to week 5 (as shown in Study 4a), but only a trend for improved performance from week 1 to week 10. There was no significant improvement in performance from week 5 to week 10. These results indicate that practising the scale-playing task over a period of five weeks brought about an improved performance of the task. This improved performance from week 1 was also observed at week 10, although the improvement actually took place within the first five weeks.

Table 8.2: Mean millisecond differences in how closely the participants played in time with the metronome during the ten-week training study.

	Week 1	Week 5	Week 10
Difference between metronome and note (ms)	749.5 (± 1074)	272.9 (± 582)	133.2 (± 218)

8.6 – Discussion

The aim of this study was to investigate changes in the pre-movement components of the MRCP associated with a ten-week period of training on the guitar. Study 4a reported a decrease in the amplitude of the NS' and MP components of the MRCP at electrode sites C3 and Cz, after five weeks of training on the guitar. It was unclear however why no significant reduction in amplitude was found at other electrode sites, and why no significant change in MRCP onset times had occurred. The purpose of this study was to extend the training period by a further five weeks, to determine if a longer training period would bring about significant changes in the onset times or the amplitudes of the various MRCP components at other electrode sites. Before discussing the results of the study however, it should be reiterated that the data recorded at week 10 had a different profile to that recorded at weeks 1 and 5. Specifically, at week 10 the MRCP appeared as one continuous negative increase, and it was not possible to distinguish the individual BP and NS' components. It is unclear why the data recorded at week 10 were so different to the data recorded in previous weeks, given that the testing procedures were identical at all testing sessions. Although it was predicted that training on the guitar would bring about changes in the MRCP, it was still expected that the BP

and NS' components would be clearly identifiable. This unexpected difference in the profile of the week 10 data makes it difficult to draw firm conclusions from the data. Any explanations offered in the remainder of this discussion should therefore be treated with caution.

With that in mind, the results of this study challenge the hypotheses for this experiment. The results for the BP indicated that the onset time at FC3 and FC4 occurred significantly earlier at week 10, compared to weeks 1 and 5. Additionally, although not statistically significant, Figure 8.2 shows a trend for the BP to occur earlier at week 10 than at weeks 1 and 5 at all electrode sites. In terms of the BP amplitude, Figures 8.2 and 8.3 illustrate a trend for larger BP amplitudes at week 10 compared to weeks 1 and 5. As with the BP onset time data, this trend was in the opposite direction to the experimental hypothesis. In relation to the NS' data, no significant changes in the NS' onset time were found across time at any electrode site. There was however a significant increase in the amplitude of the NS' at anterior electrode sites FC3 and FC4 from week 1 to week 10. Figures 8.2 and 8.3 also indicate a trend for this effect at site FCz. At site Cz however there was a reduction in the amplitude of the NS' from week 1 to week 5 and week 1 to 10. This effect was also seen at C3, but only from week 1 to week 5. For the MP, there was an increase in amplitude across the training programme at anterior electrode sites, significant at FC3 and FC4. A trend for this effect was also evident at FCz (see Figures 8.2 and 8.3). This was in direct contrast to the predictions made prior to the study. As with the NS' however, the amplitude of the MP was reduced from week 1 to week 5 at C3 and Cz. This difference remained significant at week 10 but only for Cz. Only electrode sites C3 and Cz therefore produced the hypothesised reduction in amplitude for the NS' and MP, with the amplitude values at the anterior sites increasing over the training programme.

In summary, training on the guitar brought about: (i) an increase in the amplitude of the NS' and MP components at the anterior electrode sites FC3 and FC4, together with a trend for this result at FCz; and (ii) a decrease in the amplitude of the NS' and MP at posterior electrode sites C3 and Cz. The reason for an increase in amplitude at some sites, and a decrease at others, may relate to the functions of the cortical areas beneath these electrodes. The anterior electrodes were located over areas of the pre-motor cortex (FC3 and FC4) and the SMA (FCz); areas of the brain more involved with movement planning than movement execution. Specifically, the pre-motor cortex of the brain is involved in selecting the movement to be executed (Kolb & Whishaw, 2009). The SMA however is more involved in motor planning and bi-manual control (Cunnington et al., 1996). In contrast, the posterior electrodes were located over areas of the primary motor cortex (C3, Cz, and C4) and also approximately over the SMA (Cz). The primary motor cortex is more involved in motor execution (Kolb & Whishaw, 2009), than motor planning. The results of this study therefore indicate that a ten-week period of training on the guitar brought about an increased negativity in areas of the brain involved in motor planning, together with a decrease in negativity in some areas of the brain involved in motor execution. Deecke (1996) suggested that greater negativity in the EEG indicates increased activity in the area of the cortex beneath the electrode. Additionally, Lang et al. (1992) argued that a change in the amplitude of the MRCP reflects a change in the amount of cortical effort involved in movement preparation. Based on these proposals, it seems possible that training on the guitar resulted in less cortical activity being required to execute movements, but more cortical activity being required to select and plan those movements.

Changes in the participants' motivation and attentional involvement in the task may have accounted for the larger amplitude MRCPs at week 10, compared to previous weeks. At week 1, participants may have been excited to learn to play the guitar and were possibly attracted by the novelty of having their brain activity recorded. By the week 5 EEG session, after successfully learning to play some songs, they were possibly still enjoying taking part in the study, and looking forward to the remaining guitar lessons. By week 10 however, the participants may have become bored with constantly performing the same scale, and knew that they would be receiving no more guitar lessons. As such, by week 10, there was possibly little incentive for the participants to engage in the task, resulting in a decrease in motivation and attention to the task. These factors may have influenced participants' MRCP at week 10. Examination of the literature however reveals that if this were the case, the opposite effect would likely have been found. Increased levels of motivation have been reported to produce larger amplitude MRCPs (McAdam & Seales, 1969). If it were true that the participants were highly motivated at week 1 but not at week 10, larger amplitudes should therefore have occurred when motivation was high, and smaller amplitudes should have been found when motivation was low. The current results are in contrast with the motivation MRCP research, and so it is unlikely that changes in participants' motivation can explain these findings. Similarly, the results are unlikely to reflect the effect of participants becoming bored or paying less attention to the task. In their original MRCP experiment, Kornhuber and Deecke (1965) reported that the amplitude of the BP decreased when participants became bored and uninterested in the task, whilst Masaki et al. (1998) reported larger amplitude MRCPs when attention to the task was high. Based on this evidence, had participants lost interest in the task by week 10, larger amplitudes should have been found when attention to the task was high, and smaller amplitudes should have occurred when boredom set in. The

current study shows the opposite effect, and so it is unlikely that the increase in MRCP amplitude at week 10, at certain sites, is a direct consequence of participants' boredom or lack of attention.

An alternative explanation for the unexpected findings at week 10 could be due to the attention participants devoted to the metronome. At week 1 the participants may have found it difficult to physically perform the actions required to play the scale; to remember the correct notes and the order in which they should be played. If this were the case, the participants may have blocked out the metronome at week 1, and only focused on playing the correct notes. As this would have been a difficult task, it could explain the large amplitude MRCPs and poor performance scores at week 1. It is possible that by week 5 participants were still focused on the actions required to play the scale, and were not particularly focused on playing in time with the metronome. After practising the scale for four weeks however, they may have begun to master the physical actions required to perform the scale and played more closely in time with the metronome, despite this not being their main focus. This could explain the reduced amplitude of the MRCP and the improved performance score at week 5. By week 10, participants may have begun to master the actions required to physically perform the scale and so devoted less attention to performing the movements, and more attention to playing in time with the metronome. Participants may have divided their attention, partly focusing on playing the correct notes, and partly focusing on the timing of the metronome. Although only speculation, this shifting or dividing of attention to focus on both the metronome and playing the correct notes may have resulted in the task suddenly increasing in complexity. With their attention split between the two, a greater amount of cortical activity may have been required to plan and prepare to perform the movement at week 10, compared to

week 1. This may have resulted in the increased MRCP amplitude at week 10 at the anterior electrode sites, which are overlying areas of the brain involved in motor planning, despite the significantly improved performance scores. Although only speculative, this could be a plausible explanation for the findings.

This explanation fits in with the Five-A model of technical change proposed by Carson and Collins (2011). This model outlines five recursive stages that elite performers encounter when attempting to refine or modify their technique. The model suggests that after *analysing* a problem with their current technique, a performer must become consciously *aware* of differences between the current and desired technique. The performer then attempts to *adjust*, modify, or correct the flaw in their technique. With practice, the skill becomes *automated*, resulting in its performance shifting outside of the performer's conscious awareness, leading to the performer achieving a state of *assurance* that no further modification is required. Whilst the purpose of the model is to provide a structured framework for modifying technique in elite athletes, it is possible that a similar process, albeit less structured, occurred within the non-musician participants in this study. Between week 1 and 5 participants were gaining competence in the task, possibly resulting in the reduction in the amplitude of the MRCP at C3 and Cz. Sometime between the testing sessions at weeks 5 and 10 it is possible that the participants, perhaps prompted by reminders from the experimenter, identified the need to modify their technique in order to better play in time with the metronome. This may have resulted in participants being in the *adjustment* phase of the Five-A model by the week 10 EEG session. At this stage, the participants would be faced with an increased demand to execute the new technique correctly (Carson & Collins, 2011). This may have increased the task difficulty so that greater cortical activity was required to plan each repetition of

the scale, resulting in a MRCP of larger amplitude than in earlier weeks. With continued practice, the task would likely have become more automated and the amplitude of the MRCP may have become reduced.

Although these suggestions are speculative, it is evident that the cortical processes involved in motor skill learning may not be as simple as suggested by researchers on the basis of cross-sectional MRCP studies. The process is likely to be more complex than the simplistic explanation that practice or training in a skill causes a linear reduction in cortical activity. It is perhaps more likely that over a long-term learning period, there are fluctuations in the amount of cortical activity involved in the planning phases of a skill as a performer adjusts aspects of their performance, attempts to alter their playing style, or focuses on different aspects of their performance. This process may eventually lead to a reduced level of cortical activity being required to plan and perform the skill, compared to when the performer was a novice, but it is possible that this may take many years to occur. Future research should further explore the cortical processes involved in motor skill learning. Given the unexpected profile of the data recorded at week 10, a future study should attempt to replicate the current study to explore whether the same change in the MRCP profile occurs, and to establish if the unexpected increase in amplitude at week 10 is a consistent finding. Future research should also extend the length of the training programme and record EEG more frequently throughout the training programme to better establish the time course of these reported changes. In the following chapter, the effect of a period of de-training following this ten-week training programme is explored.

Chapter 9

Study 4c: The effect of a period of de-training on the movement-related cortical potential

9.1 – Introduction

Studies 4a and 4b investigated changes in the amplitude and onset time of the MRCP that were associated with extended practice of a scale-playing task on the guitar. By the end of Study 4b, participants had spent ten weeks learning to play the guitar. After investigating changes in cortical activity over this period, a period of de-training was included. Participants refrained from any form of practice on the guitar for a period of five weeks, before attending a final EEG testing session. The purpose of this was to establish the permanence of any changes in MRCP amplitude as a result of the training programme. It is important to point out that only five of the ten participants who took part in the extended training study participated in this de-training section of the experiment. Whilst it is acknowledged that this is a small sample size, it is common for studies that have employed a de-training period to have smaller samples for the de-training element of the study. For example, Jensen, Marstrand, and Nielsen (2005) used a sample of eight participants in their TMS study, which investigated cortical plasticity following visuomotor skill learning, but only four of those participants were retained for de-training.

9.2 – Aims of the investigation

The aim of this de-training study was to establish the permanence of any training-related changes in the MRCP. The purpose of this study was to establish the effect of

withdrawing from the task for five weeks. Specifically, the aim was to determine whether the training programme resulted in a relatively permanent change in cortical activity, or whether regular training was necessary to maintain a reduced level of cortical activity during motor preparation.

9.3 – Hypothesis

As a result of the fluctuations in the MRCP during the training study, it was hypothesised that there would be a further change in the MRCP following a period of de-training.

9.4 – Method

9.4.1 – Participants

Five of the participants (2 male, 3 female; mean age 26.2 ± 10.57) who took part in the ten-week training study agreed to take part in the de-training study. The other participants did not participate either because they had decided to carry on learning to play the guitar after the training study had finished, and so did not qualify for the de-training study, or they could not be contacted to arrange a testing date.

9.4.2 – Electrophysiological recording

The EEG recording procedure for the de-training study was identical to that described in Study 1.

9.4.3 – Experimental procedure

The experimental procedure was identical to that described in Study 1. After completing the training study, all participants withdrew from any form of training on the guitar for a period of five weeks. The protocol for the de-training study can be seen in Figure 9.1.

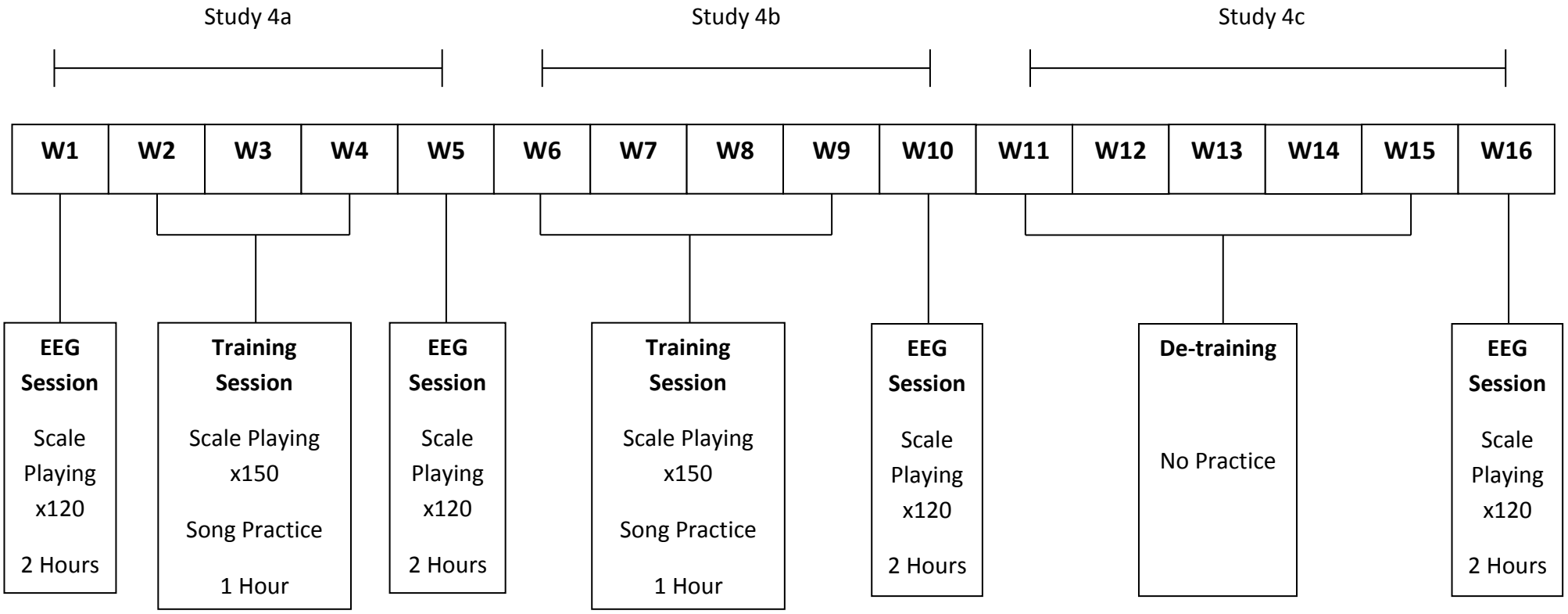

Figure 9.1: Protocol for the full training and de-training study. Study 4c represents the de-training phase of the study.

9.4.4 – Data analysis

The procedure used to extract the MRCP from the raw EEG was the same as that described in Study 1. During the EOG rejection phase of the data analysis, an average of 10.5 trials was rejected per participant as they contained eye-movement artefacts. The amplitude and onset times for the MRCP components were identified in the same way as described in Studies 4a and 4b. Given the small sample size for this de-training aspect of the study, analysis of the data using inferential statistics was deemed inappropriate, and so this study focused on descriptive statistics.

Performance was assessed over the course of the training programme in terms of how closely the participants played the scale in time with the metronome. This performance measure was recorded in the same way as in Study 2. As with the EEG data, given the small sample size, no statistical analyses were performed on the performance data.

9.5 – Results

9.5.1 – Electrophysiological data

MRCP waveforms were present in all participants and at all electrode sites in the de-training study. Figure 9.2 shows the MRCP waveforms at weeks 1, 5, 10, and 16 from the five participants who took part in de-training. Data from the five participants who did not take part in the de-training were removed from the waveforms shown in Figure 9.2. Due to the small number of participants who took part in the de-training study it was suitable to also present the grand average waveforms at each week from those five participants (see Figure 9.3).

9.5.1.1 – Bereitschaftspotential (BP)

The mean onset times for the BP can be seen in Table 9.1. The table shows that the onset time of the BP was stable throughout the training and de-training programme, not varying by more than 80 ms between testing sessions. Furthermore, it is not possible to distinguish any differences in the onset time of the BP between testing sessions, when examining the MRCP waveforms in either Figures 9.2 or 9.3.

In relation to the amplitude of the BP, there was little change across the training and de-training programme. The mean *z*-score amplitude of the BP in these five participants was -1.61 (± 2.33) at week 1, compared to -1.99 (± 3.07) at week 5, -2.25 (± 1.99) at week 10, and -1.74 (± 2.27) at week 16. Figure 9.4 indicates that there may have been a small increase in the amplitude of the BP during the training phase of the study, followed by a small decrease in amplitude at de-training. Figure 9.5 indicates that this change in amplitude occurred mainly at the anterior electrodes FC3, FCz and FC4. When examining the MRCP waveforms however, any differences in BP amplitude were negligible (see Figures 9.2 and 9.3).

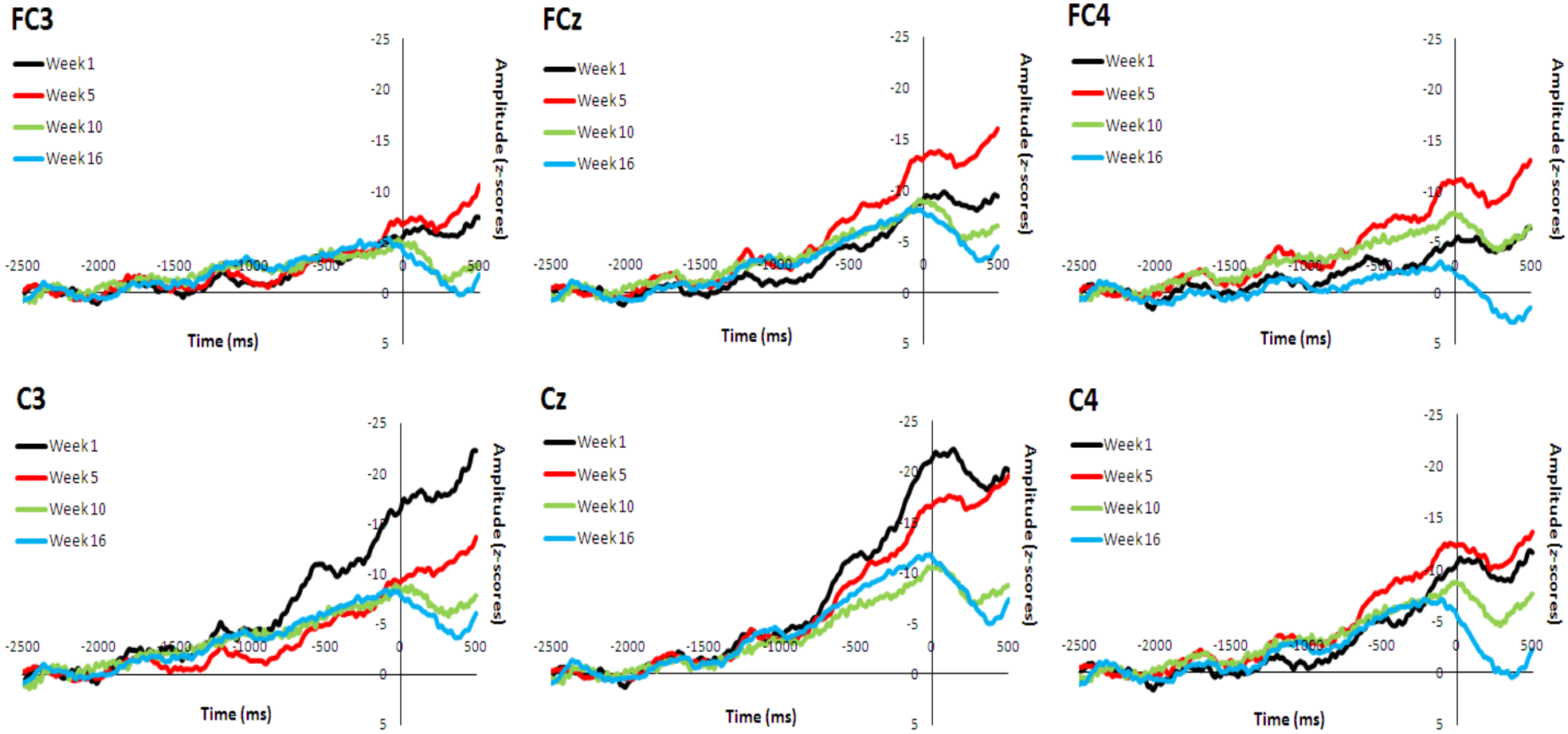

Figure 9.2: Movement-related cortical potential waveforms recorded from five participants at weeks 1, 5, 10 (training), and 16 (de-training) of the training programme on the guitar.

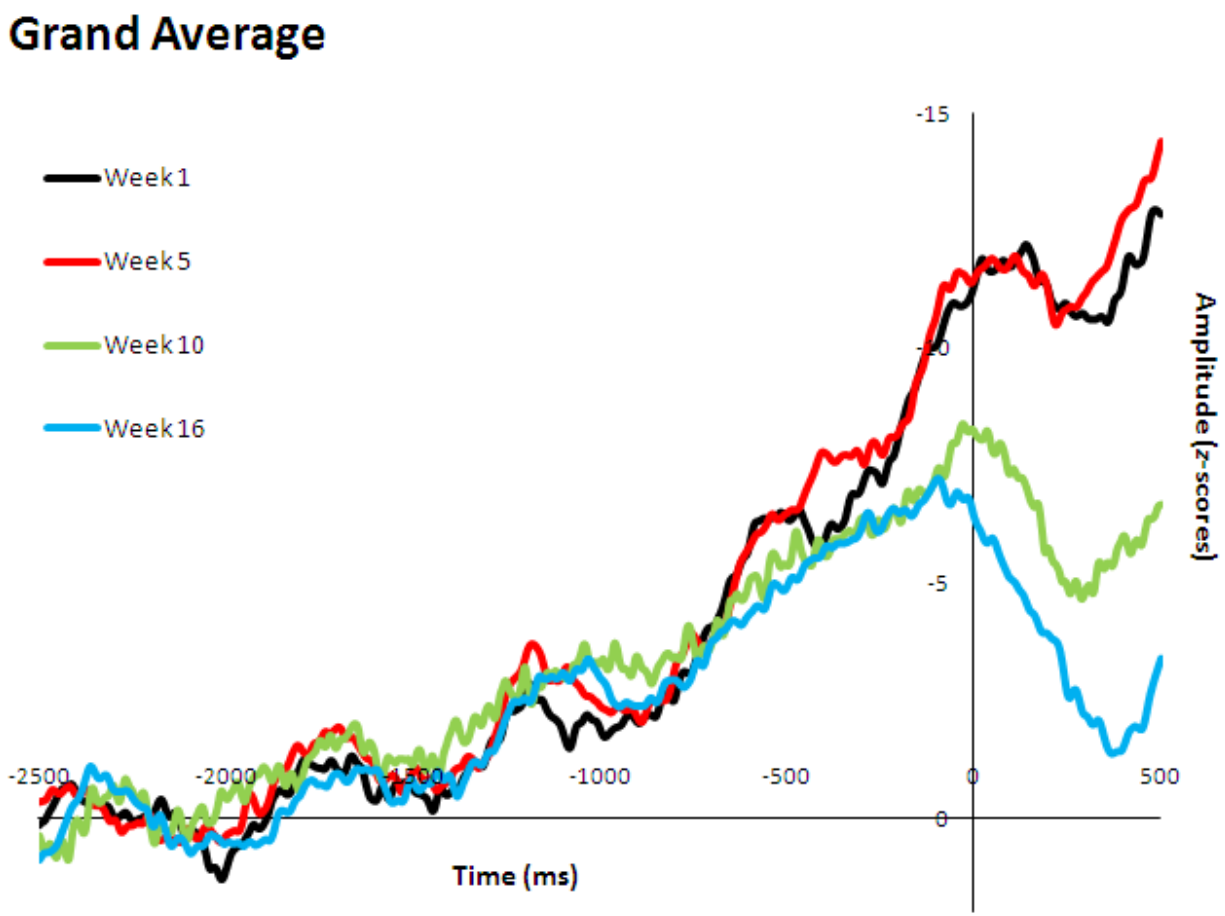

Figure 9.3: Grand average MRCP waveforms recorded from five participants who took part in all EEG testing sessions at weeks 1, 5, 10, and 16 of the training/de-training study.

9.5.1.2 – Negative Slope (NS')

The mean onset times for the NS' can be seen in Table 9.1. The table shows that the onset time of the NS' was stable throughout the training and de-training programme, not varying by more than around 35 ms between testing sessions. Furthermore, when examining the MRCP waveforms (Figures 9.2 and 9.3), it is not possible to distinguish any meaningful differences in the onset time of the NS' between testing sessions.

Unlike the BP amplitude data, there seems to be a clear change in the amplitude of the NS' as a result of the participants' training and de-training on the guitar. The mean *z*-score amplitude of the NS' in these five participants was -7.22 (± 5.34) at week 1, compared to -7.57 (± 6.94) at week 5, -5.95 (± 3.59) at week 10, and -5.6 (± 5.65) at week 16. Examination of the grand average waveform in these five participants (see Figure 9.3) shows a large amplitude for the NS' at weeks 1 and 5, which was reduced considerably by week 10 and remained low at week 16. This decrease in NS' amplitude was most evident at electrode sites C3 and Cz (see Figures 9.2 and 9.5).

9.5.1.3 – Motor Potential (MP)

The mean *z*-score amplitude of the MP in these five participants was -11.77 (± 7.22) at week 1, compared to -12.08 (± 8.52) at week 5, -8.83 (± 4.07) at week 10, and -8.52 (± 6.56) at week 16. The amplitude of the MP therefore reduced throughout the training programme, following a similar pattern to the NS'. The amplitude of the MP was smaller at week 10 of the training programme, compared to weeks 1 and 5 (see Figures 9.3 and 9.4). This reduction, particularly strong at the posterior electrode sites, was still evident at week 16. This indicates that, in these five participants, training on the guitar

caused a reduction in the amplitude of the MP. As this reduced amplitude was still present at de-training, it was a relatively permanent change.

Table 9.1: Mean onset times (ms) for BP and NS' components of the MRCP at weeks 1, 5, 10, and 16 of the training/de-training study.

	Training			De-training
	Week 1	Week 5	Week 10	Week 16
BP Onset (ms)	-1880 (± 277)	-1935 (± 305)	-1901 (± 453)	-1851 (± 244)
NS' Onset (ms)	-773 (± 183)	-741 (± 110)	-757 (± 114)	-738 (± 258)

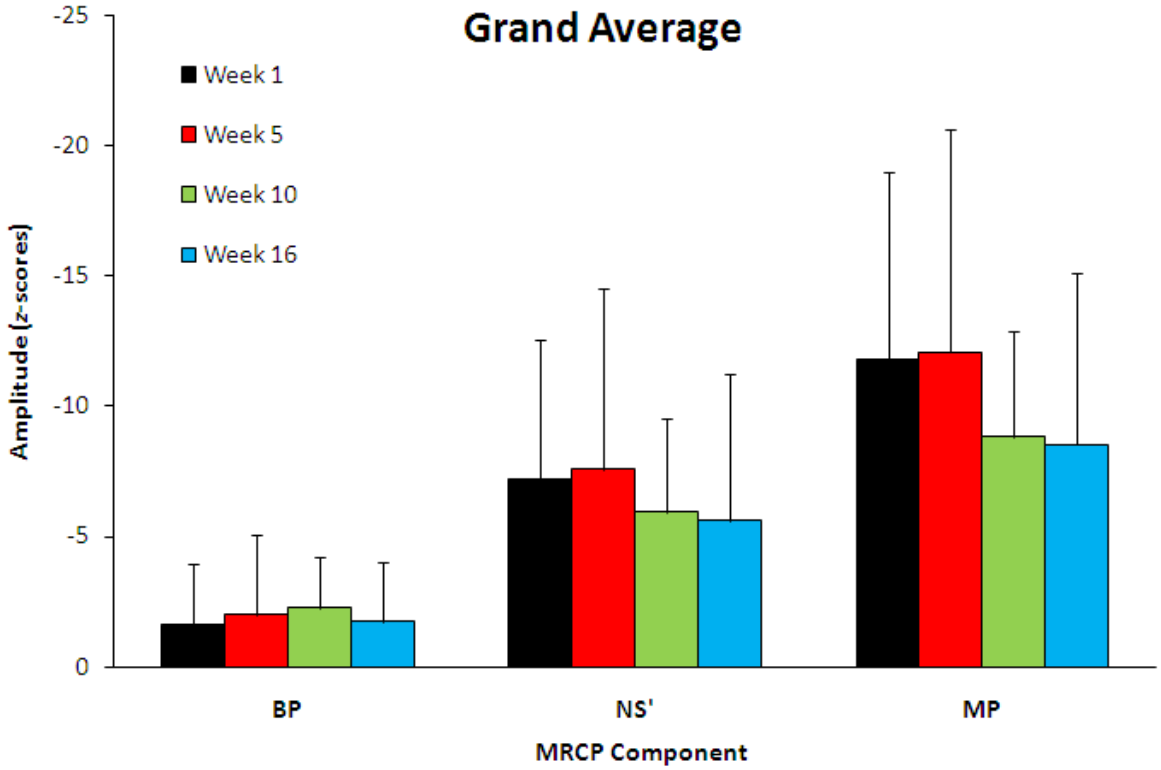

Figure 9.4: Grand average values for the BP, NS', and MP for the five participants who took part in all EEG sessions during the sixteen-week training/de-training study.

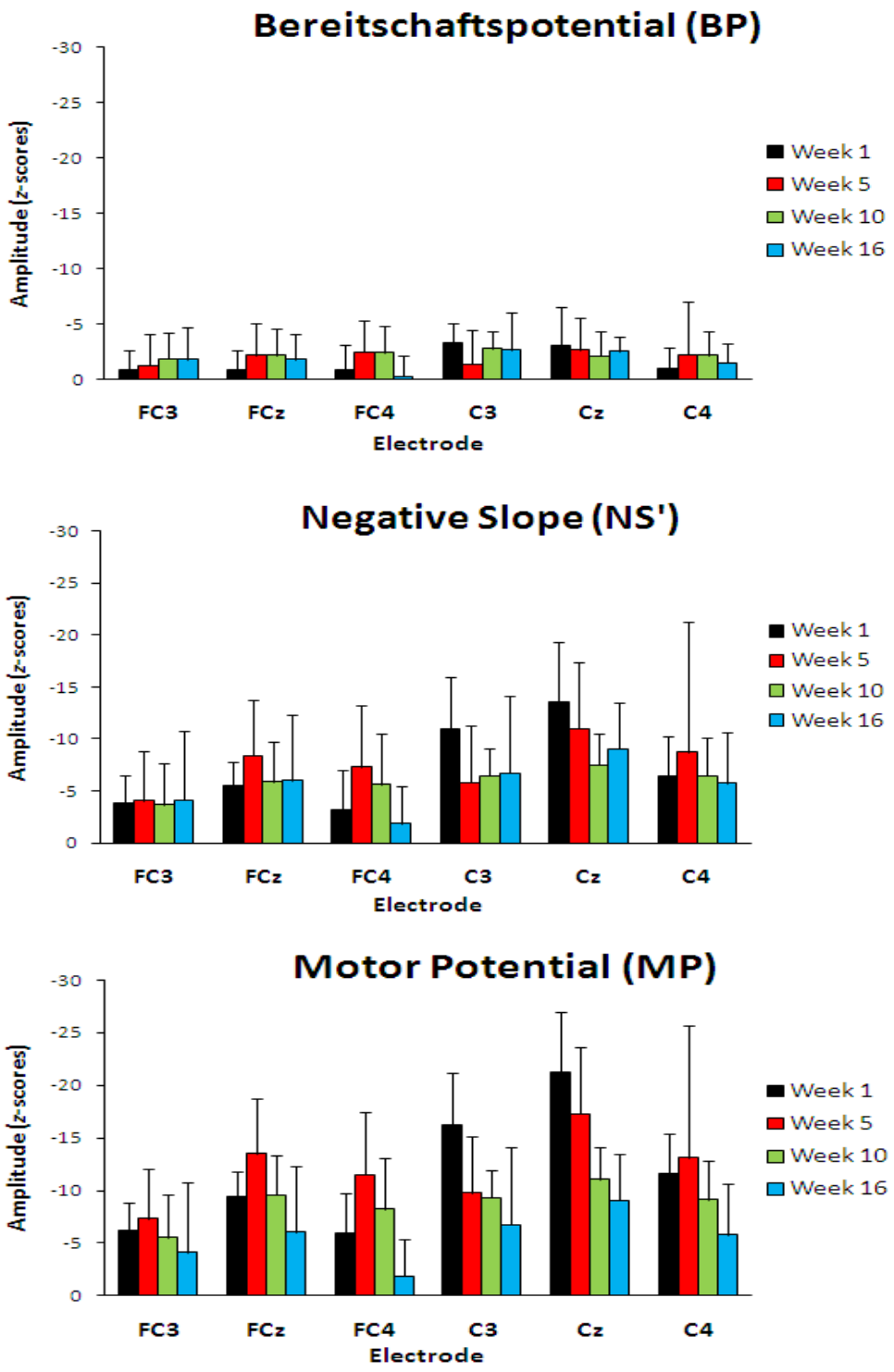

Figure 9.5: Mean amplitude values for the BP, NS', and MP components of the MRCP recorded from the five participants who took part in all EEG testing sessions at week 1 (black), week 5 (red), week 10 (green) and week 16 (blue).

9.5.2 – Performance data

As with the EEG data, the performance data reported here represent the average values reported from the five participants who took part in all four training and de-training testing sessions. Table 9.2 shows the average millisecond difference between the beat of the metronome and the note being played at weeks 1, 5, 10, and 16. The table shows an improvement in performance across the training phase of the study. Participants were unable to play closely in time with the metronome at week 1. By week 5, the participants showed a large improvement in their performance and they continued to show gradual improvements between weeks 5 and 10. At week 16, after the five-week period of de-training, the participants' performance remained comparable to week 10, indicating that the ten-week training programme had brought about a relatively permanent change in their ability to play the scale in time with the metronome.

Table 9.2: Mean millisecond differences in how closely the participants played in time with the metronome during the sixteen-week training and de-training study.

	Week 1	**Week 5**	**Week 10**	**Week 16**
Difference between the beat metronome and the note being played (ms)	328.5 (± 587)	62.5 (± 53)	43.1 (± 19)	48.4 (± 33)

9.6 – Discussion

Before discussing the results of this study, it is first important to point out the differences between the data presented here and that presented in the earlier studies. The data presented in Studies 4a and 4b were the averaged data from ten participants who took part in the ten-week training programme. In this de-training study, only five of those ten participants took part. As a result of the smaller sample in this de-training study, when presenting the data from earlier weeks in the training programme, only the data from participants who took part in the full sixteen-week training and de-training programme are presented. The data from the five participants who did not take part in de-training have been removed from the week 1, 5, and 10 data. This substantially altered the MRCP waveforms presented in this study. Study 4b unexpectedly reported MRCPs of larger amplitude at week 10, compared to weeks 1 and 5. When the data from those participants who did not take part in de-training were removed from the averaged data, the amplitude of the MRCP at week 10 was smaller than in the previous weeks at most electrode sites. It is a coincidence that those participants who produced the largest amplitude MRCPs at week 10 did not take part in the de-training study.

The result of using this small sample is that the grand average data for the whole training and de-training study meets the hypothesis of the original training study, in that training on the guitar over a period of ten weeks reduced the amplitude of the MRCP. This reduction was still present at week 16, after a five-week period of de-training, indicating that the effects of the training programme were relatively permanent in these five participants. The decrease in MRCP amplitude across the training programme was accompanied by an improvement in performance, as measured by how closely the participants played in time with the metronome. The participants' performance scores

(shown in Table 9.2) indicate a large improvement in performance from week 1 to week 5, followed by a smaller improvement from week 5 to 10. By week 16, after the de-training period, the participants' performance remained comparable to their week 10 performance.

Motor skill learning is defined as the process associated with practice or experience that leads to a relatively permanent change in a performer's ability to perform a motor skill (Schmidt & Lee, 2011). Based on this definition, the changes in participants' cortical activity and performance are possibly learning-related, brought about by long-term practice, and still evident after a period of de-training. These results verify the claims made by authors of cross-sectional MRCP research, who speculated that smaller amplitude MRCPs in experts, compared to novices, are learning-related (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001). These results can be explained in line with the concept of neural efficiency. According to this concept, individuals who perform a skill to a high standard are likely to have a more efficient cortical functioning when performing that skill, compared to individuals who perform to a lower standard (Babiloni et al., 2010). The results presented here are consistent with this hypothesis, as participants required a large amount of cortical activity to plan and perform the scale-playing task when their performance was poor. As their scale-playing performance improved with training, the cortical activity required to plan and perform the scale decreased, which could indicate a more efficient motor preparation. Cortical activity involved in planning to perform the scale remained reduced at de-training, possibly indicating that the reduced cortical activity brought about by motor skill learning had a long-lasting effect. This is an important finding as most of the data that has been used by researchers to support the concept of neural efficiency have

come from cross-sectional studies (e.g., Babiloni et al., 2010; Del Percio et al., 2008). These results offer the first longitudinal evidence in support of this concept.

Although these results are interesting, further research is required before any firm conclusions can be drawn. It was unclear why the data presented in Study 4b showed an increase in the amplitude of the MRCP following a ten-week period of motor skill learning. It is equally unclear why, after the removal of five participants' data, the training and de-training data supported the experimental hypothesis for the study. A decrease in MRCP amplitude in only five participants does not provide strong evidence that there is a meaningful effect, particularly given the lack of statistical analysis and the fact that when more participants were included, the opposite effect was reported. There is therefore a need for future research to replicate this training and de-training study. This research should incorporate a larger sample size for both training and de-training elements of the study in order for meaningful statistical analyses to be performed. Ideally, the research should also be conducted over a longer training period and with more frequent EEG testing sessions. This would provide a clearer picture of the cortical processes involved in motor skill learning.

Chapter 10

Study 5: Within session changes in the movement-related cortical potential associated with extended motor skill training

10.1 – Introduction

In Study 3 (Chapter 6) changes in activity of the motor cortex associated with short-term practice of a scale-playing task on the guitar were examined by comparing the MRCP recorded from early trials with the MRCP recorded from late trials in the practice session. The results indicated that following short-term practice of the scale playing task, more cortical activity was required by the motor cortex to plan the performance of the task. This finding was in contrast to the hypotheses of the study as well as the published literature in the area (e.g., Dirnberger et al., 2004; Lang et al., 1992).

Two explanations were offered for the finding in Study 3, but it was unclear which explanation was likely to be the most accurate. Consistent with the work by Taylor (1978) and Toni et al. (1998), it was proposed that the process of motor skill learning is characterised by an initial increase in cortical activity as participants have difficulty learning and performing the task, followed by a decrease in cortical activity once participants become competent in the task. As the motor task used in Study 3 was a relatively complex, novel, bi-manual task, participants may have still had some difficulty performing the scale in the late block of trials. This may have led to an increase, rather than a decrease, in amplitude in the late block of trials. It was speculated in Study 3 that if the practice session had been longer, a decrease in the amplitude of the MRCP may have been found.

The second explanation offered for the results reported in Study 3 was that, as participants were performing 100 repetitions of a relatively complex bi-manual task, they may have become fatigued towards the end of the practice session. Fatigue has consistently been shown to increase the amplitude of the MRCP (e.g., Falvo et al., 2011; Freude & Ullsperger, 1987; Johnston et al., 2001; Schillings et al., 2006). The increased amplitude in the late block of trials reported in Study 3 may not therefore have been learning-related, but rather due to participant fatigue. The purpose of this study was to determine which of these explanations could be supported. This was achieved by analysing the week 5 and week 10 training study data in the same way as in Study 3. If the fatigue explanation were correct, the results should mirror those reported in Study 3, in that the amplitude of the MRCP in the late block of trials at week 5 and week 10 should be larger, compared to the early block of trials. If the skill learning explanation were correct, as participants became familiar with the task, the amplitude of the MRCP should be smaller in the late block of trials, compared to the early block of trials, at weeks 5 and 10.

10.2 – Aims of the investigation

The aim of this experiment was to investigate within-session changes in the activity of the motor cortex that were associated with practice of a motor task over a longitudinal period of ten weeks. By analysing the week 5 and week 10 data from the training study in the same way as the week 1 data were analysed in Study 3, it would be possible to establish which of the two proposals for the Study 3 data best explains the data.

10.3 – Hypotheses

It was hypothesised that short-term practice of the scale-playing task over a period of ten weeks would modulate the amplitude of the MRCP. Specifically, it was hypothesised that the MRCP would either: (i) be of larger amplitude in late, compared to early blocks of trials at week 5 and week 10, similar to the results of Study 3; or (ii) show the opposite result to Study 3, with smaller amplitude in the late blocks of trials, compared to the early trials, at weeks 5 and 10. If the results were as outlined in the first scenario, this would offer support for fatigue influencing the MRCP. If the results were as outlined in the second scenario, this, together with the results of Study 3, would provide support for the claims by Taylor (1978) and Toni et al. (1998), that the process of skill learning is characterised by an initial increase in cortical activity during early learning, followed by a decrease in activity in later learning.

10.4 – Method

10.4.1 – Participants

The same participants who took part in Study 4a and Study 4b took part in this study.

10.4.2 – Electrophysiological recording

The EEG recording in this study was identical to that described in Study 1.

10.4.3 – Experimental procedure

The experimental procedure in this study was identical to that described in Studies 4a and 4b.

10.4.4 – Data analysis

The week 5 and week 10 data from the training study were analysed in the same way as described in Study 3. Due to the small number of trials comprising the MRCP waveforms, the data were noisier than in Studies 1, 2, and 4, and so it was difficult to identify onset times of the BP and NS' components accurately. As such, only amplitude values of the BP, NS' and MP were analysed.

10.5 – Results

10.5.1 – Week 5 data

MRCP waveforms were evident for all participants at all electrode sites in both early and late blocks of trials (see Figure 10.1). The only exception to this was at site FC3 in the late blocks of trials, where the typical characteristics of the MRCP could not be identified. Mean amplitude values for each component of the MRCP can be seen in Figure 10.2.

10.5.1.1 – Bereitschaftspotential (BP)

The BP amplitude was taken as the mean amplitude in the time period -2000 to -500 ms. The mean *z*-score amplitude for the BP was -1.91 (± 2.94) in the early block of trials, compared to -1.02 (± 1.83) in the late block of trials. The repeated measures ANOVA revealed that there was no significant main effect of time ($F_{1, 9} = 1.45$, $p = .26$, $\eta^2_\rho = .14$) and no significant main effect of electrode ($F_{3.3, 29.5} = .51$, $p = .70$, $\eta^2_\rho = .05$). In addition, there was no significant time x electrode interaction ($F_{1.9, 17.4} = .31$, $p = .73$, $\eta^2_\rho = .03$).

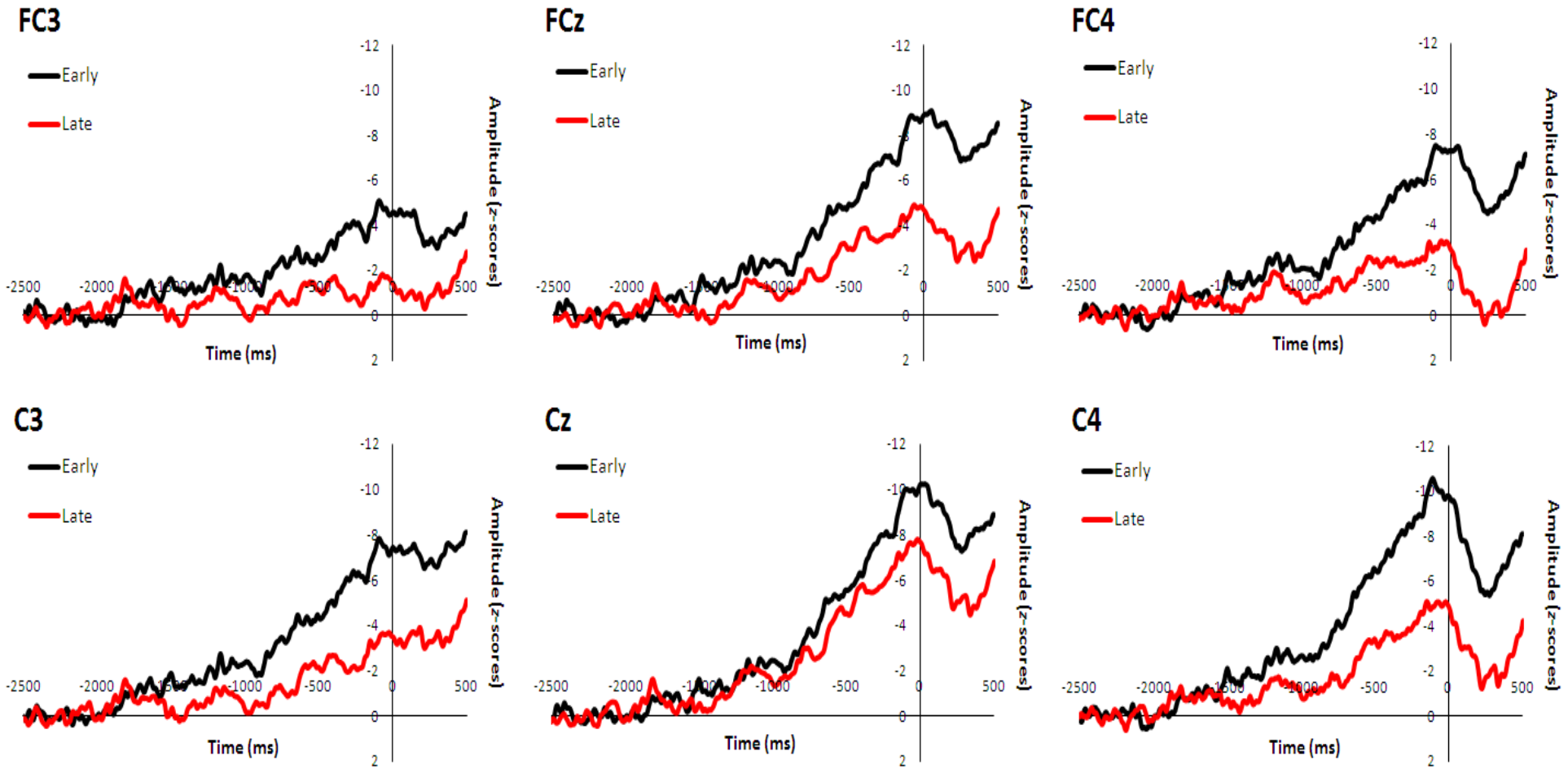

Figure 10.1: Movement-related cortical potential waveforms recorded at week 5 from the motor cortex of non-musicians in early (black) and late (red) blocks of trials prior to performance of the G Major scale on the guitar at a tempo of 100 beats per minute.

10.5.1.2 – Negative Slope (NS')

The amplitude of the NS' was taken as the mean amplitude in the period from -500 ms to 0 ms. The mean *z*-score amplitude for the NS' was -6.57 (± 6.82) in the early block of trials, compared to -3.44 (± 4.25) in the late block of trials. The repeated measures ANOVA revealed that there was no significant main effect of time ($F_{1, 9} = 2.93$, $p = .12$ $\eta^2_\rho = .25$). There was however a significant main effect of electrode ($F_{2.8, 25.3} = 5.18$, $p = .007$, $\eta^2_\rho = .37$). The post-hoc analysis indicated that the amplitude of the NS' at Cz and C4 were significantly larger than at FC3. In addition, there was no significant time x electrode interaction ($F_{3.8, 34.6} = 1.24$, $p = .31$, $\eta^2_\rho = .12$).

10.5.1.3 – Motor Potential (MP)

The MP amplitude was taken at the peak of the MRCP, corresponding to the maximum negative peak immediately prior to movement onset. The mean *z*-score amplitude for the MP was -9.55 (± 7.91) in the early block of trials at week 5, compared to -5.73 (± 4.81) in the late block of trials at week 5. Despite the large difference in mean values, the repeated measures ANOVA revealed no significant main effect of time ($F_{1, 9} = 3.48$, $p = .10$, $\eta^2_\rho = .28$). There was however a significant main effect of electrode ($F_{3.5, 31.4} = 4.54$, $p = .007$, $\eta^2_\rho = .34$). The post-hoc analysis indicated that the MP amplitude at Cz was significantly larger than at sites FC3. In addition, there was no significant time x electrode interaction ($F_{3.1, 27.9} = .42$, $p = .75$, $\eta^2_\rho = .04$).

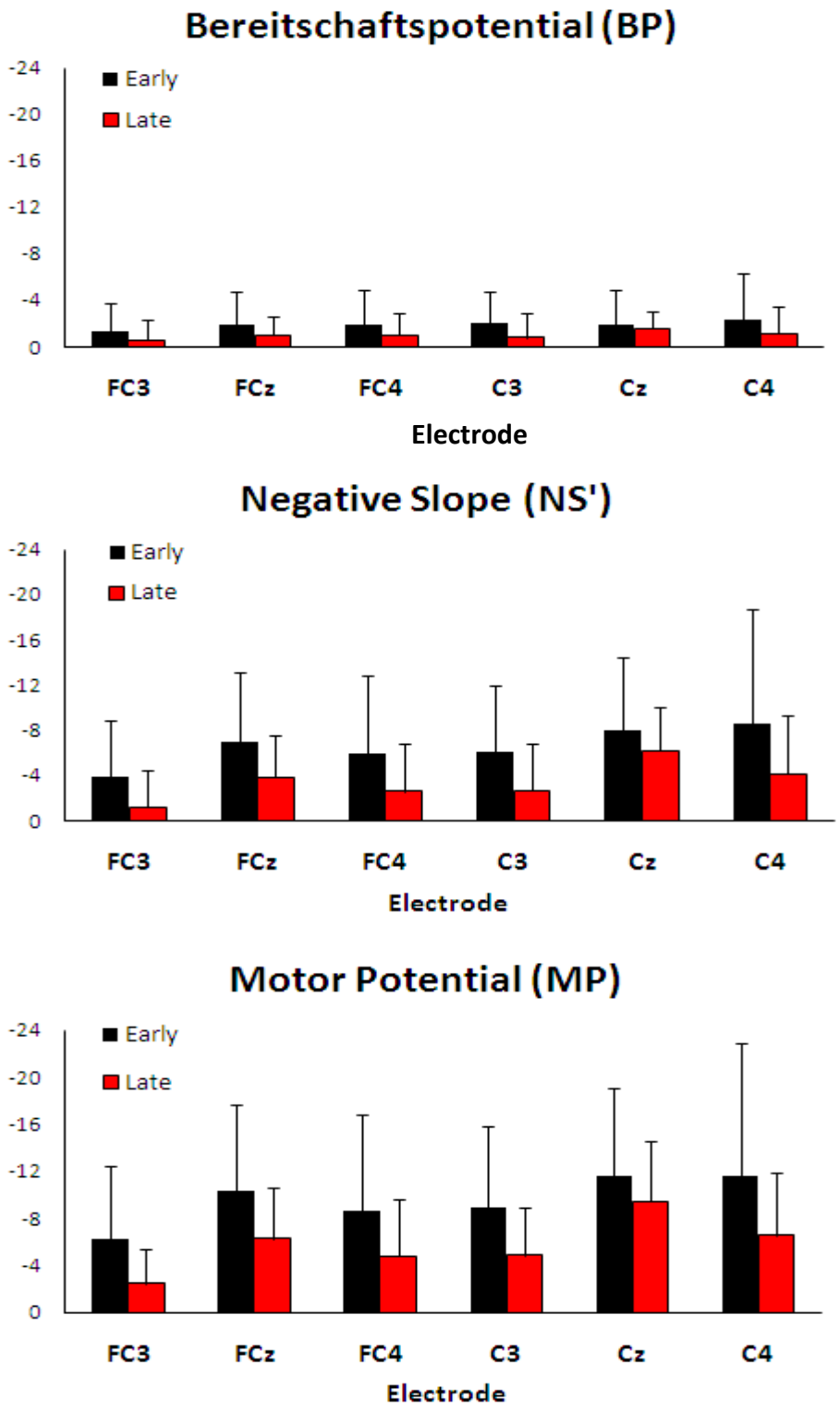

Figure 10.2: Mean amplitude values of the BP, NS', and MP components of the MRCP for early (black) and late (red) blocks of trials at week 5. Data was recorded from electrode sites FC3, FCz, FC4, Cz, C3, and C4, prior to performance of the G Major scale on the guitar.

10.5.2 – Week 10 data

MRCP waveforms were evident in all participants at all electrode sites in both the early and the late blocks of trials (see Figure 10.3). The amplitude of the BP component was of similar amplitude in both the early and the late blocks of trials. In approximately the final 700 ms, corresponding to the NS' component, the amplitude in the late block of trials was smaller than in the early block. Mean amplitude values for each component of the MRCP in early and late trials at week 10 can be seen in Figure 10.4.

10.5.2.1 – Bereitschaftspotential (BP)

The BP amplitude was taken as the mean amplitude in the time period -2000 to -500 ms. The mean *z*-score amplitude for the BP was -2.32 (± 1.96) in the early block of trials, compared to -2.12 (± 1.6) in the late block of trials. The repeated measures ANOVA revealed that there was no significant main effect of time ($F_{1, 9} = .15$, $p = .71$, $\eta^2_\rho = .02$), and no significant main effect of electrode ($F_{3.3, 29.9} = .47$, $p = .72$, $\eta^2_\rho = .05$). In addition, there was no significant time x electrode interaction ($F_{3.1, 28} = .58$, $p = .64$, $\eta^2_\rho = .06$).

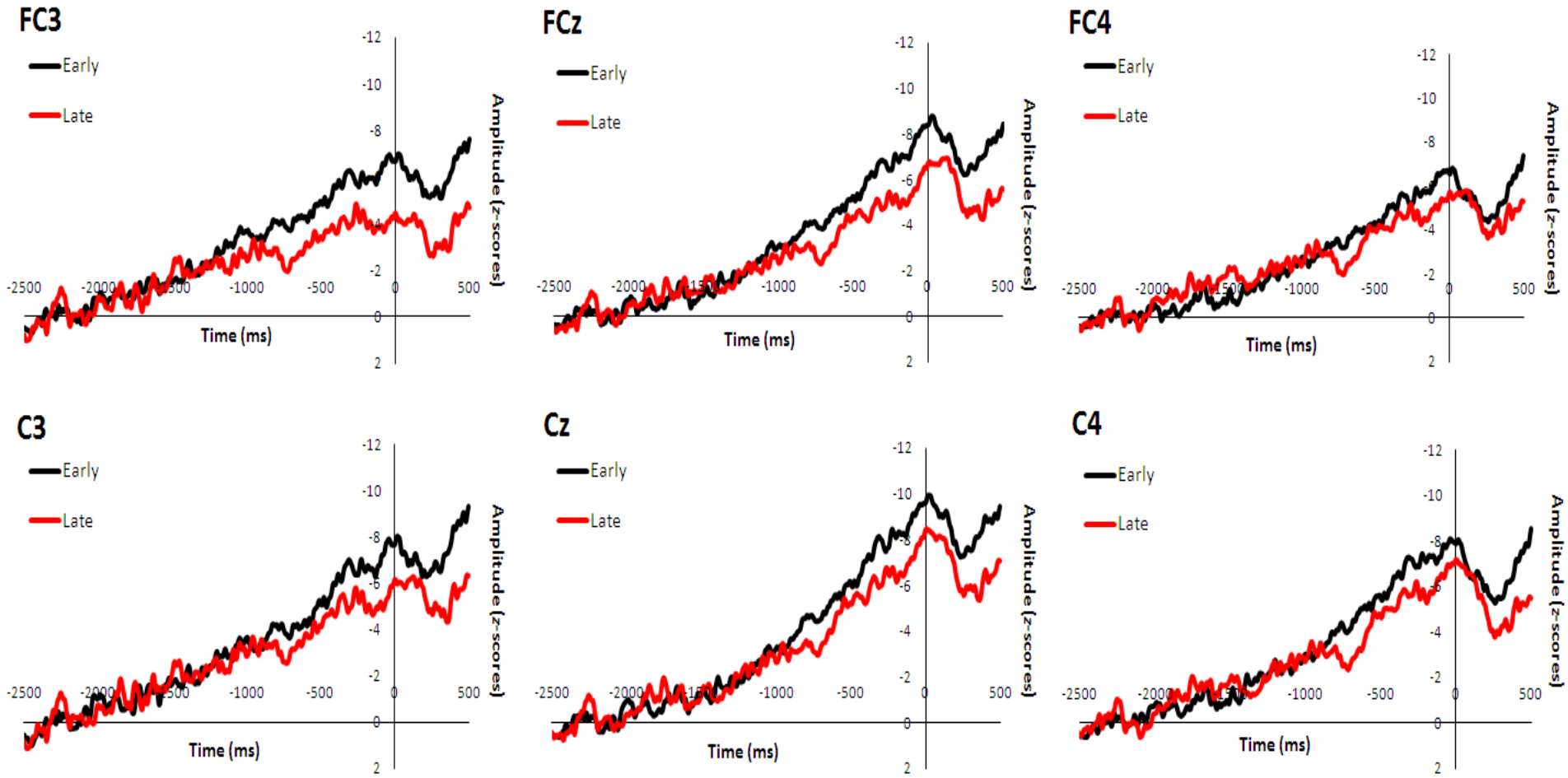

Figure 10.3: Movement-related cortical potential waveforms recorded at week 10 from the motor cortex of non-musicians in early (black) and late (red) blocks of trials prior to performance of the G Major scale on the guitar at a tempo of 100 beats per minute.

10.5.2.2 – Negative Slope (NS')

The amplitude of the NS' was taken as the mean amplitude between -500 ms to 0 ms. The mean *z*-score amplitude for the NS' at week 10 was -6.59 (± 3.88) in the early block of trials, compared to -5.15 (± 3.68) in the late block of trials. The repeated measures ANOVA revealed a significant main effect of time ($F_{1, 9} = 12.56$, $p = .006$, $\eta^2_\rho = .58$), with the NS' amplitude in the late block of trials being significantly smaller than in the early block. There was also a significant main effect of electrode ($F_{3.8, 32.3} = 2.92$, $p = .04$, $\eta^2_\rho = .25$). The post-hoc analysis indicated that the NS' amplitude at C4 was significantly larger than at FC3. In addition, there was no significant time x electrode interaction ($F_{2.6, 23.8} = .24$, $p = .84$, $\eta^2_\rho = .03$).

10.5.2.3 – Motor Potential (MP)

As with the week 5 data, the MP was taken at the peak of the MRCP, which corresponded to the maximum negative peak immediately prior to movement onset. The mean *z*-score amplitude for the MP at week 10 was -8.57 (± 4.34) in the early block of trials, compared to -7.21 (± 4.12) in the late block of trials. The repeated measures ANOVA revealed a significant main effect of time ($F_{1, 9} = 11.41$, $p = .008$, $\eta^2_\rho = .56$), with the MP amplitude in the late block of trials being smaller than in the early block. There was also a significant main effect of electrode ($F_{3.8, 34.2} = 4.46$, $p = .006$, $\eta^2_\rho = .33$). The post-hoc analysis indicated that the MP amplitude at Cz was significantly larger than at FC3. In addition, there was no significant time x electrode interaction ($F_{3, 27} = .28$, $p = .84$, $\eta^2_\rho = .03$).

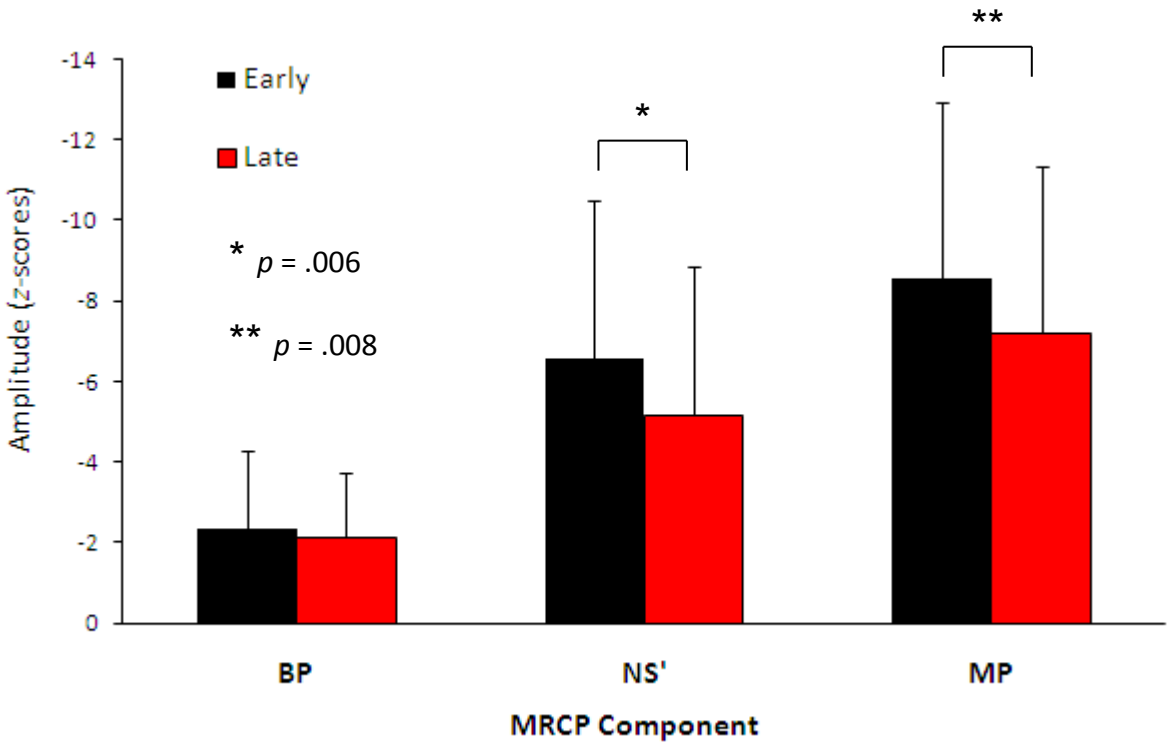

Figure 10.4: Mean amplitude values of the BP, NS', and MP components of the MRCP for early (black) and late (red) blocks of trials at week 10. Data was recorded from electrode sites FC3, FCz, FC4, Cz, C3, and C4, prior to performance of the G Major scale on the guitar. Significant effects are indicated by asterisks.

10.6 – Discussion

The purpose of this study was to examine within-session changes in the amplitude of the MRCP that were associated with practice of a guitar-playing task over a ten-week training period. Study 3 in this thesis showed that short-term practice of a scale-playing task on the guitar brought about an increase in the amplitude of the MRCP. This finding was in contrast to previous research that had studied short-term practice of simple motor actions and reported a decrease in MRCP amplitude following practice (e.g., Dirnberger et al., 2004; Lang et al., 1992). Two explanations for these contrasting findings were proposed in Study 3. The first explanation was that repetitive practice of a complex scale-playing task on the guitar may have led to participants becoming fatigued, resulting in MRCPs of larger amplitude in later trials at sites FC3, FCz and FC4. The second explanation was that early motor skill learning may be characterised by an increase in cortical activity as participants begin to learn the skill. As participants become more competent in the skill however, the cortical activity involved in planning to perform the skill may become reduced. It was not possible to establish which proposal was most accurate based on the data from Study 3. By replicating Study 3 with the week 5 and week 10 data from the extended training study, it was possible to provide a clearer picture.

The within-session changes in the week 5 and week 10 MRCP showed the opposite profile to the within-session changes reported in Study 3 (which were based on the week 1 data). The week 5 data showed differences in the mean amplitudes of the MRCP recorded from the early and the late blocks of trials. Specifically, the MRCP waveforms from the late block of trials were smaller than those from early block of trials (see Figure 10.1). Despite the large difference in the mean values, these differences were not statistically significant. Whilst several participants exhibited large decreases in MRCP

amplitude from early to late trials, a similar number of participants exhibited small increases in MRCP amplitude. This caused an overall decrease in the mean values, but due to the lack of consistency in these changes across participants, these differences were not significant for any component of the MRCP. The week 10 data showed the same profile as the week 5 data, with smaller amplitude waveforms in the late block of trials, compared to the early block (see Figure 10.3). The difference in the mean values was smaller at week 10 than at week 5, but as most participants showed this decrease in amplitude from early to late trials, this difference was significant for both the NS' and MP.

These results provide evidence against the suggestion that the increase in MRCP amplitude following short-term practice at week 1 (Study 3) were fatigue related. Fatigue has been consistently shown to increase the amplitude of the MRCP (e.g., Falvo et al., 2011; Freude & Ullsperger, 1987; Johnston et al., 2001; Schillings et al., 2006). In Study 3 it was proposed that the high level of co-ordination and concentration required to perform a novel and complex scale-playing task on the guitar may have induced fatigue in the participants, causing a larger amplitude NS' in the late block of trials, compared to the early block. If fatigue were the cause of this increase in amplitude then it is likely that the same effect would have been seen in the week 5 and week 10 data. This was not the case; therefore the fatigue explanation is not supported by the data presented here.

The data presented support the alternative proposal made in Study 3, that early skill learning is characterised by an increase in motor cortex activity as participants have difficulty attempting to learn the task. As participants became more competent and began to master the task, there was a decrease in motor cortex activity involved in planning that task. At week 1, the participants may have had difficulty performing the complex bi-manual skill of playing a musical scale on the guitar in time with the

metronome. This may have caused an increase in the amplitude of the MRCP as more cortical activity was required to plan performance of the task. By week 5 some participants probably began to find performing the scale less challenging and so may have been able to devote less cortical activity to planning performance of the scale. This could explain the trend for a decrease in amplitude within the practice session. By week 10, most participants had probably begun to master the scale-playing task and so less effort was devoted to planning performance of the task, resulting in a significant decrease in the amplitude of the MRCP across the practice session. Taylor's (1978) EEG study presented early evidence indicating that this phenomenon occurs in the motor skill learning process, and similar findings have since been reported using both fMRI (e.g., Toni et al., 1998) and TMS (e.g., Pascual-Leone et al., 1994). This study is the first to demonstrate this phenomenon associated with practice of a real-world motor task, as opposed to practice of more simple motor actions. The more complex nature of the motor task used in this study may explain why this process took longer to occur compared to the other studies.

The following chapter will summarise the five experiments reported in this thesis before discussing possible applications and implications of the research and suggesting ideas for future research.

Chapter 11

General Discussion

The purpose of this section of the thesis is to bring together and explore the findings of this series of five studies as a whole. The key findings from the research programme are summarised and reviewed. Possible applications and implications of the research are then discussed, before recommendations for future research are made.

11.1 – Summary of the research programme

The aim of this research programme was to provide a more detailed understanding of the cortical processes involved in motor skill learning by addressing limitations of and omissions in the currently published literature. Specifically, the literature review (Chapter 3) highlighted a lack of ecological validity and a lack of longitudinal research as key concerns. Consequently, a series of five experiments was carried out to address these limitations. The data from Study 1 allowed the successful identification of an ecologically valid scale-playing motor task on the guitar, from which it was possible to record the MRCP accurately prior to performance of the task. This motor task was then used in all subsequent experiments in this thesis. In Study 2, differences in the MRCP recorded prior to performance of the scale-playing task between a group of experienced guitarists and a group of non-musicians were compared. The results indicated that the experienced guitarists allocated less cortical activity to planning performance of the motor task than the non-musicians. These results represent a successful replication of previous cross-sectional studies that have recorded the MRCP during the performance of simple motor actions and extrapolated the results to more complex motor skills (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et

al., 2009; Kita et al., 2001). The findings signified an advance on previous literature, in that this study was the first to present cross-sectional MRCP recordings obtained during performance of an ecologically valid motor task.

The purpose of the subsequent studies reported in this thesis were to address the lack of longitudinal research in the area and to verify claims made in cross-sectional studies that the differences in cortical activity between the expert and novice performers were the result of the long-term training undertaken by the experts. Study 3 investigated whether short-term practice of the scale-playing task on the guitar would modulate the participants' cortical activity. In contrast to previous research by both Dirnberger et al. (2004) and Lang et al. (1992), short-term practice of the scale-playing task resulted in an increased amount of cortical activity involved in motor preparation. It was unclear from the results of this study however if this increased activity was part of the learning process or the result of participants becoming fatigued towards the end of the practice session, after performing multiple repetitions of the scale-playing task.

Study 4 was a three-part experiment that investigated the effects of extended motor task training and de-training on the cortical activity involved in motor planning. This study was the first of its kind within the cognitive and behavioural neuroscience and motor skill learning literature. When considering the data from the five participants who took part in the full training and de-training programme (Study 4c), the results indicated that longitudinal motor skill training caused a reduction in the amplitude of the MRCP. The reduced amplitude, which Lang et al. (1992) suggested may indicate a reduced effort during motor preparation, was still present at de-training. This indicates that training may cause a relatively permanent change in participants' cortical activity related to motor preparation for the learned task, and so the results could indicate that learning had

occurred. This linear reduction in cortical activity as a result of motor skill learning was accompanied by an improvement in performance and is therefore consistent with the concept of neural efficiency following motor skill learning (Babiloni et al., 2010; Del Percio et al., 2008).

When examining the data from the ten participants who completed the ten-week training part of the experiment (Studies 4a and 4b) the results did fit with this concept. Specifically, there was a decrease in the amplitude of the MRCP at certain sites involved in motor execution between weeks 1 and 5 of the training programme, followed by an increase in the amplitude of the MRCP at the anterior sites involved in motor planning from weeks 5 to 10. The unexpected profile of the week 10 MRCP made it difficult to draw firm conclusions from the data. This difficulty may be explained however by drawing upon recent work from outside of psychophysiology, such as the Five-A model of technical change proposed by Carson and Collins (2011). This model outlines five stages that elite performers pass through when attempting to modify their technique. The model proposes that after analysing and identifying a problem with their technique, the performer goes through an adjustment process, practising the skill with the aim of achieving a new movement pattern. This new movement pattern/technique eventually becomes automated before the performer reaches the assurance stage, where no further technical modifications are required. Using this model as a guide, the results of Study 4b may reflect the cortical processes that occur as a performer modifies or adjusts aspects of their technique. Specifically, the increased amplitude of the MRCP reported in Study 4b may represent the cortical changes that occur in the *adjustment* phase of the model, as participants attempted to refine or modify aspects of their technique to play in time better with the metronome. Based on this model, it is likely that throughout the learning

process there may be fluctuations in the amount of cortical activity involved in the planning phases of a skill as a performer adjusts aspects of their performance, attempts to alter their playing style, or focuses on different aspects of their performance. For example, when beginning to learn to play the guitar, a guitarist may focus solely on learning to perform the required movements involved in a specific task, and this may lead to a reduced level of cortical activity during motor preparation (as shown in Study 4a). As the guitarist begins to master the physical movements required to perform the skill, their focus may change to other aspects of their performance, such as learning how to play in time with a metronome or in time with other instruments, taking direction from a conductor, or playing and singing concurrently. Focusing on these additional aspects of performance may increase the level of difficulty, leading to an increase in cortical activity whilst the guitarist attempts to master these additional task requirements (as speculated in Study 4b). Once these additional requirements are mastered, a further decrease in cortical activity related to the planning of that motor skill may occur. These fluctuations in cortical activity may occur throughout the learning process and eventually may lead to a reduced level of cortical activity compared to when that performer was a novice. This may however take many years to occur. The results of the training study therefore indicate two possible cortical mechanisms involved in the motor skill learning process: (i) a linear decrease in cortical activity occurring alongside training that is in line with the concept of neural efficiency, and (ii) a more recursive and fluctuating change in cortical activity, in line with the Five-A model, that may eventually lead to a decrease in cortical activity. Future research should explore these possibilities further.

Finally, Study 5 examined within-session changes in cortical activity that were associated with long-term motor skill learning. The results did not support the argument

that the increases in cortical activity reported in Study 3 were fatigue related. Instead, Studies 3 and 5 indicate that the process of motor skill learning may be characterised by an initial increase in the amount of cortical activity devoted to motor planning in early learning, when performers are having difficulty learning and performing the task. This may then be followed by a decreased level of cortical activity required for movement preparation when participants become competent in the task. This explanation is consistent with research using a variety of neuroscientific techniques that have indicated that a similar process may occur during short-term learning of simple motor tasks (e.g., Pascual-Leone et al., 1994; Taylor, 1978; Toni et al., 1998).

11.2 – Applications and implications of the research programme

In recent years, there has been an increased demand for evidence-based practice in applied sport and performance psychology (e.g., Williams & Hodges, 2005). With that in mind, it is important to discuss some of the practical applications of this programme of research that could help inform motor skill learning, teaching, and coaching practices, as well as informing the work of applied sport and performance psychologists. The results of this research programme have potential implications for the learning and teaching of motor skills, the assessment of motor skill learning, and the identification and development of talented musicians and athletes.

11.2.1 – Learning and teaching motor skills

The training study in this thesis showed that it is possible to study changes in the MRCP that occur as a result of motor skill learning. Future research should expand on this finding by investigating changes in the MRCP associated with different learning and teaching techniques. For example, researchers could compare observational learning

techniques, where participants learn a skill by observing and repeating the actions of an instructor, to discovery learning techniques, where participants learn by themselves, through a process of trial and error. Alternatively, researchers could compare learning skills through 'whole practice' techniques, where participants learn and practice a complex skill as a whole, with 'part practice' techniques, where different aspects of the skill are first learnt and practiced in isolation, before being performed as a whole. If such research were to find that one technique produced a greater reduction in the amplitude of the MRCP, or brought about changes in the MRCP more quickly than the other technique, this could potentially indicate the most beneficial teaching practices for bringing about changes at a cortical level. If the same technique were also found to bring about greater performance improvements, such results could inform motor skill learning and teaching techniques.

11.2.2 – Assessment of motor skill learning

Historically, there has been an over-reliance on the use of performance measures when assessing motor learning (Davids, Button, & Bennett, 2008). In terms of musical assessment, performance is often measured subjectively by just one individual, who attempts to balance and synthesize multiple aspects of the performance, before providing a judgment or ranking as to the quality of the performance (McPherson & Thompson, 1998). McPherson and Thompson (1998) explain that this method of assessment is flawed as assessor biases often influence the results, and reliability between assessors (when more than one is used) is sometimes low. More objective markers of changes in skill that focus on changes in cortical activity are therefore warranted. Based on the findings presented here, it may be possible to use the MRCP to provide an objective marker of musical skill learning that could be used in addition to

subjective performance assessments in order to provide a more valid overall assessment. Although the musical task used in these experiments was extremely simple compared to high level musical performance, if similar changes in the MRCP could be demonstrated using more complex musical skills, musical assessors could collaborate with researchers in psychophysiology and study changes in the MRCP amplitude and onset times over a longitudinal learning period. A reduced amplitude or later onset of the MRCP at the end of the learning period compared to the start could provide a marker or indication that some instrument-specific learning had occurred, resulting in reduced cortical activity when preparing for the physical and psychological elements of the musical performance. It would not be possible to infer exclusively from a reduction in MRCP amplitude that the standard of performance was higher. Changes in performance would need to be measured alongside any changes in the EEG signal, but a combination of the two measures may provide a more complete picture of the learning process.

11.2.3 – Talent identification and development

As the MRCP has been shown to change throughout the motor skill learning process, it is possible that this change could inform the talent identification and development process in musical or sporting skills. Traditionally, talent identification procedures in sport have used one-off performance assessments to identify talented performers (Button, 2011). In recent years this one-off assessment approach to talent identification has received much criticism (e.g., Abbott, Button, Pepping, & Collins, 2005; Abbott & Collins, 2002, 2004; Button, 2011). MacNamara and Collins (2009) suggested that, in addition to performance scores or physiological measurements, an array of psychological, social, and environmental factors contribute to the development of excellence. As such, combined talent identification and development programmes that

continually monitor multiple markers and measures of talent are now generally favoured over the one-off performance assessment approach to talent identification (Abbott et al., 2005; Abbott & Collins, 2002, 2004; Button, 2011; MacNamara, Button, & Collins, 2010). Monitoring changes in the MRCP as individuals learn different motor skills could provide an additional marker that could be used in conjunction with other psychological and performance markers of talent development. For example, if a certain individual showed a large reduction in the amplitude of the MRCP following a period of training, which was accompanied by improvements in performance and high levels of commitment, motivation, and an ability to cope under pressure, it might be possible to identify that individual as having the potential for success at an elite level. It should be noted that a change in the MRCP should probably not be one of the crucial factors for selecting or de-selecting individuals for talent development programmes. It could however form a small part of a talent development package, and may be useful in monitoring the development of talented musicians or athletes.

11.3 – Directions for future research

Research into the cortical processes involved in motor skill learning is still at an early stage. These studies represent the first attempts to study the motor skill learning process using ecologically valid motor tasks and over an extended learning period. As such, the results of this thesis cannot provide a definitive answer as to the complex processes occurring within the brain as an individual learns to perform a motor task. Further research is required to verify any claims made here and to provide a more comprehensive explanation of the learning process. This could be best achieved by combining a number of psychophysiological techniques, such as EEG, TMS, and fMRI, together with EMG, movement kinematics, and performance data.

Future research should first attempt to replicate the longitudinal training and de-training study. Ideally, such a replication study would recruit a larger sample than was used in Study 4 (n = 10), would be conducted over a longer learning period, would involve more frequent training sessions, and would record the EEG at more frequent intervals. This would determine whether the unexpected larger amplitude and the uncharacteristic profile of the week 10 MRCP in Study 4b is a consistent finding. By recording the EEG more frequently throughout the study, it would be possible to better establish whether the reduction in MRCP amplitude that occurs with training is a linear reduction (as indicated by the data from Study 4c), or whether the learning process is characterised by many fluctuations in MRCP amplitude, that may eventually lead to a reduced amplitude, compared to the beginning (as speculated in the discussion for Study 4b). It would also be worthwhile to use a larger electrode montage, with a more dense array of electrodes over the motor areas, and with electrodes placed over non-motor areas. This would allow researchers to localise any changes in the MRCP that occurred throughout the training programme to specific cortical areas, and would in turn allow researchers to make stronger claims as to the cortical areas involved in the motor skill learning process.

It would be valuable for researchers to conduct similar longitudinal training studies to those reported in this thesis using different neuroscientific techniques, or preferably a combination of multiple techniques. It would be particularly interesting to investigate possible changes in the brain resulting from motor skill learning with fMRI, as this technique can provide data from other movement-related brain areas such as the cerebellum and basal ganglia, which are not possible to study using EEG (Hatfield et al., 2006). With recent advances in neuroscientific techniques it is now possible to record EEG and fMRI concurrently, providing the opportunity to gain a more comprehensive insight

into neural basis of behaviour and brain function (Menon & Crottaz-Herbette, 2005). Research combining these two techniques could better test the idea of neural efficiency following motor skill learning. For example, it would be possible to determine if motor skill learning brought about a reduction in activity in all movement-related brain areas, supporting the concept of neural efficiency. Alternatively, in contrast to the concept of neural efficiency, the results could indicate that a reduction in motor cortex activity is accompanied by an increase in activity in, for example, the cerebellum or basal ganglia.

Future research could also test the suggestion proposed in section 5.6, that the reduced cortical activity shown by the experienced guitarists during movement preparation may 'free up' neurons, allowing the guitarists to devote more cortical activity to other aspects of performance that could be described as more advanced, relating to creativity, artistic expressivity, or improvisation (Gruber et al., 2010). Researchers could explore this further by studying changes in the motor regions of the brain, as well as from areas of the brain that have been associated with creativity, such as the prefrontal cortex (Dietrich & Kanso, 2010). As mentioned above, this could be best done by combining multiple techniques such as EEG and fMRI. If such a study were to find a decrease in activity in the motor areas over the course of a learning period, which was accompanied by an increase in activity in certain areas of the prefrontal cortex, the results could provide support for suggestion made by Gruber et al. (2010).

Additionally, rather than focusing only on the cortical processes involved in motor skill learning, another avenue of investigation would be to explore changes in cortical activity, movement kinematics, and performance concurrently. It would be possible for researchers to record both EEG and movement kinematic data, using a Vicon motion capture system, over a learning period. In his 'degrees of freedom problem', Bernstein

(1967) suggested that the process of motor skill acquisition is characterised by (i) freezing the degrees of freedom; (ii) releasing and re-organising the degrees of freedom; and (iii) exploiting the degrees of freedom. This theory has been supported by Anderson and Sidaway (1994) and Vereijken, van Emmerik, Whiting, and Newell (1992). It would be worth investigating, for example, whether changes in the MRCP occur concurrently with the process of freeing and exploiting the degrees of freedom, or whether a change at a cortical level is first required before a change in movement kinematics can occur.

In a more practical sense, as mentioned in section 11.2.1, another possibility for future research is to study changes in the MRCP associated with learning motor tasks by different learning and teaching techniques. For example, researchers could compare changes in the MRCP resulting from observational learning of a motor task to changes resulting from discovery learning, or they could compare changes in the MRCP resulting from 'whole practice' of a motor task to changes resulting from 'part practice'. If one technique were found to produce changes in the MRCP more quickly or to a greater extent, the results could indicate the most beneficial teaching techniques for learning a particular motor skill.

Future research could also investigate the effect of imagery or observation training on the MRCP. Both imagery and observation of motor tasks are commonly used as intervention techniques to regain motor function following stroke (e.g., Ertelt et al., 2007; Holmes & Ewan, 2007; Sharma, Pomeroy, & Baron, 2006) and to improve sports performance (e.g., Holmes & Collins, 2001; Smith et al., 2007; Smith et al., 2008). The premise behind using these techniques for regaining motor function or improving sports performance is that the cortical activity involved in imagery, observation, and execution of a movement share similar neural networks (e.g., Clark, Tremblay, & Ste-Marie, 2004;

Decety & Grezes, 1999; Jeannerod, 2001). Performing imagery or observation of a motor skill can therefore induce activity in the cortical areas involved in physical performance of that skill, and so may help aid recovery of motor function following stroke or improve sports performance. Although both techniques may be useful, Holmes and Calmels (2008) proposed that observation might be the more effective technique as the process can be controlled more easily and provide a more effective access to the cortical areas involved in motor execution. To date no research has tested this prediction. Future research could therefore compare the effect of motor imagery and observation training over a longitudinal period, to determine whether one technique was more effective in bringing about a change in cortical activity when physically performing the observed/imaged motor skill. If, for example, observation were found to reduce the amplitude of the MRCP to a greater extent than imagery, the results could indicate that observation is a more beneficial technique to use in stroke rehabilitation or sport psychology interventions. The technology is now available to investigate all the proposals outline in this section, but the ideas remain to be tested.

11.4 – Conclusions

This thesis explored the cortical processes involved in motor skill learning. EEG was used to record the MRCP from areas of the pre-motor and primary motor cortex whilst participants performed a scale-playing task on the guitar in different contexts. Differences in the MRCP were compared between experienced guitarists and non-musicians in Study 2. Changes in the MRCP associated with short-term practice and extended learning of the scale-playing task by non-musicians were investigated in Studies 3, 4, and 5. This work was novel, in that it represents the first time that the cortical processes involved in motor skill learning have been studied in an ecologically valid way,

and over an extended learning period. The results indicated that the cortical processes involved in motor skill learning are probably more complex than the simplistic explanation proposed in cross-sectional (e.g., Di Russo, Pitzalis, et al., 2005; Fattapposta et al., 1996; Hatta et al., 2009; Kita et al., 2001) and short-term within-participant (e.g., Dirnberger et al., 2004; Lang et al., 1992) MRCP studies, where the researchers have suggested that training in a task produces a linear reduction in cortical activity. Overall, there may be a reduction in motor cortex activity as a performer learns and becomes more competent in a motor task. Rather than a linear reduction however, the results presented in this thesis indicate that the process may be more recursive, with fluctuations in the amount of cortical activity devoted to motor planning occurring at different stages of the learning process. The results of these experiments were explained in relation to: (i) the concept of neural efficiency (Babiloni et al., 2010; Del Percio et al., 2008) and, (ii) the Five-A model of technical change (Carson & Collins, 2011). Rather than occurring solely as outlined by the concept of neural efficiency, it is likely that learning process can be better explained by a combination of both these models. The results of Study 4c indicate that as performance in a task improves, reduced cortical activity is allocated to the planning of that performance. This finding is in line with the concept of neural efficiency. The results of Study 3 however indicate that early learning may be characterised by increased motor cortex activity as the participant has difficulty learning the required movements to perform a motor skill. Similarly, in line with the Five-A model (Carson & Collins, 2011), the results of Study 4b indicate that further increases in motor cortex activity may occur as a participant adjusts or alters aspects of their performance or their technique. Neural efficiency of the motor cortex may therefore occur as a result of long-term training in a motor task; however this process is unlikely to be a linear reduction in motor cortex activity. Instead a series of fluctuations throughout the learning process may eventually

lead to a reduced level of cortical activity being required to plan performance of the learnt motor task. Further research is required into the cortical processes involved in motor skill learning to verify or refute the claims made here.

References

Abbott, A., Button, C., Pepping, G. J., & Collins, D. (2005). Unnatural selection: Talent identification and development in sport. *Nonlinear Dynamics, Psychology, and Life Sciences, 9*(1), 61-88.

Abbott, A., & Collins, D. (2002). A theoretical and empirical analysis of a 'state of the art' talent identification model. *High Ability Studies, 13*, 157-178. doi:10.1080/1359813022000048798

Abbott, A., & Collins, D. (2004). Eliminating the dichotomy between theory and practice in talent identification and development: Considering the role of psychology. *Journal of Sports Sciences, 22*, 395-408. doi:10.1080/02640410410001675324

Abernethy, B., & Neal, R. J. (1999). Visual characteristics of clay target shooters. *Journal of Science and Medicine in Sport, 2*, 1-19. doi:10.1016/S1440-2440(99)80180-7

Amaro, J. E., & Barker, G. J. (2006). Study design in fMRI: Basic principles. *Brain and Cognition, 60*, 220-232. doi:10.1016/j.bandc.2005.11.009

Anderson, D. I., & Sidaway, B. (1994). Coordination changes associated with practice of a soccer kick. *Research quarterly for exercise and sport 65*(2), 93-99.

Andreassi, J. L. (2007). *Psychophysiology: Human behavior & physiological response* (5th ed.). Mahwah, New Jersey: Lawrence Erlbaum Associates.

Ansari, T. L., & Derakshan, N. (2011). The neural correlates of cognitive effort in anxiety: Effects on processing efficiency. *Biological Psychology, 86*, 337-348. doi: 10.1016/j.biopsycho.2010.12.013

Arthurs, O. J., & Boniface, S. (2002). How well do we understand the neural origins of the fMRI BOLD signal? *Trends in Neurosciences, 25*, 27-31. doi:10.1016/S0166-2236(00)01995-0

Babiloni, C., Carducci, F., Cincotti, F., Rossini, P. M., Neuper, C., Pfurtscheller, G., & Babiloni, F. (1999). Human movement-related potentials vs desynchronization of EEG alpha rhythm: a high-resolution EEG study. *Neuroimage, 10*, 658-665. doi:10.1006/nimg.1999.0504

Babiloni, C., Marzano, N., Infarinato, F., Iacoboni, M., Rizza, G., Aschieri, P., . . . Del Percio, C. (2010). "Neural efficiency" of experts' brain during judgement of actions: A high-resolution EEG study in elite and amateur karate athletes. *Behavioural Brain Research, 207*, 466-475. doi:10.1016/j.bbr.2009.10.034

Bauer, H. (1993). DC Recording Methods. In W. C. McCallum & S. H. Curry (Eds.), *Slow Potential Changes in the Human Brain* (pp. 55-62). New York: Plenum Press.

Bauer, H., Korunka, C., & Leodolter, M. (1989). Technical requirements for high-quality scalp DC recordings. *Electroencephalography and clinical Neurophysiology, 72*, 545-547. doi:10.1016/0013-4694(89)90232-0

Bear, M. F., Connors, B. W., & Paradiso, M. A. (2007). *Neuroscience: Exploring the Brain* (3rd ed.). Baltimore, MD: Lippincott Williams & Wilkins.

Becker, W., Iwase, K., Jurgens, R., & Kornhuber, H. H. (1976). Bereitschaftspotential preceding voluntary slow and rapid hand movements. In W. C. McCallum & R. J. Knott (Eds.), *The Responsive Brain: The Proceecings of the Third International Congress on Event-related Slow Potentials of the Brain* (pp. 99-102). Bristol: John Wright & Sons Ltd.

Becker, W., & Kristeva, R. (1980). Cerebral potentials prior to various force deployments. *Progress in Brain Research, 54*, 189-194. doi:10.1016/S0079-6123(08)61624-6

Berger, H. (1929). Über das Elektrenkephalogramm des Menschen [About the electroencephalogram of humans]. *European Archives of Psychiatry and Clinical Neuroscience, 87*, 527-570. doi:10.1007/BF01797193

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Oxford, UK: Pergamon Press.

Birbaumer, N., Elbert, T., Canavan, A. G., & Rockstroh, B. (1990). Slow potentials of the cerebral cortex and behavior. *Physiological Reviews, 70*(1), 1-41.

Brewer, M. B. (2000). Research design and issues of validity. In H. T. Reis & C. M. Judd (Eds.), *Handbook of Research Methods in Social and Personality Psychology*. Cambridge, UK: Cambridge University Press.

Butler, S. (1993). Methodological Issues in the Measurement of DC Biopotentials. In W. C. McCallum & S. H. Curry (Eds.), *Slow Potential Changes in the Human Brain* (pp. 63-76). New York: Plenum Press.

Button, A. (2011). Aims, principles and methodologies in talent identification and development. In D. Collins, A. Button & H. Richards (Eds.), *Performance Psychology: A Practitioner's Guide* (pp. 9-30). Edinburgh: Churchill Livingstone.

Carson, H. J., & Collins, D. J. (2011). Refining and regaining skills in fixation/diversification stage performers: The Five-A Model. *International Review of Sport and Exercise Psychology, 4*, 146-167. doi: 10.1080/1750984X.2011.613682

Casey, B. J., Davidson, M., & Rosen, B. (2002). Functional magnetic resonance imaging: basic principles of and application to developmental science. *Developmental Science, 5*, 301-309. doi:10.1111/1467-7687.00370

Caton, R. (1875). The electric currents of the brain. *The British Medical Journal, 2*, 278.

Chatrian, G. E., Lettich, E., & Nelson, P. L. (1985). Ten percent electrode system for topographic studies of spontaneous and evoked EEG activities. *American Journal of EEG Technology, 25*, 83-92.

Chatrian, G. E., Lettich, E., & Nelson, P. L. (1988). Modified nomenclature for the "10%" electrode system. *Journal of Clinical Neurophysiology, 5*, 183-186. doi:10.1097/00004691-198804000-00005

Clark, S., Tremblay, F., & Ste-Marie, D. (2004). Differential modulation of corticospinal excitability during observation, mental imagery and imitation of hand actions. *Neuropsychologia, 42*, 105-112. doi:10.1016/S0028-3932(03)00144-1

Coolican, H. (2009). *Research Methods and Statistics in Psychology* (5th ed.). London, UK: Hodder Education.

Crews, D. J., & Landers, D. M. (1993). Electroencephalographic measures of attentional patterns prior to the golf putt. *Medicine & Science in Sports & Exercise, 25*, 116-126. doi:10.1249/00005768-199301000-00016

Croft, R. J., & Barry, R. J. (2000). Removal of ocular artifact from the EEG: a review. *Clinical Neurophysiology, 30*, 5-19. doi:10.1016/S0987-7053(00)00055-1

Cui, R. Q., & Deecke, L. (1999). High resolution DC-EEG analysis of the Bereitschaftspotential and post movement onset potentials accompanying uni- or bilateral voluntary finger movements. *Brain Topography, 11*, 233-249. doi:10.1023/A:1022237929908

Cunnington, R., Bradshaw, J. L., & Iansek, R. (1996). The role of the supplementary motor area in the control of voluntary movement. *Human Movement Science, 15*, 627-647. doi:10.1016/0167-9457(96)00018-8

Davids, K., Button, C., & Bennett, S. (2008). *Dynamics of Skill Acquisition: A Constraints-Led Approach*. Champaign, IL: Human Kinetics.

Decety, J., & Grezes, J. (1999). Neural mechanisms subserving the perception of human actions. *Trends in Cognitive Sciences, 3*, 172-178. doi:10.1016/S1364-6613(99)01312-1

Deecke, L. (1990). Electrophysiological correlates of movement initiation. *Revue Neurologique, 146*(10), 612-619.

Deecke, L. (1996). Planning, preparation, execution, and imagery of volitional action. *Cognitive Brain Research, 3*, 59-64. doi:10.1016/0926-6410(95)00046-1

Deecke, L., Englitz, H. G., & Schmitt, G. (1978). Age-dependence of the bereitschaftspotential. In D. A. Otto (Ed.), *Multidisciplinary Perspectives in Event-Related Brain Potential Research* (pp. 330-332). Washington: U.S. Environmental Protection Agency.

Deecke, L., Scheid, P., & Kornhuber, H. H. (1969). Distribution of readiness potential, pre-motion positivity, and motor potential of the human cerebral cortex preceding voluntary finger movements. *Experimental Brain Research, 7*, 158-168. doi:10.1007/BF00235441

Deeny, S. P., Hillman, C. H., Janelle, C. M., & Hatfield, B. D. (2003). Cortico-cortical communication and superior performance in skilled marksmen: An EEG coherence analysis. *Journal of Sport & Exercise Psychology, 25*(2), 188-204.

Degabriele, R., & Lagopoulos, J. (2008). Techniques for effective EEG subject preparation. *Acta Neuropsychiatrica, 20*, 218-219. doi:10.1111/j.1601-5215.2008.00318.x

Dietrich, A., & Kanso, R. (2010). A review of EEG, ERP, and neuroimaging studies of creativity and insight. *Psychological Bulletin, 136*, 822-848. doi:10.1037/a0019749

Del Percio, C., Rossini, P. M., Marzano, N., Iacoboni, M., Infarinato, F., Aschieri, P., . . . Eusebi, F. (2008). Is there a "neural efficiency" in athletes? A high-resolution EEG study. *Neuroimage, 42*, 1544-1553. doi:10.1016/j.brainresbull.2009.02.001

Di Russo, F., Incoccia, C., Formisano, R., Sabatini, U., & Zoccolotti, P. (2005). Abnormal motor preparation in severe traumatic brain injury with good recovery. *Journal of Neurotrauma, 22*, 297-312. doi:10.1089/neu.2005.22.297

Di Russo, F., Pitzalis, S., Aprile, T., & Spinelli, D. (2005). Effect of practice on brain activity: An investigation in top-level rifle shooters. *Medicine & Science in Sports & Exercise, 37*, 1586-1593. doi:10.1249/01.mss.0000177458.71676.0d

Dirnberger, G., Duregger, C., Lindinger, G., & Lang, W. (2004). Habituation in a simple repetitive motor task: A study with movement-related cortical potentials. *Clinical Neurophysiology, 115*, 378-384. doi:10.1016/S1388-2457(03)00328-6

Domingues, C. A., Machado, S., Cavaleiro, E. G., Furtado, V., Cagy, M., Ribeiro, P., & Piedade, R. (2008). Alpha absolute power: Motor learning of practical pistol shooting. *Arquivos de Neuro-Psiquiatria, 66*, 336-340. doi:10.1590/S0004-282X2008000300010

Eccles, J. C. (1977). *The Understanding of the Brain*. New York: McGraw Hill.

Elbert, T. (1993). Slow cortical potentials reflect the regulation of cortical excitability. In W. C. McCallum & S. H. Curry (Eds.), *Slow Potential Changes in the Human Brain* (pp. 235-251). New York: Plenum Press.

Ertelt, D., Small, S., Solodkin, A., Dettmers, C., McNamara, A., Binkofski, F., & Buccino, G. (2007). Action observation has a positive impact on rehabilitation of motor deficits after stroke. *NeuroImage, 36*, T164-T173. doi:10.1016/j.neuroimage.2007.03.043

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion, 7*, 336-353. doi: 10.1037/1528-3542.7.2.336

Falvo, M. J., Sirevaag, E. J., Rohrbaugh, J. W., & Earhart, G. M. (2011). Central adaptations to repetitive grasping in healthy aging. *Brain Topography*. doi:10.1007/s10548-011-0183-0

Fattapposta, F., Amabile, G., Cordischi, M. V., Di Venanzio, D., Foti, A., Pierelli, F., . . . Morrocutti, C. (1996). Long-term practice effects on a new skilled motor learning:

an electrophysiological study. *Electroencephalography and clinical Neurophysiology, 99*, 495-507. doi:10.1016/S0921-884X(96)96560-1

Ferree, T. C., Luu, P., Russell, G. S., & Tucker, D. M. (2001). Scalp electrode impedance, infection risk, and EEG data quality. *Clinical Neurophysiology, 112*, 536-544. doi:10.1016/S1388-2457(00)00533-2

Fitts, P. M., & Posner, M. I. (1967). *Human Performance*. Belmont, CA: Brooks/Cole.

Freude, G., & Ullsperger, P. (1987). Changes in Bereitschaftspotential during fatiguing and non-fatiguing hand movements. *European Journal of Applied Physiology and Occupational Physiology, 56*, 105-108. doi:10.1007/BF00696384

Gerbrandt, L. (1978). Methodological criteria for the validation of movement-related potentials. In D. A. Otto (Ed.), *Multidisciplinary Perspectives in Event-Related Brain Potential Research* (pp. 97-104). Washington: U.S. Environmental Protection Agency.

Gratton, G. (1998). Dealing with artifacts: The EOG contamination of the event-related brain potential. *Behavior Research Methods, Instruments, & Computers, 30*, 44-53. doi:10.3758/BF03209415

Gruber, H., Jansen, P., Marienhagen, J., & Altenmuller, E. (2010). Adaptations during the acquisition of expertise. *Talent Development & Excellence, 2*(1), 3-15.

Hallett, M. (1994). Movement-related cortical potentials. *Electromyography and clinical Neurophysiology, 34*(1), 5-13.

Haslinger, B., Erhard, P., Altenmuller, E., Hennenlotter, A., Schwaiger, M., Grafin von Einsiedel, H., . . . Ceballos-Baumann, A. O. (2004). Reduced recruitment of motor association areas during bimanual coordination in concert pianists. *Human Brain Mapping, 22*, 206-215. doi:10.1002/hbm.20028

Hatfield, B. D., Haufler, A. J., & Spalding, T. W. (2006). A cognitive neuroscience perspective on sport performance. In E. O. Acevedo & P. Ekkekakis (Eds.), *Psychobiology of Physical Activity*. Champaign, Il: Human Kinetics.

Hatta, A., Nishihira, Y., Higashiura, T., Kim, S. R., & Kaneda, T. (2009). Long-term motor practice induces practice-dependent modulation of movement-related cortical potentials (MRCP) preceding a self-paced non-dominant handgrip movement in kendo players. *Neuroscience Letters, 459*, 105-108. doi:10.1016/j.neulet.2009.05.005

Haufler, A. J., Spalding, T. W., Santa Maria, D. L., & Hatfield, B. D. (2000). Neuro-cognitive activity during a self-paced visuospatial task: comparative EEG profiles in marksmen and novice shooters. *Biological Psychology, 53*, 131-160. doi:10.1016/S0301-0511(00)00047-8

Hazemann, P., Metral, S., & Lille, F. (1978). Influence of force, speed and duration of isometric contraction upon slow cortical potentials in man. In D. A. Otto (Ed.), *Multidisciplinary Perspectives in Event-Related Brain Potential Research* (pp. 107-111). Washington: U.S. Environmental Protection Agency.

Hillyard, S. A., & Galambos, R. (1970). Eye movement artifact in the CNV. *Electroencephalography and clinical Neurophysiology, 28*, 173-182. doi:10.1016/0013-4694(70)90185-9

Holmes, P. S. (2000). *The development of a functional equivalence model for motor imagery.* (Unpublished doctoral thesis). Manchester Metropolitan University, Manchester, UK.

Holmes, P., & Calmels, C. (2008). A neuroscientific review of imagery and observation use in sport. *Journal of Motor Behavior, 40*, 433-445. doi:10.3200/JMBR.40.5.433-445

Holmes, P. S., & Collins, D. J. (2001). The PETTLEP approach to motor imagery: A functional equivalence model for sport psychologists. *Journal of Applied Sport Psychology, 13*, 60-83. doi:10.1080/10413200109339004

Holmes, P., Collins, D., & Calmels, C. (2006). Electroencephalographic functional equivalence during observation of action. *Journal of Sports Sciences, 24*, 605-616. doi:10.1080/02640410500244507

Holmes, P., & Ewan, L. (2007). The use of structured observation as a stroke rehabilitation aid: An opinion from neuroscience. *The British Journal of Occupational Therapy, 70*(10), 454-456.

Hung, T. M., Haufler, A. J., Lo, L. C., Mayer-Kress, G., & Hatfield, B. D. (2008). Visuomotor expertise and dimensional complexity of cerebral cortical activity. *Medicine & Science in Sports & Exercise, 40*, 752-759. doi:10.1249/MSS.0b013e318162c49d

Ikeda, A., Luders, H. O., Burgess, R. C., & Shibasaki, H. (1992). Movement-related potentials recorded from the supplementary motor area and primary motor area. *Brain, 115*, 1017-1043. doi:10.1093/brain/115.4.1017

Jahanshahi, M., & Hallett, M. (2003). The Bereitschaftspotential: What does it measure and where does it come from? In M. Jahanshahi & M. Hallett (Eds.), *The Bereitschaftspotential: Movement-related cortical potentials* (pp. 1-16). New York: Kluver Academic/Plenum.

Jancke, L. (2002). What is special about the brains of musicians? *Neuroreport, 13*(6), 741-742.

Jancke, L., Shah, N. J., & Peters, M. (2000). Cortical activations in primary and secondary motor areas for complex bimanual movements in professional pianists. *Cognitive Brain Research, 10*, 177-183. doi:10.1016/S0926-6410(00)00028-8

Janelle, C. M., Hillman, C. H., Apparies, R. J., Murray, N. P., Meili, L., Fallon, E. A., & Hatfield, B. D. (2000). Expertise differences in cortical activation and gaze behavior during rifle shooting. *Journal of Sport & Exercise Psychology, 22*(2), 167-182.

Jasper, H. H. (1958). The ten twenty electrode system of the international federation. *Electroencephalography and clinical Neurophysiology, 10*, 371-375.

Jeannerod, M. (2001). Neural simulation of action: A unifying mechanism for motor cognition. *NeuroImage, 14*, S103-S109. doi:10.1006/nimg.2001.0832

Jensen, J. L., Marstrand, P. C. D., & Nielsen, J. B. (2005). Motor skill training and strength training are associated with different plastic changes in the central nervous system. *Journal of Applied Physiology, 99*, 1558-1568. doi:10.1152/japplphysiol.01408.2004

Johnston, J., Rearick, M., & Slobounov, S. (2001). Movement-related cortical potentials associated with progressive muscle fatigue in a grasping task. *Clinical Neurophysiology, 112*, 68-77. doi:10.1016/S1388-2457(00)00452-1

Joyce, C. A., Gorodnitsky, I. F., & Kutas, M. (2004). Automatic removal of eye movement and blink artifacts from EEG data using blind component separation. *Psychophysiology, 41*, 313-325. doi:10.1111/j.1469-8986.2003.00141.x

Kerick, S. E., Hatfield, B. D., & Allender, L. E. (2007). Event-Related Cortical Dynamics of Soldiers During Shooting as a Function of Varied Task Demand. *Aviation, Space, and Environmental Medicine, 78*, B153-B164.

Kita, Y., Mori, A., & Nara, M. (2001). Two types of movement-related cortical potentials preceding wrist extension in humans. *Neuroreport, 12*, 2221-2225. doi:10.1097/00001756-200107200-00035

Koeneke, S., Lutz, K., Wustenberg, T., & Jancke, L. (2004). Long-term training affects cerebellar processing in skilled keyboard players. *Neuroreport, 15*(8), 1279-1282.

Kolb, B., & Whishaw, I. Q. (2009). *Fundamentals of Human Neuropsychology* (6th ed.). New York: Worth.

Konttinen, N., & Lyytinen, H. (1992). Physiology of preparation - Brain slow waves, heart-rate, and respiration preceding triggering in rifle shooting. *International Journal of Sport Psychology, 23*(2), 110-127.

Konttinen, N., & Lyytinen, H. (1993). Individual variability in brain slow-wave profiles in skilled sharpshooters during the aiming period in rifle shooting. *Journal of Sport & Exercise Psychology, 15*(3), 275-289.

Kornhuber, H. H., & Deecke, L. (1964). Hirnpotentialänderungen beim Menschen vor und nach Willkürbewegungen, dargestellt mit Magnetbandspeicherung und Rückwärtsanalyse [Changes in human brain potentials before and after voluntary movement, displayed by magnetic tape storage and backward analysis]. *Pflugers Archiv fur die gesamte Physiologie des Menschen und der Tiere, 281*, 52.

Kornhuber, H. H., & Deecke, L. (1965). Changes in the Brain Potential in Voluntary Movements and Passive Movements in Man: Readiness Potential and Reafferent Potentials. *Pflugers Archiv fur die gesamte Physiologie des Menschen und der Tiere, 284*, 1-17.

Krings, T., Topper, R., Foltys, H., Erberich, S., Sparing, R., Willmes, K., & Thron, A. (2000). Cortical activation patterns during complex motor tasks in piano players and control subjects. A functional magnetic resonance imaging study. *Neuroscience Letters, 278*, 189-193. doi:10.1016/S0304-3940(99)00930-1

Kristeva, R. (1984). Bereitschaftspotential of pianists. *Annals of the New York Academy of Sciences, 425*, 477-482. doi:10.1111/j1749-6632.1984.tb23570x

Kristeva, R., Chakarov, V., Schulte-Monting, J., & Spreer, J. (2003). Activation of cortical areas in music execution and imagining: A high-resolution EEG study. *NeuroImage, 20*, 1872-1883. doi:10.1016/S1053-8119(03)00422-1

Kutas, M., & Donchin, E. (1974). Studies of squeezing: handedness, responding hand, response force, and asymmetry of readiness potential. *Science, 186*, 545-548. doi:10.1126/science.186.4163.545

Lang, W., Beisteiner, R., Lindinger, G., & Deecke, L. (1992). Changes of cortical activity when executing learned motor sequences. *Experimental Brain Research, 89*, 435-440. doi:10.1007/BF00228259

Lang, W., Obrig, H., Lindinger, G., Cheyne, D., & Deecke, L. (1990). Supplementary motor area activation while tapping bimanually different rhythms in musicians. *Experimental Brain Research, 79*, 504-514. doi:10.1007/BF00229320

Lins, O. G., Picton, T. W., Berg, P., & Scherg, M. (1993). Ocular artifacts in EEG and event-related potentials. I: Scalp topography. *Brain Topography, 6*, 51-63. doi:10.1007/BF01234127

Loze, G. M., Collins, D., & Holmes, P. S. (2001). Pre-shot EEG alpha-power reactivity during expert air-pistol shooting: A comparison of best and worst shots. *Journal of Sports Sciences, 19*, 727-733. doi:10.1080/02640410152475856

Luck, S. J. (2005). *An introduction to the event-related potential technique*. Cambridge, MA: The MIT Press.

MacNamara, A., Button, A., & Collins, D. (2010). The role of psychological characteristics in facilitating the pathway to elite performance part 1: Identifying mental skills and behaviors. *The Sport Psychologist, 24*(1), 52-73.

MacNamara, A., & Collins, D. (2009). More than the 'X' factor! A longitudinal investigation of the psychological characteristics of developing excellence in musical

development. *Music Education Research, 11*(3), 377-392. doi:10.1080/14613800903144270

Magill, R. A. (2011). *Motor Learning and Control: Concepts and Applications* (9th ed.). New York: McGraw Hill.

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences of the United States of America, 97*, 4398-4403. doi:10.1073/pnas.070039597

Maguire, E. A., Spiers, H. J., Good, C. D., Hartley, T., Frackowiak, R. S. J., & Burgess, N. (2003). Navigation expertise and the human hippocampus: A structural brain imaging analysis. *Hippocampus, 13*, 250-259. doi:10.1002/hipo.10087

Maguire, E. A., Woollett, K., & Spiers, H. J. (2006). London taxi drivers and bus drivers: A structural MRI and neuropsychological analysis. *Hippocampus, 16*, 1091-1101. doi:10.1002/hipo.20233

Martinez, J. L., & Derrick, B. E. (1996). Long-term potentiation and learning. *Annual Review of Psychology, 47*, 173-203. doi:10.1146/annurev.psych.47.1.173

Masaki, H., Takasawa, N., & Yamazaki, K. (1998). Enhanced negative slope of the readiness potential preceding a target force production task. *Electroencephalography and clinical Neurophysiology, 108*, 390-397. doi: 10.1016/S0168-5597(98)00019-7

Masaki, H., Takasawa, N., & Yamazaki, K. (2000). Human movement-related brain potentials preceding voluntary movements in different arousal states monitored with skin potential level. *Perceptual and Motor Skills, 90*, 299-306. doi: 10.2466/PMS.90.1.299-306

McAdam, D. W., & Seales, D. M. (1969). Bereitschaftspotential enhancement with increased level of motivation. *Electroencephalography and clinical Neurophysiology, 27*, 73-75. doi:10.1016/0013-4694(69)90111-4

McBurney, D. H., & White, T. L. (2010). *Research Methods* (8th ed.). Belmont, CA: Wadsworth.

McPherson, G. E., & Thompson, W. F. (1998). Assessing music performance: Issues and influences. *Research Studies in Music Education, 10*, 12-24. doi:10.1177/1321103x9801000102

Menon, V., & Crottaz-Herbette, S. (2005). Combined EEG and fMRI studies of human brain function. *International Review of Neurobiology, 66*, 291-321. doi:10.1016/S0074-7742(05)66010-2

Munte, T. F., Altenmuller, E., & Jancke, L. (2002). The musician's brain as a model of neuroplasticity. *Nature Reviews Neuroscience, 3*(6), 473-478.

Nakata, H., Yoshie, M., Miura, A., & Kudo, K. (2010). Characteristics of athletes' brain: Evidence from neurophysiology and neuroimaging. *Brain Research Reviews, 62*, 197-211. doi:10.1016/j.brainresrev.2009.11.006

Niedermeyer, E. (2005). The Normal EEG of the Waking Adult. In E. Niedermeyer & F. H. Lopes da Silva (Eds.), *Electroencephalography: Basic Principles, Clinical Applications and Related Fields* (5th ed., pp. 167-192). Philadelphia, PA: Lippincott, Williams & Wilkins.

Niemann, J., Winker, T., Gerling, J., Landwehrmeyer, B., & Jung, R. (1991). Changes of slow cortical negative DC-potentials during the acquisition of a complex finger motor task. *Experimental Brain Research, 85*, 417-422. doi:10.1007/BF00229418

Norton, A., Winner, E., Cronin, K., Overy, K., Lee, D. J., & Schlaug, G. (2005). Are there pre-existing neural, cognitive, or motoric markers for musical ability? *Brain and Cognition, 59*, 124-134. doi:10.1016/j.bandc.2005.05.009

Nuwer, M. R., Comi, G., Emerson, R., Fuglsang-Frederiksen, A., Guerit, J. M., Hinrichs, H., . . . Rappelsburger, P. (1998). IFCN standards for digital recording of clinical EEG. International Federation of Clinical Neurophysiology. *Electroencephalography and clinical Neurophysiology, 106*, 259-261. doi:10.1016/S0013-4694(97)00106-5

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*, 97-113. doi:10.1016/0028-3932(71)90067-4

Oostenveld, R., & Praamstra, P. (2001). The five percent electrode system for high-resolution EEG and ERP measurements. *Clinical Neurophysiology, 112*, 713-719. doi:10.1016/S1388-2457(00)00527-7

Pascual-Leone, A., Grafman, J., & Hallett, M. (1994). Modulation of cortical motor output maps during development of implicit and explicit knowledge. *Science, 263*, 1287-1289. doi:10.1126/science.8122113

Pfurtscheller, G. (1992). Event-related synchronization (ERS): an electrophysiological correlate of cortical areas at rest. *Electroencephalography and clinical Neurophysiology, 83*, 62-69. doi:10.1016/0013-4694(92)90133-3

Pfurtscheller, G. (2001). Functional brain imaging based on ERD/ERS. *Vision Research, 41*, 1257-1260. doi:10.1016/S0042-6989(00)00235-2

Pfurtscheller, G., & Lopes da Silva, F. H. (1999a). Event-related EEG/MEG synchronization and desynchronization: basic principles. *Clinical Neurophysiology, 110*, 1842-1857. doi:10.1016/S1388-2457(99)00141-8

Pfurtscheller, G., & Lopes da Silva, F. H. (1999b). Functional meaning of event-related desynchronization (ERD) and synchronization (ERS). In G. Pfurtscheller & F. H.

Lopes da Silva (Eds.), *Handbook of Electroencephalography and Clinical Neurophysiology* (Vol. 6). Amsterdam: Elsevier.

Pfurtscheller, G., Stancak, A., Jr., & Neuper, C. (1996). Event-related synchronization (ERS) in the alpha band--an electrophysiological correlate of cortical idling: a review. *International Journal of Psychophysiology, 24*, 39-46. doi:10.1016/S0167-8760(96)00066-9

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., . . . Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology, 37*, 127-152. doi:10.1111/1469-8986.3720127

Picton, T. W., & Hillyard, S. A. (1972). Cephalic skin potentials in electroencephalography. *Electroencephalography and clinical Neurophysiology, 33*, 419-424. doi:10.1016/0013-4694(72)90122-8

Pinel, J. P. J. (2009). *Biopsychology* (7th ed.). Boston, MA: Pearson.

Poldrack, R. A. (2000). Imaging brain plasticity: Conceptual and methodological issues - A theoretical review. *Neuroimage, 12*, 1-13. doi:10.1006/nimg.2000.0596

Rockschool. (2006). *Guitar Syllabus Guide: 2006-2012*. Twickenham, UK: Rockschool.

Rockschool. (2008). *Guitar Grade 2*. Twickenham, UK: Rockschool.

Rockstroh, B., Elbert, T., Birbaumer, N., & Lutzenberger, W. (1982). *Slow Brain Potentials and Behavior*. Baltimore, MD: Urban & Schwarzenberg.

Rosler, F., Heil, M., & Roder, B. (1997). Slow negative brain potentials as reflections of specific modular resources of cognition. *Biological Psychology, 45*, 109-141. doi:10.1016/S0301-0511(96)05225-8

Rossi, S., Pasqualetti, P., Rossini, P. M., Feige, B., Ulivelli, M., Glocker, F. X., . . . Kristeva-Feige, R. (2000). Effects of repetitive transcranial magnetic stimulation on

movement-related cortical activity in humans. *Cerebral Cortex, 10*, 802-808. doi:10.1093/cercor/10.8.802

Salazar, W., Landers, D. M., Petruzzello, S. J., Han, M., Crews, D. J., & Kubitz, K. A. (1990). Hemispheric asymmetry, cardiac response, and performance in elite archers. *Research Quarterly for Exercise and Sport, 61*(4), 351-359.

Schillings, M. L., Kalkman, J. S., van der Werf, S. P., Bleijenberg, G., van Engelen, B. G. M., & Zwarts, M. J. (2006). Central adaptations during repetitive contractions assessed by the readiness potential. *European Journal of Applied Physiology, 97*, 521-526. doi:10.1007/s00421-006-0211-z

Schmidt, R. A., & Lee, T. D. (2011). *Motor Control and Learning: A Behavioral Emphasis* (5th ed.). Champaign, IL: Human Kinetics.

Sharma, N., Pomeroy, V. M., & Baron, J. C. (2006). Motor imagery: A backdoor to the motor system after stroke? *Stroke, 37*, 1941-1952. doi:10.1161/01.STR.0000226902.43357.fc

Shibasaki, H., Barrett, G., Halliday, E., & Halliday, A. M. (1980). Components of the movement-related cortical potential and their scalp topography. *Electroencephalography and clinical Neurophysiology, 49*, 213-226. doi:10.1016/0013-4694(80)90216-3

Shibasaki, H., & Hallett, M. (2006). What is the Bereitschaftspotential? *Clinical Neurophysiology, 117*, 2341-2356. doi:10.1016/j.clinph.2006.04.025

Siemionow, V., Yue, G. H., Ranganathan, V. K., Liu, J. Z., & Sahgal, V. (2000). Relationship between motor activity-related cortical potential and voluntary muscle activation. *Experimental Brain Research, 133*, 303-311. doi:10.1007/s002210000382

Singh, J., Knight, R. T., Woods, D. L., Beckley, D. J., & Clayworth, C. (1990). Lack of age effects on human brain potentials preceding voluntary movements. *Neuroscience Letters, 119*, 27-31. doi:10.1016/0304-3940(90)90747-W

Smith, D., & Collins, D. (2004). Mental practice, motor performance, and the late CNV. *Journal of Sport & Exercise Psychology, 26*(3), 412-426.

Smith, D., Wright, C., Allsopp, A., & Westhead, H. (2007). It's all in the mind: PETTLEP-based imagery and sports performance. *Journal of Applied Sport Psychology, 19*, 80-92. doi:10.1080/10413200600944132

Smith, D., Wright, C., & Cantwell, C. (2008). Beating the bunker: The effect of PETTLEP imagery on golf bunker shot performance. *Research Quarterly for Exercise and Sport, 79*(3), 385-391.

Srinivasan, N. (2007). Cognitive neuroscience of creativity: EEG based approaches. *Methods, 42*, 109-116. doi:10.1016/j.ymeth.2006.12.008

Tallgren, P., Vanhatalo, S., Kaila, K., & Voipio, J. (2005). Evaluation of commercially available electrodes and gels for recording of slow EEG potentials. *Clinical Neurophysiology, 116*, 799-806. doi:10.1016/j.clinph.2004.10.001

Tarkka, I. M. (1994). Electrical source localization of human movement-related cortical potentials. *International Journal of Psychophysiology, 16*, 81-88. doi:10.1016/0167-8760(94)90044-2

Taylor, M. J. (1978). Bereitschaftspontential during the acquisition of a skilled motor task. *Electroencephalography and clinical Neurophysiology, 45*, 568-576. doi:10.1016/0013-4694(78)90157-8

Thompson, T., Steffert, T., Ros, T., Leach, J., & Gruzelier, J. (2008). EEG applications for sport and performance. *Methods, 45*, 279-288. doi:10.1016/j.ymeth.2008.07.006

Toma, K., & Hallett, M. (2003). Generators of the movement-related cortical potentials and dipole source analysis. In M. Jahanshahi & M. Hallett (Eds.), *The Bereitschaftspotential: Movement-related cortical potentials* (pp. 113-130). New York: Kluwer Academic/Plenum.

Toni, I., Krams, M., Turner, R., & Passingham, R. E. (1998). The time course of changes during motor sequence learning: a whole-brain fMRI study. *Neuroimage, 8*, 50-61. doi:10.1006/nimg.1998.0349

Vereijken, B., van Emmerik, R., E. A., Whiting, H. T. A., & Newell, K. M. (1992). Free(z)ing degrees of freedom in skill acquisition. *Journal of Motor Behavior, 24*, 133-142. doi:10.1080/00222895.1992.9941608

Ward, J. (2010). *The Student's Guide to Cognitive Neuroscience* (2nd ed.). Hove, East Sussex: Psychology Press.

Watson, A. H. D. (2006). What can studying musicians tell us about motor control of the hand? *Journal of Anatomy, 208*, 527-542. doi:10.1111/j.1469-7580.2006.00545.x

Wilke, J. T., & Lansing, R. W. (1973). Variations in the motor potential with force exerted during voluntary arm movements in man. *Electroencephalography and clinical Neurophysiology, 35*(3), 259-265. doi:10.1016/0013-4694(73)90237-X

Williams, A. M., & Hodges, N. J. (2005). Practice, instruction and skill acquisition in soccer: Challenging tradition. *Journal of Sports Sciences, 23*, 637-650. doi:10.1080/02640410400021328

Appendix A – Pilot study: Minimising signal drift

Introduction

When recording DC EEG signals a number of technical issues must be taken into consideration if valid EEG data are to be obtained. Factors such as the choice of electrode, amount of skin abrasion, the choice of electrolyte and the length of the electrode 'settling period' can all affect the quality of the signal. If these issues are not properly addressed it can result in the signal drifting away from baseline, distorting the recording. Baseline drift is thought to occur as a result of a slow, spontaneous change in electrode polarisation (Tallgren et al., 2005), caused by differences in the fluid content between the electrolyte and fluid on the scalp (e.g., sweat). Current research recommends that in order to reduce levels of drift and obtain valid DC recordings, silver/silver chloride electrodes should be used in conjunction with an electrolyte gel with a high sodium chloride content (Tallgren et al., 2005; Butler, 1993; Bauer et al., 1989). Despite these recommendations for the choice of electrode and electrolyte, Bauer (1993) pointed out that when something is placed on the skin that is not in ionic balance with the contents of the skin, a settling period will always be required to minimise signal drift. It is unclear how long a period is necessary to obtain a stable EEG recording. Bauer et al. (1989) reported that a 30-minute settling period results in a stable enough signal for valid recordings to obtained, yet the length of the settling period employed by researchers is rarely stated in the literature.

The purpose of this pilot study was to determine how long a settling period was required to obtain stable EEG recordings with minimal baseline drift. It was important to establish this so as to guarantee stable EEG recordings, whilst not leaving the participant waiting unnecessarily long before beginning an experiment.

Method

Four participants (three female, one male) aged between 21-26 years took part in the study. Participants were seated in a comfortable chair whilst their scalp was prepared for the EEG recording. Electrodes were placed at sites C3, Cz, and C4 of the International 10-20 system of electrode placement (Jasper, 1958). The scalp was gently abraded with Nuprep skin preparation paste and silver/silver chloride electrodes were attached to the scalp with Ten20 conductive EEG paste; an adhesive paste, with a high sodium chloride concentration. The electrodes were then secured in place with tape smeared with glue. Electrodes were referenced to linked mastoids and a ground electrode was placed on the forehead. Electrode impedances were kept homogenous at or below 5 kΩ. The EEG was recorded using a Neuroscan Synamps amplifier, with a gain of 500 and a bandpass from 0 – 40 Hz. Participants remained as still as possible whilst EEG was recorded following settling periods of 15, 30, 45, and 60 minutes. At each of the four testing times, two 2-minute recordings were taken from each participant. Prior to each recording, the baseline drift was corrected manually, using the DC Offset Correction transform of the Scan 4.3 software. The first recording monitored the percentage drift as it deviated from baseline, without the use of DC correction. The second recording configuration included an automatic DC correction that brought the drift level back to baseline once it deviated by 5%. The purpose of the first recording was to establish the maximum amount of signal drift, whereas the second recording was to determine the frequency of signal drift.

Results

Maximum drift percentage

Table A.1 shows the individual and mean values for the percentage drift from baseline at each of the four time points:

Table A.1: Individual and mean values for the percentage drift from baseline after each settling period

		Length of settling period (minutes)			
		15	**30**	**45**	**60**
Drift from baseline (%)	**P1**	11	8	1	2
	P2	5	2	3	2
	P3	15	8	4	3
	P4	9	3	2	3
Mean (SD)		**10** (±4.16)	**5.25** (±3.2)	**2.5** (±1.29)	**2.5** (±0.58)

The results indicate that after a fifteen minute settling period the signal was rather unstable, drifting an average of 10% from baseline. After thirty minutes the amount of drift was approximately 50% less than at fifteen minutes. In two participants the level of drift had settled after thirty minutes, but was still high in the remaining two participants.

By forty-five minutes the level of drift was low in all participants, and remained low at sixty minutes.

Automatic DC correction

Table A.2 shows the individual and mean values for the number of automatic DC corrections that occurred when the signal drifted from the baseline by 5%.

Table A.2: Individual and mean values for the frequency of the automatic DC correction during each settling period

		Length of settling period (minutes)			
		15	**30**	**45**	**60**
Drift from baseline (%)	**P1**	1	2	0	0
	P2	1	0	0	0
	P3	2	1	0	0
	P4	1	0	0	0
	Mean (SD)	**1.25** (±0.5)	**0.75** (±0.95)	**0** (±0)	**0** (±0)

The results displayed in Table A.2 show a similar pattern to the maximum amount of drift in Table A.1. After fifteen minutes, the automatic DC correction occurred at least once in all participants, indicating that the signal had drifted by 5% within the two minute period. By thirty minutes, the number of times the automatic DC correction occurred was

reduced. In two participants the signal was stable and did not reach the 5% correction, whilst in the other two participants the DC correction was required. After settling periods of both forty-five and sixty minutes, the automatic DC correction was not required. This indicates that the signal was stable and did not deviate from baseline by more than 4%.

Discussion

This study aimed to establish the duration of the settling period required to minimise signal drift before stable DC EEG signals could be recorded. The results show that a settling period of forty-five minutes is required to obtain stable recordings. This finding differs from the recommendation by Bauer et al. (1989), who suggested that a thirty minute period should be sufficient to obtain stable recordings. The results indicate that, whilst thirty minutes may be sufficient to provide a stable recording in some participants, a forty-five minute settling period is more appropriate. As such, in all studies reported in this thesis, a forty-five minute settling period was adhered to after the electrodes were attached to the scalp.

Appendix B – Extracting the MRCP from the EEG recording

The MRCP typically ranges between 5 – 30 μV in amplitude, whilst spontaneous variation in the EEG may range between 10 – 100 μV in amplitude (Birbaumer et al., 1990). As a result, the MRCP is barely, if at all, visible in the raw EEG trace. In order to extract a meaningful MRCP, multiple recordings of the same trials must be taken and averaged across these trials (Birbaumer et al., 1990). The EEG data recorded from a single trial consists of both the MRCP waveform and random, spontaneous noise (Luck, 2005). As such, when multiple trials are averaged, the background noise in each trial will cancel itself out, leaving only the MRCP waveform. The six steps undertaken to extract the MRCP waveform from the raw EEG data in the experiments reported in this thesis are described below:

Step 1 – Marking movement onset

The point of movement onset must be marked on the EEG trace. In the studies described in this thesis, a thin electrode was attached onto the neck of the guitar at the third fret. When the bottom E string was pressed to play the first note of the scale, the string made contact with the electrode and caused a 100 μV deflection to occur on the EEG trace (see Figures 4.4. and 4.5). This deflection was used as the point of movement onset.

Step 2 – Inserting event markers into the EEG recording

The voltage threshold transform of Scan 4.3 software allows digital event markers to be inserted offline, onto a continuous EEG recording, at points where the voltage in a specified channel exceeds a certain value. Using this function, event markers were inserted onto the EEG recording at points where the sharp deflection on the ‘movement

onset' channel, caused by the first note of the scale being played, exceeded 50 µV in amplitude (see Figure B.1). These digital markers served as the point of movement onset, with any further data processing being referenced to these markers. Once an event marker was placed, there was a refractory period of 7 seconds. Any further deflections on the movement onset channel during this period were not marked. The reason for this was that participants had been instructed to leave a 10-second gap between performances of the scale, to ensure that subsequent repetitions were not being played during analysis periods of the previous repetition. Any deflections on the movement onset channel during this refractory period were therefore accidental, and so did not represent the onset of a repetition.

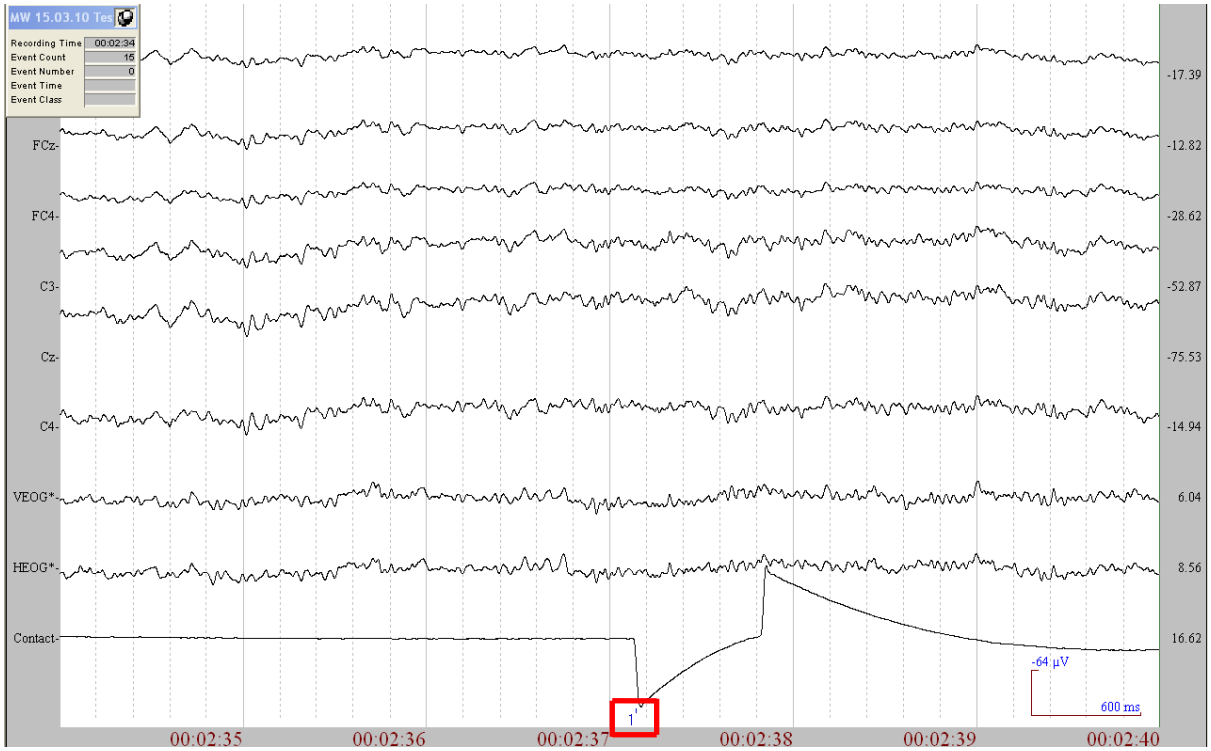

Figure B.1: Screen shot of an EEG recording showing where event markers were inserted at the point of movement onset, using the voltage threshold transform. The event marker is highlighted by the red square.

Step 3 – Removing EOG artefacts

The artefact rejection transform function of Scan 4.3 software automatically rejects any sections of the EEG recording where the voltage in a designated channel exceeds a pre-defined criterion. This transform was used to remove sections of the EEG recording that contained artefacts caused by eye-movements and blinks. Using the procedure described by Croft and Barry (2000), any deflections in the VEOG or HEOG channels in excess of 50 µV were rejected from the recording (see Figure B.2).

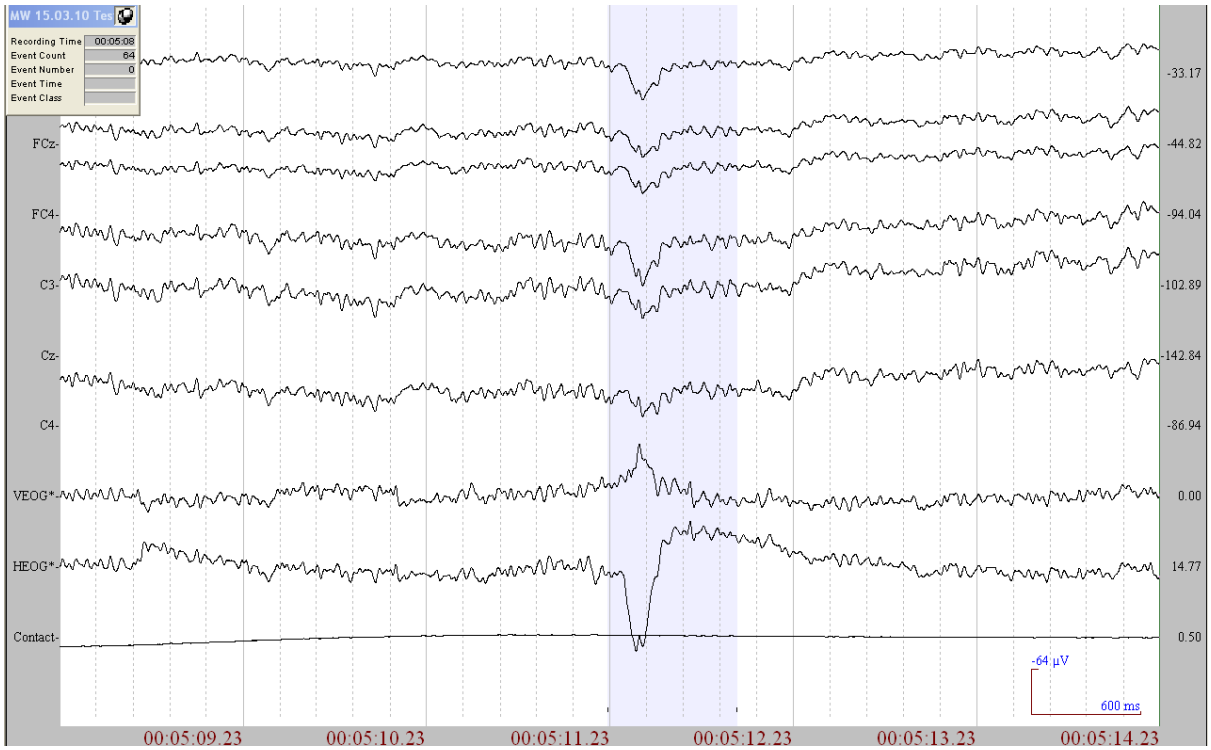

Figure B.2: Screen shot of an EEG recording showing a section of data that was rejected from analysis due to the presence of eye-movement artefacts in the EOG channels. The purple band highlights the rejected section of the recording.

Step 4 – Filtering the recording

The amplitude of the MRCP is smaller than the amplitude of the spontaneous background EEG. As such, in order to extract the MRCP the recording is filtered offline. This removes the higher frequency EEG components from the recording. In the studies reported in this thesis the data were recorded with a 0 – 30 Hz bandpass. As these studies were only concerned with the lower end of this spectrum, a 0 – 5 Hz bandpass filter was applied offline to the data. The difference between the original data and the filtered data is shown in Figure B.3.

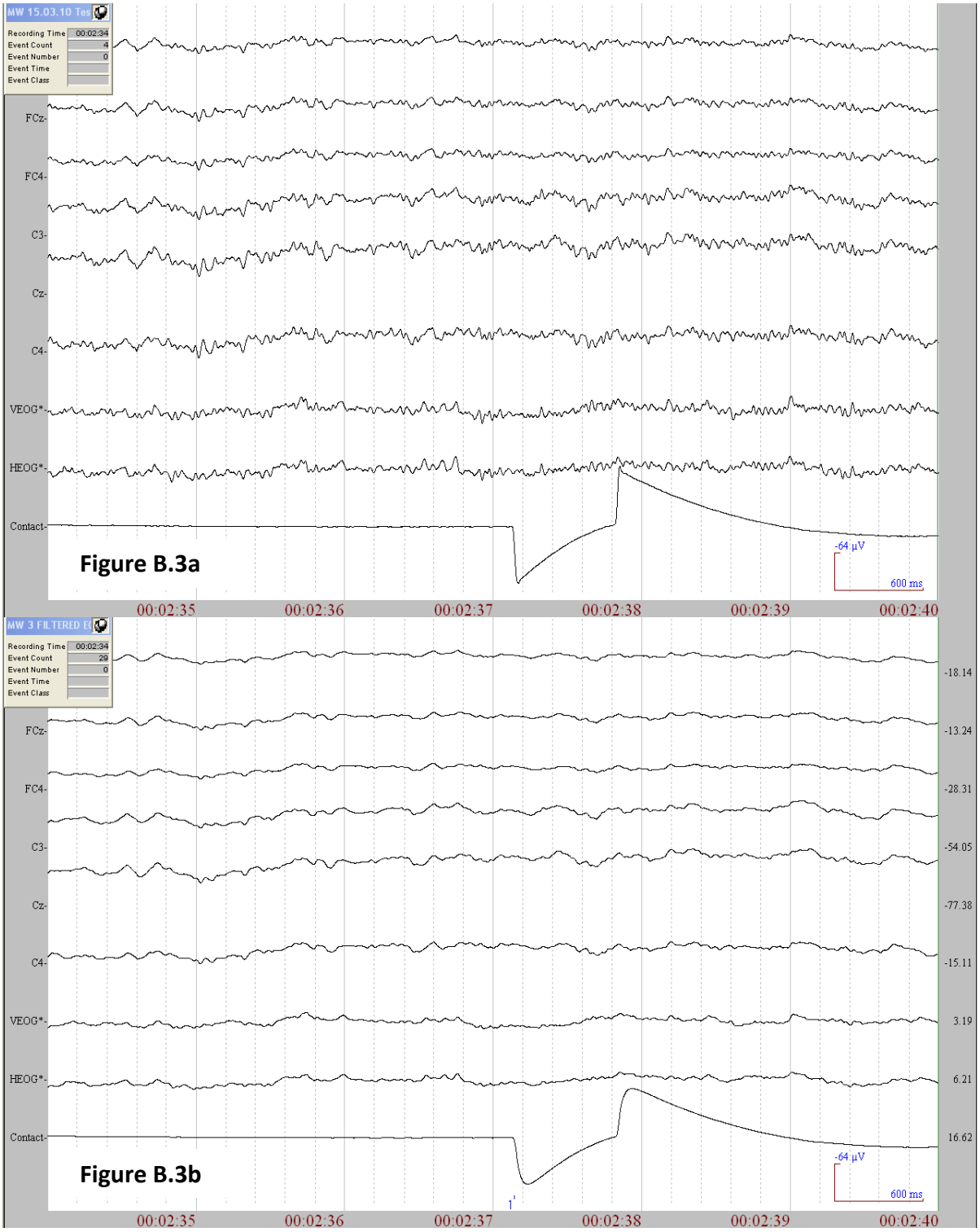

Figure B.3: Screen shots of EEG data highlighting the differences between filtered and unfiltered data. Figure B.3a shows the raw EEG data recorded from one participant. Figure B.3b shows the same section of data after the 0 – 5 Hz filter had been applied.

Step 5 – Epoching the data

As the EEG was recorded continuously throughout the experiments described in this thesis, prior to averaging, the data had to be split offline into the individual movement trials. This process is called epoching. As the early components of the MRCP occur approximately 1.5 – 2 seconds before movement onset and the later components occur several milliseconds after movement onset (Jahanshahi & Hallett, 2003; Shibasaki & Hallett, 2006), it is important that these time periods are included in the epochs. It is also wise to include a few seconds prior to the expected onset time of the early MRCP components to provide a measure of the baseline EEG activity. Using the epoch transform of the Scan 4.3 software, it was possible to epoch the file around event markers that were inserted into the EEG recording. In these studies, epochs of 3 seconds (2500 ms prior to movement onset until 500 ms post movement onset) were created around the movement onset markers (see Figure B.4). Any sections of the EEG that were rejected due to eye-movement artefacts were not epoched. Trials that contained eye-movement artefacts were therefore not included in the final analysis.

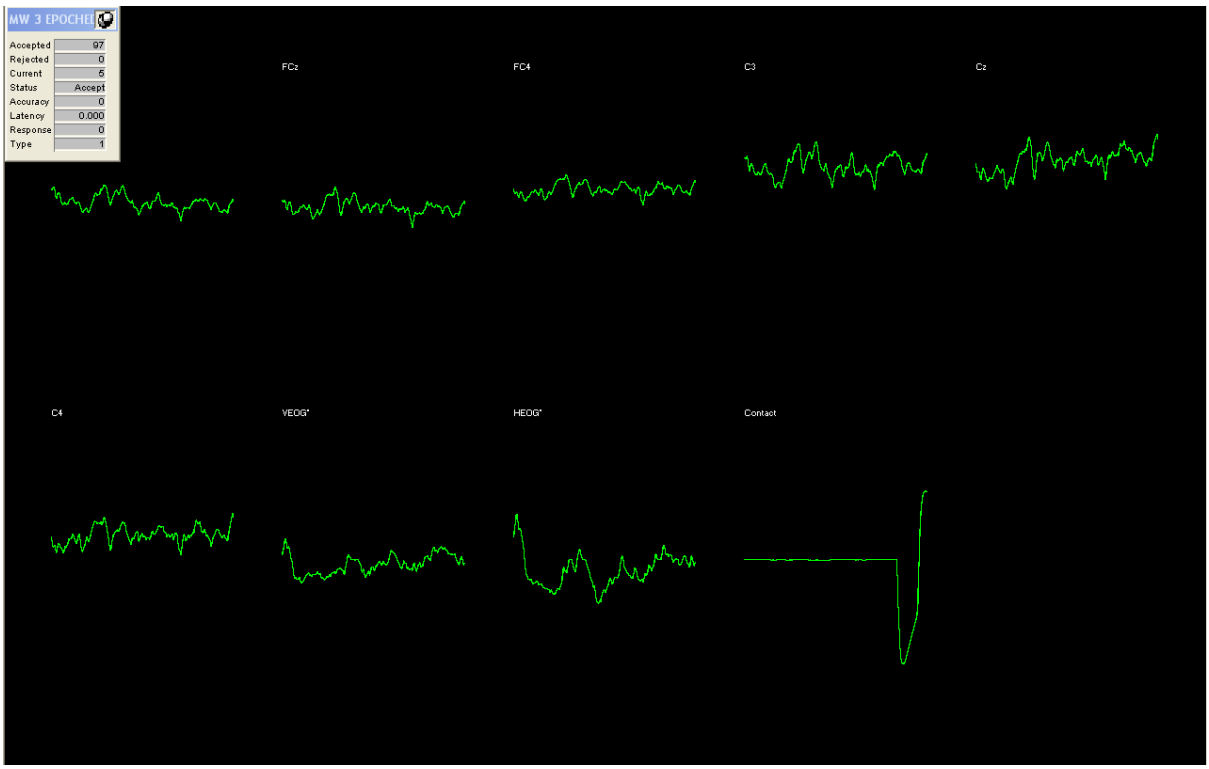

Figure B.4: Screen shot containing epoched EEG data from one participant. Each green trace represents three seconds worth of data from one electrode. Approximately 100 epochs (depending on how many trials were lost due to eye-movement artefacts) were taken from each participant.

Step 6 – Averaging the data

With the data split into individual epochs, the final step is to average all the epochs to produce the MRCP waveform (see Figure B.5).

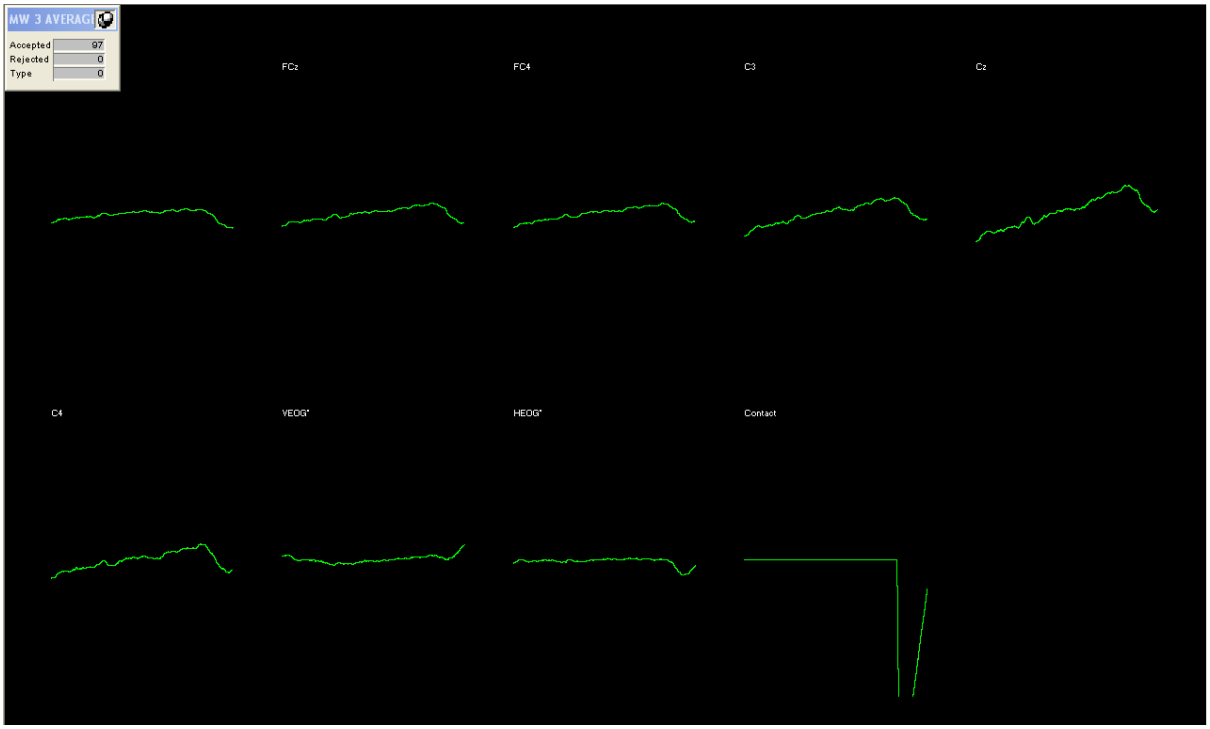

Figure B.5: Screen shot showing the MRCP recorded from one participant after individual epochs were averaged.

Appendix C – The Edinburgh Handedness Inventory (Oldfield, 1971)

Name: Date:

Please indicate your preference in the use of hands in the following activities by putting a + in the appropriate column. Where your preference is so strong that you would never try to use the other hand unless absolutely forced to, put ++. If you are really indifferent put a + in both columns.

Some of the activities require both hands. In these cases, the part of the task, or object, for which hand preference is wanted is indicated in parentheses.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

		Right	Left
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Comb		
6	Toothbrush		
7	Knife (without fork)		
8	Spoon		
9	Hammer		
10	Screwdriver		
11	Tennis Racquet		
12	Knife (with fork)		
13	Cricket Bat (lower hand)		
14	Golf Club (lower hand)		
15	Broom (upper hand)		
16	Rake (upper hand)		
17	Striking Match (match hand)		
18	Opening Box/Jar (lid hand)		
19	Dealing Cards (card dealing hand)		
20	Threading Needle (needle or thread hand, whichever one moves)		
21	Which foot do you prefer to kick with?		
22	Which eye do you use when using only one?		

Appendix D – Differences in the quality of the EEG recording when playing the guitar electrically and acoustically

In addition to the EEG measure used in this research programme, it was important to have a performance measure. This was necessary as cortical differences between the experienced guitarists and non-musicians described in Study 2, and the changes in cortical activity across the training programme in Study 4, were predicted to be skill- or learning-related. It was therefore essential to have a method for assessing the quality of participants' performances. In this research programme, performance was assessed by how closely the participants were able to play the scale in time with a metronome. This was measured by connecting the guitar into an Apple Mac Mini computer and recording performance using Logic Express software. Using this software, it was possible to measure the millisecond disparity between the beat of the metronome and the note being played. The time differences for each note were averaged to provide a measure of how well participants were able to play the scale in time with the metronome.

It was not possible to record performance concurrently with the EEG recording, as connecting the guitar into the computer introduced electrical interference into the EEG recording. This made it impossible to record any meaningful EEG data. Figure D.1 shows two sections of an EEG recording, recorded continuously whilst a participant sat completely still. Figure D.1a shows the EEG recording whilst the guitar was connected into the computer, whilst Figure D.1b shows the EEG recording with the guitar disconnected from the computer. A cleaner EEG signal was evident when the guitar was disconnected from the computer, compared to when it was connected. It was therefore decided that the guitar would be played acoustically during the EEG data acquisition period for all studies reported in this thesis. This meant that performance had to be assessed separately to the EEG

recording. Once participants had performed 100 repetitions of the scale whilst EEG was recorded, participants then performed another 20 repetitions of the scale, without EEG, whilst performance was recorded using Logic Express software. Performance measures were taken based on these 20 trials. Although this was not the ideal solution as performances cannot be matched to specific EEG trials, it was important to obtain valid EEG recordings, and so performance and EEG could not be recorded concurrently.

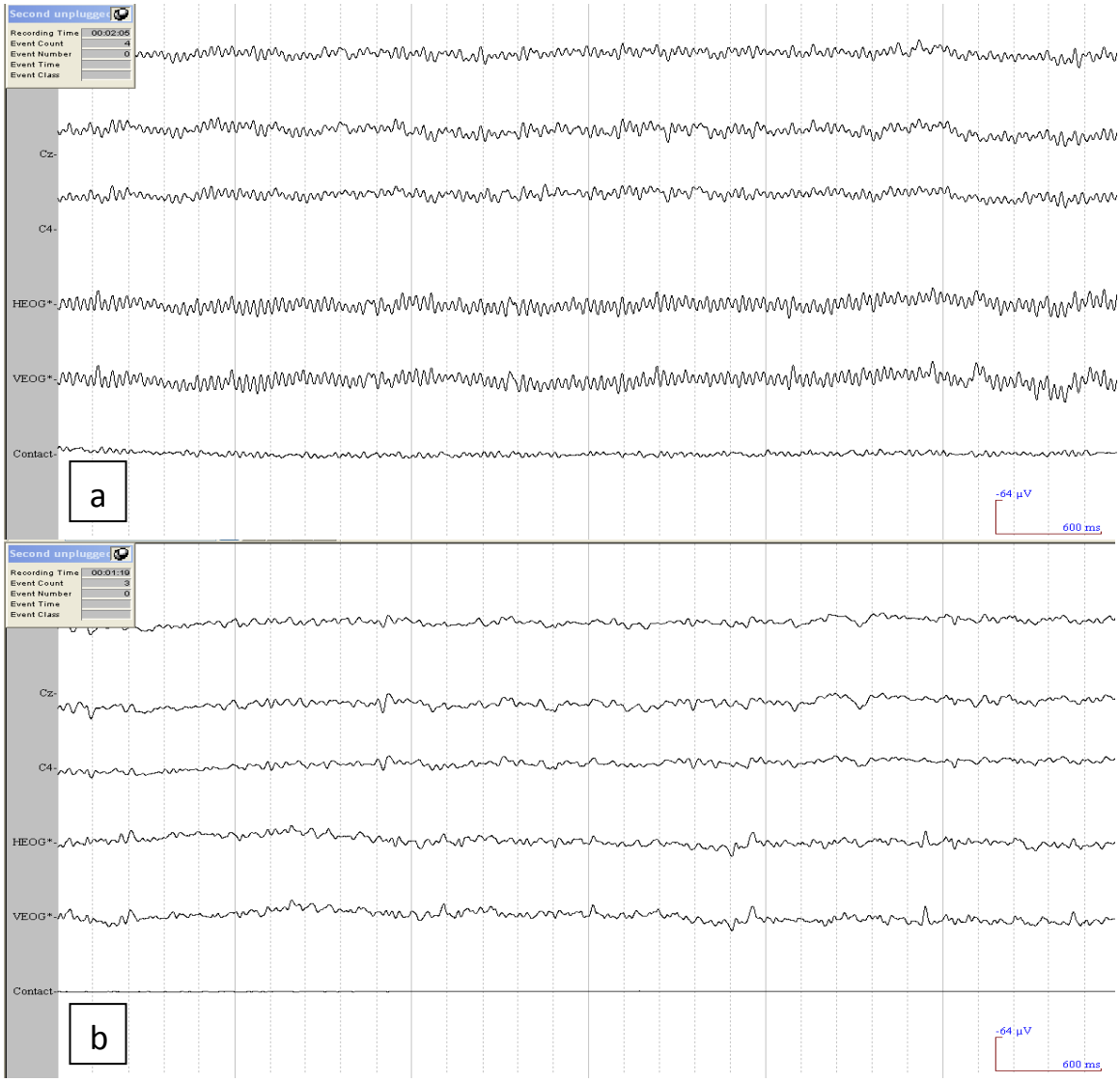

Figure D.1: EEG recordings when the guitar was connected to the computer for performance analysis (a) and when the guitar was not connected to the computer (b).

Appendix E – Participant information sheet and informed consent form for the cross-sectional study

MANCHESTER METROPOLITAN UNIVERSITY

MMU Cheshire

Department of Exercise and Sport Science

Information Sheet for Participants

Title of Study:

Cortical differences between expert and novice musicians prior to performance

Ethics Committee Reference Number: 21.03.09(i)

Participant Information Sheet

1) This is an invitation to take part in a piece of research.

You are being invited to take part in a research study. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Please take time to decide whether or not you wish to take part.

2) What is the purpose of the research?

The purpose of the study is to investigate whether the brains of expert performers operate more efficiently than the brains of novice performers prior to motor skill

performance. The study will use a technique called electroencephalography (EEG) to measure activity from the motor areas of the brain prior to and during performance of a guitar playing task.

3) Why is the study being performed?

Previous research indicates that expert performers are able to execute a motor skill using fewer cortical resources than novice performers. This concept has been termed neural efficiency. However, this research has lacked ecological validity, in that the movement tasks used are far removed from the skill being investigated. No research has yet investigated differences in the brains of expert and novice performers during the performance real-world motor skills, such as playing a scale on the guitar. If the results of this study provide support for the concept of neural efficiency it will aid our understanding of the adaptations in human brain functioning that occur as a result of long-term motor skill learning.

4) Why am I being asked to take part?

You and approximately twenty other people will be invited to take part in this study. The study requires normal, healthy individuals to take part. You have been selected because you are either an experienced guitarist or a non-musician with no prior experience of playing any musical instrument.

5) Do I have to take part?

You are under no obligation to take part in this study. If, after reading this information sheet and asking any additional questions, you do not feel comfortable taking part in the study you do not have to. If you do decide to take part you are free to withdraw from the study at any point, without having to give a reason. If you do withdraw from the study you are free to take any personal data with you and this will not be included when the research is reported. If you decide not to take part or withdraw from the study it will not affect the standard of care you receive in any way, nor will it affect your relationship with any of the staff at the Manchester Metropolitan University.

If you do decide to take part you will be asked to sign an informed consent form stating your agreement to take part and you will be given a copy together with this information sheet to keep.

6) What will happen to me if I agree to take part?

If you agree to take part in the study you will be asked to come to the Psycho-physiology laboratory in the Department of Exercise and Sport Science at the Manchester Metropolitan University for a testing session.

Whilst at the university you will be asked to sit at a desk and your scalp will be prepared for an EEG recording. This will involve cleaning your scalp with an alcohol wipe and gently abrading the skin with a preparation cream. EEG

electrodes will then be attached to your scalp with an adhesive paste. The EEG preparation and recording procedure is a completely safe and painless procedure.

You will then be asked to perform 100 repetitions of a simple scale on a guitar. EEG will be continuously recorded during guitar performance.

7) Are there any disadvantages or risks in taking part?

EEG is a completely safe and non-invasive technique for recording electrical signals generated by the brain through electrodes placed on the scalp. The EEG preparation and recording process is completely painless and will cause you no physical or psychological discomfort.

8) What are the possible benefits of taking part?

If you have been selected as a non-musician participant, the study will provide you with the opportunity to take part in a fun musical activity that you may otherwise never get the chance to attempt.

Your involvement in the study may also help further our understanding of human brain function during skill performance.

9) Who are the members of the research team?

The principal investigator conducting the study is Mr David Wright. Dr Dave Smith, Dr Paul Holmes, Dr. Craig McAllister, Dr Martin Blain and Miss Michela Loporto are the additional members of the research team. If you require further information on the study before taking part please feel free to contact the principal investigator, Mr David Wright via email: d.j.wright@mmu.ac.uk.

10) Who is funding the research?

The research is being conducted by the Manchester Metropolitan University and is funded through a HEFCE PhD studentship.

11) Who will have access to the data?

All data collected during the course of the research will remain confidential and will only be used for the purposes of the study. The data will be stored in coded form and only the principal investigator and members of the research team will have access to the data. The data will be kept stored for five years before being destroyed. The data is being collected as part of the principal investigator's PhD project, and therefore the results of the study will be reported in the final thesis. Any information linking your identity to the study will not be included in this. It is also likely that the findings will be communicated in scientific journals or at academic conferences in the future. In this event, your name or identity will not be disclosed. Should you wish to obtain a summary of the results please feel free to contact the principal investigator via email: d.j.wright@mmu.ac.uk

12) Who do I contact if I feel my rights have been violated?

If at any point during the study you feel that your rights as a participant have been violated and you wish to make a complaint regarding your involvement in the study please contact:

The University Secretary and Clerk to the Board of Governors, Manchester Metropolitan University, Ormond Building, Manchester, M15 6BX. Tel: 0161 247 3400,

Thank you for considering participation in this study.

Manchester Metropolitan University — Cheshire —

Department of Exercise and Sport Science

MSc Sport and Exercise Science

Informed Consent Form

Name of Participant:

Supervisor/Principal Investigator: Dr Dave Smith / Mr David Wright

Project Title: Cortical differences between expert and novice musicians prior to performance

Ethics Committee Approval Number: 21.03.09(i)

Participant Statement

I have read the participant information sheet for this study and understand what is involved in taking part. Any questions I have about the study, or my participation in it, have been answered to my satisfaction. I understand that I do not have to take part and that I may decide to withdraw from the study at any point without giving a reason. Any concerns I have raised regarding this study have been answered and I understand that any further concerns that arise during the time of the study will be addressed by the investigator. I therefore agree to participate in the study.

It has been made clear to me that, should I feel that my rights are being infringed or that my interests are otherwise being ignored, neglected or denied, I should inform the The University Secretary and Clerk to the Board of Governors, Manchester Metropolitan University, Ormond Building, Manchester, M15 6BX. Tel: 0161 247 3400 who will undertake to investigate my complaint.

Signed (Participant): Date:

Signed (Investigator): Date:

Appendix F – Participant information sheet and informed consent form for the training study

MANCHESTER METROPOLITAN UNIVERSITY

MMU Cheshire

Department of Exercise and Sport Science

Information Sheet for Participants

Title of Study:

Modulation of cortical processes associated with long-term motor skill training

Ethics Committee Reference Number: 30.11.09(i)

Participant Information Sheet

1) This is an invitation to take part in a piece of research.

You are being invited to take part in a research study. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Please take time to decide whether or not you wish to take part.

2) What is the purpose of the research?

Previous research has shown that the brains of expert performers operate more efficiently than the brains of novice performers prior to performance of a motor skill. However, no studies have adequately assessed changes in the brain as a result of long-term motor skill learning. The purpose of this study is to assess changes in the brains of novice musicians as they learn to play the guitar over a 5 week period using a technique called electroencephalography (EEG). This will allow us to determine whether, following long-term training, the brains of novice performers begin to operate in a similar way to experienced performers.

3) Why is the study being performed?

Previous research has suggested that as a result of long-term skill learning, expert performers are able to execute a skill using less brain activity than novice performers. This concept has been termed neural efficiency. However, the research that has been conducted previously has typically only compared differences in the brains of expert and novice performers. To date, no research has examined the changes in the brain of a novice performer as they pass through a long-term skill learning process. This study will therefore help aid our understanding of the adaptations in human brain functioning that occur as a result of long-term training in a skill and may provide evidence for the concept of neural efficiency.

4) Why am I being asked to take part?

You and approximately twenty other people will be invited to take part in this study. The study requires healthy individuals to take part. You have been asked to take part because you are a non-musician with no prior experience of guitar playing.

5) Do I have to take part?

You are under no obligation to take part in this study. If, after reading this information sheet and asking any additional questions, you do not feel comfortable taking part in the study you do not have to. If you do decide to take part you are free to withdraw from the study at any point, without having to give a reason. If you do withdraw from the study you are free to take any personal data with you and this will not be included when the research is reported. If you decide not to take part or withdraw from the study it will not affect the standard of care you receive in any way, nor will it affect your relationship with any of the staff at the Manchester Metropolitan University.

If you do decide to take part you will be asked to sign an informed consent form stating your agreement to take part and you will be given a copy together with this information sheet to keep.

6) What will happen to me if I agree to take part?

If you agree to take part in the study you will be asked to come to the Psycho-physiology laboratory in the Department of Exercise and Sport Science at the Manchester Metropolitan University for an initial testing session.

Whilst at the university you will be asked to sit at a desk and your scalp will be prepared for an EEG recording. This will involve cleaning your scalp with an alcohol wipe and gently abrading the skin with a preparation cream. EEG electrodes will then be attached to your scalp with an adhesive paste. The EEG preparation and recording procedure is a completely safe and painless procedure.

You will be shown how to perform a simple scale on the guitar and will then be asked to perform 100 repetitions of this scale. EEG will be continuously recorded during guitar performance.

Following this initial testing session you will be asked to come back to the laboratory once per week for the following 4 weeks. During these sessions you will receive a 30 minute guitar lesson. These lessons will involve practising musical scales and popular songs on the guitar.

At week 5 of training programme you will be asked to come back to the laboratory and repeat the initial testing session to allow us to assess the changes that occurred in the brain as a result of skill learning.

7) Are there any disadvantages or risks in taking part?

EEG is a completely safe, non-invasive technique for recording electrical signals generated by the brain through electrodes placed on the scalp. The EEG preparation and recording process is completely painless and will cause you no physical or psychological discomfort.

8) What are the possible benefits of taking part?

You have been selected to participate in this study because you have no prior experience of playing a musical instrument. Should you agree to take part in this study you will receive 5 weeks of guitar lessons completely free of charge. By the end of the training programme it is likely that you will be able to play a number of popular songs on the guitar to a reasonable standard. Taking part in the study will therefore provide you with the opportunity to have fun learning how to play a musical instrument.

Your involvement in the study may also help further our understanding of human brain function during skill learning.

9) Who are the members of the research team?

The principal investigator conducting the study is Mr David Wright. Dr Dave Smith, Dr Paul Holmes, Dr. Craig McAllister, Dr Martin Blain and Miss Michela Loporto

are the additional members of the research team. If you require further information on the study before taking part please feel free to contact the principal investigator, Mr David Wright via email: d.j.wright@mmu.ac.uk.

10) Who is funding the research?

The research is being conducted by the Manchester Metropolitan University and is funded through a HEFCE PhD studentship.

11) Who will have access to the data?

All data collected during the course of the research will remain confidential and will only be used for the purposes of the study. The data will be stored in coded form and only the principal investigator and members of the research team will have access to the data. The data will be kept stored for five years before being destroyed. The data is being collected as part of the principal investigator's PhD project, and therefore the results of the study will be reported in the final thesis. Any information linking your identity to the study will not be included in this. It is also likely that the findings will be communicated in scientific journals or conferences in the future, however, in this event, your name or identity will not be disclosed. Should you wish to obtain a summary of the results please feel free to contact the principal investigator via email: d.j.wright@mmu.ac.uk

12) Who do I contact if I feel my rights have been violated?

If at any point during the study you feel that your rights as a participant have been violated and you wish to make a complaint regarding your involvement in the study please contact:

The University Secretary and Clerk to the Board of Governors, Manchester Metropolitan University, Ormond Building, Manchester, M15 6BX. Tel: 0161 247 3400

Thank you for considering participation in this study.

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