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Physiological coherence during live music performance -

A real-time, exploratory investigation using wireless systems.

DISSERTATION
Submitted in fulfilment of the requirements for the degree of

Magister Scientiae in Human Physiology
2016

by

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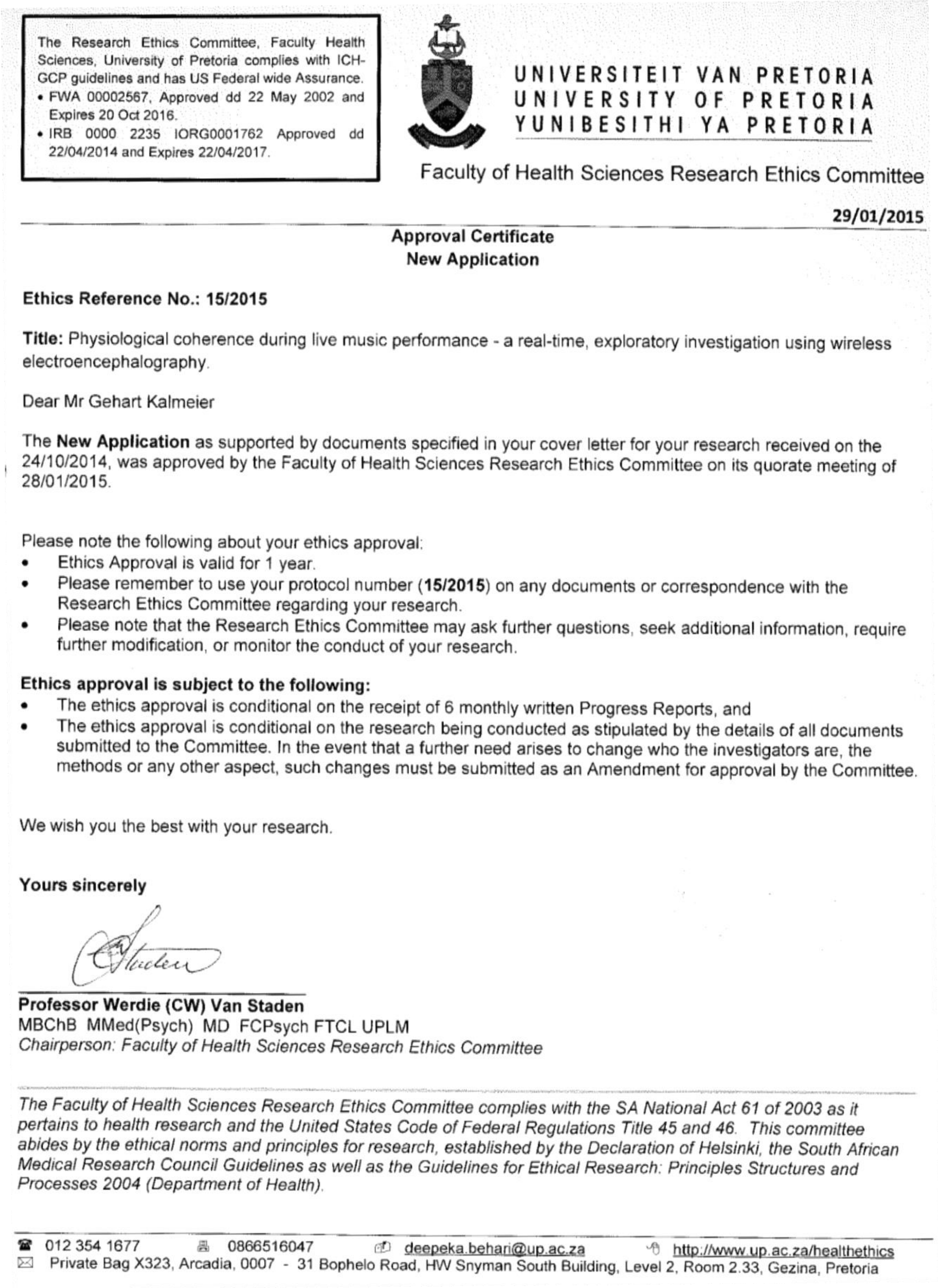

The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

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Faculty of Health Sciences Research Ethics Committee

29/01/2015

Approval Certificate
New Application

Ethics Reference No.: 15/2015

Title: Physiological coherence during live music performance - a real-time, exploratory investigation using wireless electroencephalography.

Dear Mr Gehart Kalmeier

The **New Application** as supported by documents specified in your cover letter for your research received on the 24/10/2014, was approved by the Faculty of Health Sciences Research Ethics Committee on its quorate meeting of 28/01/2015.

Please note the following about your ethics approval:

- Ethics Approval is valid for 1 year.
- Please remember to use your protocol number (**15/2015**) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, or monitor the conduct of your research.

Ethics approval is subject to the following:

- The ethics approval is conditional on the receipt of 6 monthly written Progress Reports, and
- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

Professor Werdie (CW) Van Staden
MBChB MMed(Psych) MD FCPsych FTCL UPLM
Chairperson: Faculty of Health Sciences Research Ethics Committee

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes 2004 (Department of Health).

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LIST OF ABBREVIATIONS

AC - attentional control
ADC - analogue-to-digital converter
ANS - autonomic nervous system
AP - action potential
AR - autoregressive
AV - atrial-ventricle
BCI - brain-computer interfacing
BR - breathing rate
CI - confidence interval
CNS - central nervous system
DLPFC - dorsolateral prefrontal cortex
ECG - electrocardiography
EEG - electroencephalography
EPSP -excitatory post-synaptic potential
ERP - event related potential
F - Frontal
FIR - finite impulse response
FFT - fast Fourier transformation
fMRI - functional magnetic resonance imaging
Fp - prefrontal
GHz - gigahertz
HF - high frequency
HFnu - normalised high frequency
HR - heart rate
HRV - heart rate variability
Hz - hertz
ICC - intraclass correlation
IED - interictal epileptiform discharge
IPSP - inhibitory post-synaptic potential
LF - low frequency
LFnu - normalised low frequency
LPFC - lateral prefrontal cortex
MF - middle frequency
min - minutes
MPFC - medial prefrontal cortex
ms - milliseconds
NREM - non-rapid eyes movement
O - Occipital
OS - operating system
P - Parietal
PCC - polarity coincidence correlation
PET - positron emission tomography
PFC - prefrontal cortex
PNS - parasympathetic nervous system

PSD - power spectral density
RRI - R-R interval
RSA - respiratory sinus arrhythmia
SA - sino-atrial
SDK - software development kit
sec - seconds
SMR - sensorimotor rhythm
SNS - sympathetic nervous system
SPECT - single photon emission tomography
SPS - samples per second
T - Temporal
ULF - ultralow frequency
UP - University of Pretoria
uV - microvolts
VLF - very low frequency
α - Alpha
β - Beta
δ - Delta
θ - Theta

ABSTRACT

Title: Physiological coherence between heart rate variability and electroencephalography during live music performance – A real-time, exploratory investigation using wireless systems.

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Supervisor: Prof PJ du Toit

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Department: Physiology

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Flow has been described in psychological literature as a state of energized focus where an individual becomes so engrossed in their doings that they experience an almost effortless, spontaneous and intuitive, yet highly focused state of optimal and autotelic experience. However neurophysiological research on flow is severely underdeveloped, while real-time research on flow within the context of musical creativity is surprisingly scarce considering how often optimal performance is reported in this context.

An exploratory investigation was launched in order to assess the physiological underpinning of such flow experiences in the larger context of musical improvisation through the study of heart and brain wave activity in five professional jazz musicians. Using wireless electroencephalographic and electrocardiographic devices, subjects could improvise unhindered, and did so continuously while various brain and heart parameters were recorded in real-time.

Through spectral analysis, power values for the different electroencephalographic frequency bands were quantified for the various stages of performance, and subsequently the shifts and trends in the data were described. Additionally, heart rate variability was calculated in order to assess the synergistic actions of the autonomic nervous system on the heart and the interplay between heart and brain during such high performance states of musical creativity.

The research revealed the prominence of elevated theta activity persisting through performance and showed strong associations with subjective experiences of flow. Such high theta activity has been linked to high performance states in past and further evidence suggest the primary involvement of the right frontotemporal regions during improvisation. Furthermore, heart rate variability data suggested the growing presence of parasympathetic influence during such flow states, and together with the lower band dominance suggest trance-like behaviour and activation patterns within the brain. The study serves as basis for future research and the development of neurofeedback, music therapy and musical creativity protocols.

Key terms: EEG, HRV, wireless, real-time, improvisation, theta, music, creativity.

ABSTRAK

Titel: Fisiologiese samehang tussen hartklop veranderlikheid en elektroënsefalografie tydens musiek uitvoering - 'n ware-tyd, verkennende ondersoek met behulp van koördlose sisteme.

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Graad: MSc Mens Fisiologie

‘Flow’ is al deeglik beskryf in sielkundige literatuur as 'n toestand van hoë fokus waar 'n individu so verdiep in hulle handelinge dat hulle 'n byna moeiteloos, spontaan en intuïtief, maar hoogs gefokusde toestand van optimale en ‘autotelic’ ervaring beleef. Ongelukkig is neurofisiologiese navorsing oor ‘flow’ baie onderontwikkel, terwyl ware-tyd navorsing oor vloei binne die konteks van musikale kreatiwiteit verbasend skaars is wanneer in ag geneem word hoe dikwels optimale prestasie gerapporteer word in hierdie konteks.

'n Verkennende ondersoek is van stapel gestuur om die onderliggende fisiologiese prosesse van die ‘flow’ ervaring in die groter konteks van musikale improvisasie te evalueer deur die studie van hart en brein golf aktiwiteit in vyf professionele jazz-musikante te ondersoek. Deur die gebruik van koördlose elektroënsefalografie en elektrokardiografiese toestelle, kon deelnemers ongehinderd improviseer en het so gedoen voortdurend, terwyl verskeie brein en hart parameters in ware-tyd aangeteken is.

Deur spectraalanalise, was krag waardes vir die verskillende frekwensiebande van die elektroënsefalografie gekwantifiseer vir die verskillende stadiums van elke opvoering, en daarna is die verskuiwings en tendense in die data beskryf. Daarbenewens, is hartklop veranderlikheid bereken ten ondersoek van die sinergistiese optrede van die outonome senuweestelsel op die hart en die wisselwerking tussen hart en brein tydens so 'n hoë prestasie toestand van musikale kreatiwiteit.

Die navorsing het aan die lig gebring die prominensie van verhoogde theta aktiwiteit wat volhard het deur optredes en het sterk assosiasies met subjektiewe ervarings van ‘flow’ gewys. Sulke hoë theta aktiwiteit was voornemend gekoppel aan hoë werkverrigting toestande in die verlede en verdere getuienis dui die primêre betrokkenheid van die regter frontale en temporale streke tydens improvisasie. Verder het die hartklop veranderlikheid data aan die lig gebring die groeiende teenwoordigheid van parasimpatiese invloed gedurende sodanige ‘flow’ state wat saam met die laer krag band oorheersing voorstel dat beswyming-agtige gedrag en aktivering patrone binne die brein plassvind tydens ‘flow’. Die studie dien as basis vir toekomstige navorsing en die ontwikkeling van neuro-terugvoering, musiekterapie en musikale kreatiwiteit protokolle.

Sleutelwoorde: EEG, HRV, koördloos, ware-tyd, improviseering, theta, musiek, kreatiwiteit.

Chapter 1

Introduction, objectives and motivation of the research undertaking.

> *...that music is a language which is understood by the immense majority of mankind, although only a tiny minority of people are capable of expressing it, and that music is the only language with the contradictory attributes of being at once intelligible and untranslatable, make the musical creator comparable to the gods, and music itself the supreme mystery of the science of man, a mystery that all the various disciplines come up against and which holds the key to their progress.*
>
> Claude Le´vi-Strauss (1969)

1.1 INTRODUCTION AND RATIONALE

As human beings we have an exceptional capacity to create novel ideas and associates, be it through learning or self-expression, information processing or through our implicit imaginations and erudite skills such as painting or making music. This inherent ability to innovate or envision, to be creative, sets us apart from any other species. It would be true that understanding the underlining neurocognitive mechanisms and substantiating physiological processes of such creative behaviour as innovative thinking and improvisation would bring us ever closer to understanding the elementary nature of our higher cognition and the elusive manner in which our brains are able to give birth to novel ideas and conceptions. The benefits to our society that would come in the wake of understanding such basic underpinnings of innovation and ingenuity would be irrefutable. Alas, to study creative expression, where and how it arises in the brain and the neural basis for such phenomena is a feat almost more abstract and capricious in nature than creativity itself.

Considerable progress has been made in certain areas of creativity research through exploratory investigations and techniques such as surveys, personality inventories and case studies, but laboratory-based research on creativity have been extremely limited up to this point. Up until recent times the greatest research contributions towards the field of creativity have come from psychology-based disciplines and it was only in recent times that cognitive neuroscience and neuropsychological research methodologies have been able to employ sophisticated neuroimaging techniques for creativity research. Indeed, intricate imaging technologies such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET) and neuroelectric techniques, e.g. electroencephalography (EEG), have broadened our understanding of creativity tremendously but have only been accessible in contemporary times.

Perhaps more optimistically, although creativity-focussed experimental research have maybe lacked testability and acquisition, the large variety of different approaches, methodologies and interpretations might serve as a quantifiable consolation. However, real-time testing of art or music creation and findings grounded in or during the actual live performance of music or creative expression seems almost mythical when exploring the literature. The more sophisticated technological involvement, as ground-breaking as it is, have yet to free creativity research from this bondage. Movement of participants need to be kept to an absolute minimum in order to get good resolution on imaging, while even just the idea of bringing a musical instrument close to an MRI machine would be critically abominating. Thus, there is a very clear gap, but also a strong need for research to move beyond the confines of the laboratory, yet reach still deeper into the mind of the artist, but in an environment and context where creativity can be observed not only through visualization or imagination, but through the actual making, doing and/or performing of art and, in context of this study, music.

Musical improvisation can, in some ways, be compared to the free flowing practises of e.g. freestyle painting or drawing, in that new and novel conceptions are shaped in a continuous and concurrent manner. Phenomena such as flow have been described in psychological literature as a state of consciousness where a person becomes so emerged in their doings that they experience an almost effortless, spontaneous and intuitive, yet highly focused state of conduct where their actions flow almost instinctively and is often associated with peak performance and positive affect. Strong associations have been established between flow and improvisation, creative intuition, spontaneous thought, peak performance and altered states of consciousness. However, neurophysiological research on flow is still only in its first decade of testing and understanding the physiological and neurocognitive foundations of flow has generated a great deal of interest in recent years. Dietrich [1] suggests that through the possible identification of the neurocognitive underpinnings of flow "…it becomes feasible to delineate it from other manifestations of exceptional human experience, for instance, creativity."

From the perspective of an integrative physiological and interdisciplinary approach we can further recognise that, in order to understand the workings of the brain we need to also acknowledge the impact of factors outside the central system and their influence on the CNS. Studying the deeper lying regions of the brain is extremely difficult, but by combining central and peripheral operatives (brain and body) we can look at brain functioning holistically as there is continuous communication happening between the brain and the peripheries. Such dialogues interaction between these systems can lend valuable insights into the control mechanisms, impact stimuli and affective relationships underlying complex behaviours such as creativity, insight, musicality or attentional control.

To serve as an example relevant to this study, meditation studies [2, 3] have yielded beautiful insights into the self-regulation of attention and emotional systems by combining the brain and body, showing how e.g. slowing ones breathing can induce cardiovascular changes and subsequently offer insights into the functioning of the brain stem and autonomic nervous system (ANS). Research in sleep EEG have also yielded further insights into the relationship underlying variability of the heart and its phasic relationship with different brain wave frequencies and associated changes within the brain.[4] It is essentially the amalgamation of these concepts: creative expression, musical performance, flow, physiological coherence, HRV and EEG that form the core of the present research undertaking.

HRV has been shown to be a resourceful, none-invasive method of measuring a multitude of cardiac pathologies, but can also lend insight into the status of autonomic regulation of the heart by the brain. Through the sympathetic and parasympathetic innervations to the heart, heart rate and tempo can be modulated and HRV can be used to assess such neurocardial interactions. Coherence analysis of heart and brain functioning have revealed dynamic relationships between HRV and EEG power bands and it is an aim of this investigation to examine the brain and heart functioning during the live performances of professional musicians.

It was expected that performers would experience such flow-like states during sessions of improvisation and the study intended to explore and analyse the physiological activity of the heart and brain and its associative relations with the subjective experience of flow while improvising on the piano. By utilising wireless measuring systems musicians could be tested in real-time during live recitals, offering a privileged insight into an unexplored sphere of creative expression and research.

1.2 AIM

The primary aim of the study was to do an exploratory, multi-modal physiological investigation of heart and brain activity during live music improvisation. Hemmed into this leading objective was the ancillary aim of investigating the possible occurrences of *flow* during performances and its associated psychophysiological characteristics and features within the data. In addition, the study attempted to establish rudimentary correlations and associations between frequency components of the EEG and heart rate variability data captured during improvisation and such flow-like states.

1.2.1 Objectives

The chief objectives of the study were as follow:

- First and foremost, to record EEG and ECG parameters in professional jazz musicians during real-time, continuous improvisation on the piano;
- To isolate and quantify frequency components of the EEG and HRV dynamics;
- To establish possible statistical and associative relations between variables during different stages and events of performances;
- To explore the possible occurrence of flow states during improvisation and potential representations within the data;
- To supplement the narrow existing knowledge base pertaining to the real-time music performance, improvisation and the neurophysiological underpinnings of flow;
- To investigate the utility and appropriateness of a wireless EEG system as research tool.

1.3 MOTIVATION FOR RESEARCH

Whilst combing the literature on the pertinent topics of this study it became evident that research pertaining to creativity - especially and more specifically during musical creativity and improvisation - alongside the application of EEG in this particular arena was severely limited. As will be discussed in the literature review (Chapter 2), real-time studies, which is to say the live testing of individuals during *actual* performance or improvisation, are very scarce, possibility due to technological constraints and the inability of existing research methodologies to capture accurate data during movement. In accordance, the lack of, but also the desperate necessity for research to be conducted on musicians *during* real, authentic music performances are stressed as one of the main motivations for this research. It is proposed that less direct and more commonly used approaches such as visualization, imagination, pre- and post-performance testing, and self-report can only marginally be regarded as true representation or accurate substitutions for neurocognitive activity occurring during such creative practices as improvising or other high performance states.

The wireless technologies and equipment utilised in this study allows for greater freedom on behalf of the researcher to investigate phenomena that, until recent times, might have fallen outside the jurisdiction of currently available research tools. Wireless EEG systems carry the benefit of being portable, inexpensive and user-friendly alternatives to its clinical counterpart, allowing much greater mobility and far lesser restrictions relating to movement, setup, preparation, cleaning and time requirements. Additionally, the use of such portable systems allow the investigation of such performances to occur in what could be considered more natural and conducive environment for creative expression, such as a performance hall or music room as opposed to the cold, sterile environment of the laboratory. Musicians will be able to move freely whilst performing, playing their respective instruments in an environment that better suites their creative demeanour and outlook, with far lesser intervention from the researcher or research equipment, allowing a greater sense of creative freedom.

The construct of flow is also addressed in this study and as will be discussed, neurophysiological research on flow is still only in its first decade of testing and the current research undertaking attempts to substantiate this incipient field of research. Linking EEG and HRV has also emerged in recent times as a growing field of interest, however such research has mainly been conducted during sleep or meditation studies. Nonetheless, such studies have rendered inspiring insights into the coherence and synchronization between these two oscillatory systems in human. The study explores the dynamic interplay of EEG and HRV variables during flow states, and therefore in more conscious, alert conducted, but which has also been described as trance-like. To the knowledge of the investigator this approach is novel and has not been described before.

Therefore the main motivations supporting this study lie in the following:

- The lack of research on creativity and/or music during *real-time* performance, which, once more, can be mimicked, but not purely substituted by in-direct measures;
- The shortage of EEG and other research within the context of music creativity and improvisation specifically;
- The testing of musicians in a more naturally conducive environment in order to facilitate greater creative expression (outside the lab);
- The supplementation of knowledge to a relatively new field of research regarding the physiological foundations of the flow experience;
- The use and evaluation of novelty EEG technology as a research tool and alternative for the testing of scenarios that have proven difficult to equate;
- A better understanding of the interrelations between brain and heart during creative and high performance behaviour, and the potential for development toward neurofeedback, music therapy and music practise protocols.

1.4 OVERVIEW OF CHAPTERS

All introductory and ancillary sections pertaining to the aims, objectives and content of the document has been put forward in this chapter (**Chapter 1 - Introduction, objectives and motivation of the research undertaking**).

Chapter 2 - Introduction to the physiology of the heart and brain within the context of music, creativity and flow research.

- Discusses the literature background to the study and its themes. Heart rate variability is defined through its physiological control and regulatory mechanisms and methods for analysis. Electroencephalography is also discussed accordingly, with specific focus drawn to the electrophysiology of the brain and signal generation, recording and conditioning for analysis. The chapter continues to discuss these themes within the broader literatures of creativity, improvisation and flow research.

Chapter 3 - Research approach and methodological outline.

- Outlines the approach and methods employed in the study to record, analyse and quantify heart and brain related variable. The preparation, procedure and sample population are described, following an outline of the data analysis and statistical implementations.

Chapter 4 - Research outcomes and results.

- Reports the results and findings of the data analysis. The process of analysis and statistical methods are discussed in greater detail within the overreaching and systematized perspectives employed by the study. Technical specifications are stated, before the outcomes and graphical representations of the analysis are presented accordingly.

Chapter 5 - Integrated discussion, conclusion and prospective research directions.

- Presents an integrated discussion of the results within the wider context of music creativity and other significant research areas. The findings and outcomes of the study is contextualised and expanded as the chapter concludes with the study limitations, and recommendations for further research.

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Chapter 2

Introduction to the physiology of the heart and brain within the context of music, creativity and flow research.

There's a certain groove you pick that makes the music flow, and when you have it it's in your pocket. It's the feeling behind the rhythm... to me, the hardest thing to strive for is that feeling, behind the groove.

Max Weinberg

A literature and background review on the existing knowledge base pertaining to heart rate variability, electroencephalography and the interaction of these two oscillatory systems within the body are presented in this chapter. The relativity and contextual overview of these parameters are discussed within the broader field of creativity research and more specifically within the context of flow and its physiological underpinnings.

2.1 HEART RATE VARIABILITY: FROM ATRIUM TO ANALYSIS

2.1.1 Defining heart rate variability

The cyclic activity of the heart is responsible for the phasic and periodic nature of blood circulation within the body. The length of a heart cycle is often referred to as the heart period and is inversely proportional to the heart rate (HR). HR demonstrates small fluctuations between cycles and is not a consistent measure, instead showing slight variations between beats due to the interactive nature of interaction between the heart and brain. Heart rate variability (HRV) is this beat-to-beat alteration in the heart's sinus rhythm, i.e. the time variation between consecutive heartbeats (R-R intervals), that describe the oscillations of consecutive heartbeats.

HRV has been shown to be an important indicator of physiological resilience and behavioural flexibility according to systems-oriented models and reflects the capacity of the heart to adapt to stressful and environmental demands. It is highly important for biological systems to maintain a high degree of variability as it is thought that many phase transitions often occur at certain 'critical values when variability is high'[1]. Analysis of HRV has shown to be an effective, significant and non-invasive measure to quantify and assess cardiovascular health and autonomic regulation[2] with numerous papers having been published on HRV-related cardiological health assessment methods.[3]

2.1.2 The physiology of HR modulation and variability

Initiation of the heart beat originates from the sinoatrial node (SA node) at the posterior wall of the right atrium of the heart. Unstable membrane potentials of the adapted myocytes within the heart tissue give rise to spontaneous action potentials that propagate through the heart and cause systematic contraction of its muscle fibres resulting in a heartbeat.

Physiological regulation of heart rate is complex, involving many overlapping control mechanisms that directly or indirectly influence the autorhythmicity of the SA node with the principal aim of maintaining homeostasis. This is because many factors, intrinsic and extrinsic in nature, act on the heart and blood circulation, requiring the heart rate to adapt in an effort to preserve and achieve stability. The concept of allostasis refers to this ability to maintain stability through change.[4]

Although the automaticity of the heart is intrinsic to a variety of pacemaker tissues, chief control of heart rate and rhythm resides with the autonomic nervous system (ANS). The balancing actions of the sympathetic and parasympathetic innervations to the heart, monitor and adjust the HR according to a supply and demand rapport (Figure 1).

2.1.2.1 Autonomic control of the heart

The variability and fluctuations of HR can largely be attributed to changes of the autonomic input to the SA node.[5] The ANS, as the name suggests, controls the automated functioning of e.g. blood and lymphatic vessels, smooth muscles and visceral organs. Under control of the central nervous system (CNS) it also interacts with the somatic nervous system[6] and consists of two divisions namely the parasympathetic nervous system (PNS) and the sympathetic nervous system (SNS). By altering the activity of cyclic AMP second-messenger systems within the cardiac cells[7], heart rate is modified through these innervations and the antagonistic interactions occurring between the PNS and SNS.

These two divisions of the ANS are anatomically distinct, functionally different and release different neuromediators from their respective postganglionic nervous terminals. It has been suggested that differentiation of the characteristics of parasympathetic and sympathetic mediated HR fluctuations can be attributed to the difference in response to their respective neurotransmitters by the nodal tissues in the heart.[8] The degree of variability in HR lends insights into the net effect of the PNS and SNS on the heart and also the heart's ability to adapt and respond to unpredictable stimuli.

2.1.2.2 Parasympathetic nervous system (PNS)

Parasympathetic influence on HR is facilitated through the vagus nerve (cranial nerve X). The PNS postganglionic fibres insert into the atrioventricular node (AV node), SA node, atrial and ventricular musculature and coronary vessels, however there is only a sparse amount of parasympathetic innervation of the ventricles.[7] Parasympathetic influence on heart rate is mediated through the neurotransmitter acetylcholine which, upon release from the vagus nerve, slows the rate of depolarization of the SA node by binding to the muscarinic receptors and reducing activity of the cyclic AMP pathway through inhibitory G proteins. Through this mechanism weaker atrial contractions and decreased conductivity of cardiac cells results in cardio-deceleration[3] and a reduction in heart rate.[2, 6]

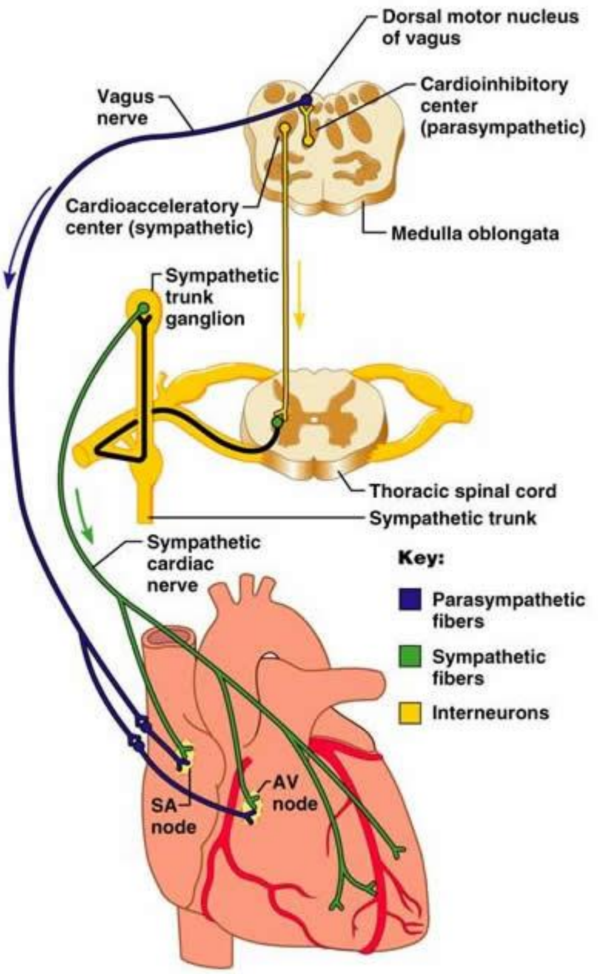

Figure 1: Autonomic innervations to the heart [118] *showing sympathetic and parasympathetic innervations to the different nodes (SA and AV) of the heart.*

Vagal stimulation of the heart is followed by a rapid response, drawing its maximum effect at approximately 0.5 seconds. Return to baseline takes less than one second and is subsequently followed by a slower rebound along the direction of decreasing R-R intervals.[9] Studies have shown that sympathetic influences on cardiac regulation are much slower than vagal influences[10] and that a decrease in fast vagal modulation leads to a worsening of the heart's ability to respond appropriately to environmental demands.

2.1.2.3 Sympathetic nervous system (SNS)

The SA node, atria, ventricles, conduction system and coronary vessels are just some of the structures of the heart that are innervated by the efferent nerve fibres of the SNS. The heart's response to sympathetic stimulation is slightly slower than parasympathetic stimulations, and is typified by a time delay of roughly one second, with a maximum decrease in RRI occurring within four seconds and a return to baseline taking up to 20 seconds.[9]

Mediation of sympathetic influence on HR occurs through the release of adrenalin and noradrenaline which increases the speed of the sinoatrial rhythm through a beta1-receptor-mediated second messenger system.[9] Such beta-adrenergic receptor acceleration increases the rate of slow diastolic depolarization which accelerates the heart rate.[2]

Through the process of syntaxis sympathetic intensity can be redoubled through positive chronotropic and inotropic effects, i.e. increased force of contraction and increased impulses to the heart.[11] In addition, impulses from the sympathetic nerves also secrete a co-transmitter from their terminals in the form of neuropeptide Y which serves to inhibit the parasympathetic nervous activity.[6]

2.1.2.4 Higher modulation of heart rate

Due to the fact that control of HR resides mainly with the autonomic input to the heart, HRV analysis offers valuable insight into not only autonomic functioning of the SNS and PNS but also assessment of the 'autonomic balance' of the ANS.[4] At any given moment, HR is determined by this balance between the stimulating effect of the SNS and inhibitory effects of the PNS. Under resting conditions vagal tone dominates, with variations of the heart period mainly dependant on vagal modulation despite the high concentration of acetylcholinesterase within the sinus node and the consequential rapid hydrolysation of acetylcholine.[12]

Coordination of the activity of these two branches of the ANS occurs within the cardiovascular control centre in the brainstem,[7] however control of these two outlets are not always reciprocal and variations of their functioning can be independent and might also demonstrate co-activation or co-inhibition.[13] HR modulation, heart rhythm and contractibility involves several higher control centres inside the medulla oblongata, cortical and diencephalic centres (inner-brain), cerebral cortex, thalamus and hypothalamus.[6] The vasomotor centre, located in the medulla oblongata, compromises of both vasoconstrictor and vasodilator areas that exert their effect on HR through the vagal and sympathetic innervations of the heart. By reducing muscle contractibility and peripheral resistance, the depressor area of the vasodilation centre decreases the HR through vagal stimulation.[12] The pressor area within the vasoconstrictor area produces a reciprocal influence on the depressor area through increased sympathetic neuronal activity to the heart, accompanied by decreased tonic activity of the vagal fibres.[6]

The autonomic centres in the brain stem are also associated with the cerebral cortex through involvement of the hypothalamus. Communal connections from the hypothalamus to the vasomotor centres can increase blood pressure in response to emotions like anger [6] while structures such as the diencephalic and cortical centres can also initiate cardiac reactions in response to emotional states such as anxiety and excitement.[6] The hypothalamus however controls many vitally important conditional and unconditional reflexes associated with functioning such as breathing, metabolism and circulation. The paraventricular nucleus located in the hypothalamus is also likely to play a central role in facilitating circadian rhythms of the ANS.[7] Therefore it is expected that hypothalamic stimulations would result in variation of the HR.

Other centres such as those in the thalamus will result in tachycardia (increased HR) upon stimulation, while those areas of the cerebral cortex that can effect cardiac functioning include the anterior temporal lobe, frontal lobe, insula, orbital cortex, cingulate gyrus, pre-motor and motor cortex.[14]

2.1.3 Factors affecting HRV

Intrinsically, cardiac contractions are modulated by a variety of pacemaker tissues which is then further regulated by other extrinsic factors. Intrinsic factors that can impact HRV include thermoregulation, circadian rhythm, neuroendocrine secretion, baroreceptor reflex activity and respiratory sinus arrhythmia [15] while extrinsic factors like changes in posture, activity, arousal and stress can also affect HR. Such intrinsic and extrinsic influences are reflected through the autonomic neural regulation of the heart by the synergistic action of the sympathetic and parasympathetic axis, as discussed.

2.1.3.1 Baroreceptor reflex

The baroreceptors (stretch receptors) in the walls of the blood vessels and heart react to distension and their afferent nerve fibres travel to the medulla via the aortic and carotid sinus nerves. There is a direct proportional relationship between the frequency of action potential generation in the baroreceptors and the changing pressure within the structure which they are located in.[16] Increased discharge of the baroreceptors results in bradycardia due to its stimulation of the vagal heart innervations and reduction of the tonic discharge of the vasoconstrictor nerves.[6] When analysing the power spectrum of HRV within the frequency domain, the lower frequency bands are associated with baroreceptor activity.[17]

2.1.3.2 Endocrine influences

It has been shown that several hormones and endocrine factors can affect HRV including reproductive hormones, thyroxine, steroids and the renin-angiotensin system.[4, 16] Quantitative data on HR responses within the time and frequency domain pertaining to hormonal modulation is limited, but evidence of non-autonomic control of HR has been gathered mostly from HRV recordings of heart transplant patients prior to sympathetic reinnervation.[9] Results from these patients suggest that HR hormonal control is only active at frequencies lower than 0.03 Hz. HRV analysis in this regard will therefore not be biased by hormonal influences and should not be of concern.

2.1.3.3 Thermoregulation

Temperature fluctuations is a significant source for HR changes.[4] Fever increases HR and with every 1°C increase in body temperature HR increases with roughly 18 beats per minute.[11] Conversely, a decrease in body temperature results in a decrease of HR such as in methods used during heart surgery where the heart is cooled. With decreased temperatures, HR keeps slowing until body temperature reaches 15.5 – 21.2 °C where death as a result of hypothermia becomes a serious risk.[6] Temperature effects on HRV is not only mediated through the ANS but can directly impact the pacemaker activity of the SA node [4] and thermal regulation of HRV should therefore always be considered when HRV experiments are conducted.

2.1.3.4 Respiratory sinus arrhythmia

During inspiration HR typically accelerates and conversely slows down during expiration. Respiratory sinus arrhythmia (RSA) reflects this coupling between autonomic neural outflow and breathing. RSA is primarily mediated by respiration-driven gating of parasympathetic influence on the heart and the exact phase relationship between HR and respiratory oscillations is dependent on the respiration rate (BR).[18] RSA therefore reflects the rhythmic ‘waxing and waning of cardiac vagal efferent effects’ on HR and upon the SA node [19] and vagal efferent outflow to the sinus node fluctuates in phase with expiration.

A linear relationship exists between parasympathetic cardiac control and the degree of RSA [20] and RSA is thus a vagally-mediated modulation of HR that is related to respiration. Such HR variations trail the respiratory rate across a range of frequencies and its upturn reflects an increase in PNS activity. Because RSA is facilitated by vagal activity fluctuations, indexing of the respiratory frequency band (ranging from 0.15 Hz to 0.4 Hz) can be used to measure vagal activity.

Here within we see the dynamic relationship that exists between the cardiovascular and respiratory systems. Both parasympathetic and sympathetic nerve trafficking fluctuates with respiration, but the time constant for fluctuations of the sympathetic tone to affect HR is too long to affect HR at normal breathing frequencies. However, corresponding changes of increased restorative parasympathetic influence on the cardiovascular system have been shown to occur during slower breathing rates.[21, 22, 23] In conjunction, slowed breathing patterns also correlate with increased synchronisation, i.e. RSA [24, 25] and the ratio of MF/(LF + HF)[a] can be used to approximate heart coherence and may further predict high quality, stable meditative states.[23] Such heart coherence states, as described through RSA can therefore be achieved easily through slow diaphragmatic breathing, as in the case of e.g. meditative practises.

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[a] LF= lower frequency; MF= medium frequency; HF= higher frequency ranges of HRV analysis.

2.1.4 Analysis of HRV

Long before modern constructs such as HRV was developed physicians already recognized the importance of cardiac sounds, rhythms and beat-to-beat rhythm shifts related to illness, ageing and psychological states. [11] Although initial methods for heart rate pattern analysis was limited to auscultation, the technology for analysing and quantifying the electrical activity of the heart has progressed tremendously. Starting with the galvanometer, the kymograph and polygraph followed, where after the electrocardiogram was developed and now digital signal processing systems are playing a very prominent role in analysis of the heart and its rhythms and electrical activity.[9]

Acting upon a growing suspicion amongst clinicians that a significant relationship existed between ANS activity and cardiovascular mortality, experimental evidence for this observation came into being through the analysis of HRV which showed to be the most promising quantitative marker for autonomic activity.[2]

In electrocardiography (ECG) the R-wave of the central waveform (QRS-complex) is easiest to identify and is used to derive the HRV data.

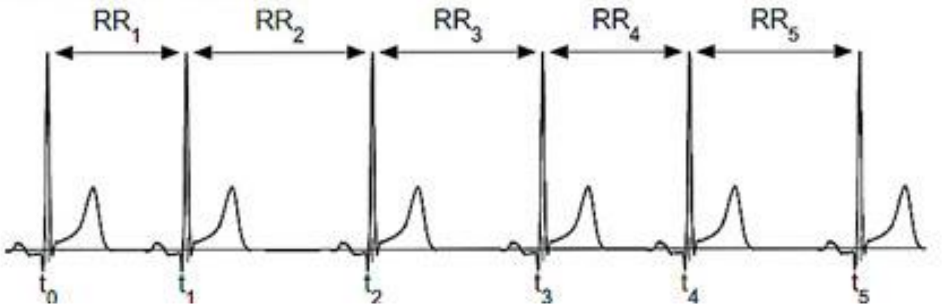

Figure 2: Variation of beat-to-beat intervals (R-R intervals) in the QRS-complex

The original method of assessment of HRV was through manually calculation the mean R-R intervals and its standard deviations over five minute electrocardiograms (short-term).[9] Smaller standard deviations in R-R intervals therefore equates to a lower HRV. Presently, detection and evaluation of RRIs can be done digitally.

A report published in 1996 by the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology[2] presented important guidelines towards the standardization of HRV analysis. These guidelines were followed in the technique evaluation and HRV analysis in this study.

2.1.4.1 Time domain analyses

(No time-domain parameters were incorporated in this study and are therefore only briefly explained for informative resolve.)

Time-domain measures are calculated from the raw beat-to-beat interval time series and is the simplest of the HRV factors to compute and can be done through statistical or geometric methods. In such calculations the interval length between successive R-R intervals are determined but can also be used to determine HR at a certain point in time. In essence the time-domain parameters measure the amount of variability and by the year 2002 more than 26 different methods of arithmetic manipulations of R-R intervals had been reported.[26]

Many time-domain measures are closely correlated with each other. The following time-domain measures were some that were recommended by the Task Force of the European Society of Cardiology: [2]

- SDNN (standard deviation of all normal R-R intervals) and HRV triangular index
  - For estimation of overall HRV;
- SDANN (standard deviation of the average normal R-R intervals)
  - For estimation of long-term components of HRV;
- RMSSD (square root of the mean differences between successive R-R intervals)
  - For estimation of the short-term components of HRV.

2.1.4.2 Frequency domain analyses

The total variance in HR can be partitioned into underlying rhythms that typically occur at different frequency ranges. These different frequencies are associated with different underlying intrinsic rhythms and physiological factors that are involved in HR regulation [9] and these oscillations and their power outputs can be determined through frequency domain analyses.[2] Spectral analysis of such HR fluctuations can provide valuable information regarding autonomic functioning and are identified as following:

- ULF (ultra-low frequency) band – can occur under 5 minutes to once in 24 hours. (0.0001-0.003 Hz);
- VLF (very-low frequency) band – cycles approximately every 20 sec - 5 min. (0.003-0.04 Hz);
- LF (low frequency) band – cycles approximately every 8 – 10 seconds (0.04 – 0.15 Hz)
- HF (high frequency) band – at respiratory frequencies, 9 - 24 cycles/min (0.15 – 0.40 Hz).

Power spectral density (PSD) can be derived through mathematical transformation of HRV data [Fast Fourier Transformation (FFT) as non-parametric, or autoregressive (AR) time series modelling as parametric method]. This can be used to differentiate sympathetic and parasympathetic influence on the heart through quantification of the relative power of these constituent frequency components of the HRV signal. The SNS and PNS operate upon the heart at distinct frequencies and their separate rhythmic contributions modulate the R-R intervals of the QRS complex.[3]

PSD provides information about power distribution (variance) as a function of frequency.[2] In a PSD graph the area (ms^2) under the frequency curve represents the respective power of the spectral components (Figure 3).

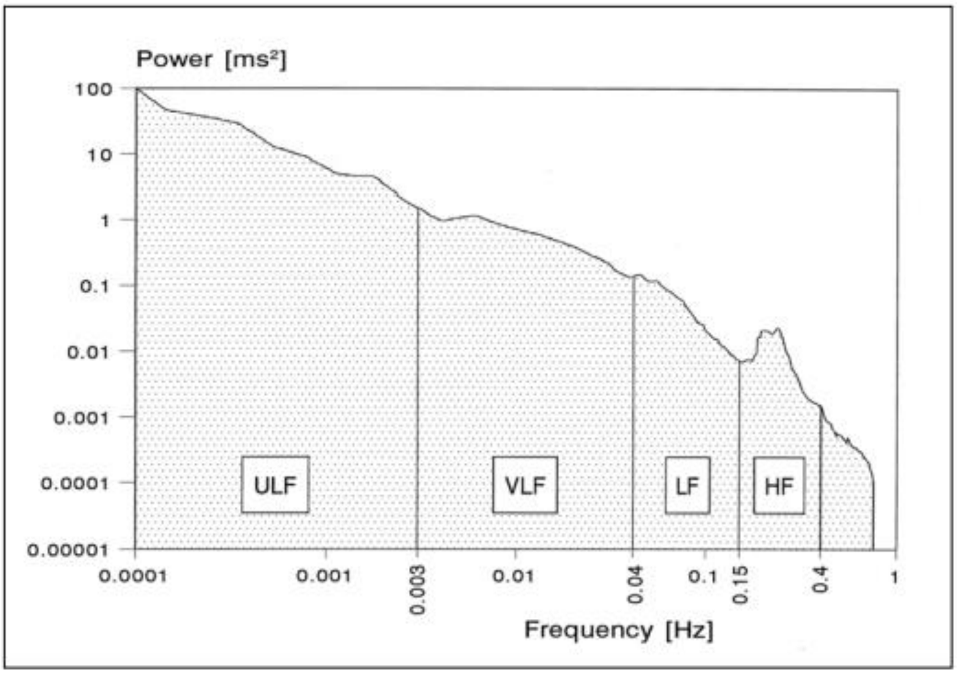

Figure 3: PSD graph showing the different power bands and their relative power.[2]

Ultra-low frequency (ULF) band activity

The ULF band oscillations are significantly influenced by the ANS, typically reflecting circadian rhythms [27] and a down-turn in ULF has been shown to be a strong predictor of mortality in e.g. fibromyalgia.[9] The ULF and VLF rhythms of HR may have psychophysiological correlates and clinical application; however the literature is ambiguous.[28]

Very-low frequency (VLF) band activity

VLF band oscillations have been linked to thermogenesis, periodic breathing and changing vasomotor tone in response to metabolic and thermoregulatory needs, but can also be affected by hormonal systems e.g. renin-angiotensin systems (dampens VLF power).[4] Additionally, VLF fades when parasympathetic activity is blocked and can therefore be used as indicator for parasympathetic abnormalities.[16]

Low frequency (LF) band activity

According to the standardisation criteria put forth by the Task Force of the European Society of Cardiology [2] the LF component directly reflects sympathetic activity upon the heart, however evidence have been brought forth that LF is also under notable influence from the PNS, baroreceptor feedback and other centrally generated rhythms from the brainstem.[3, 4, 29] LF is therefore not an unalloyed reflection of sympathetic activity but rather reflects a blend of both para- and sympathetic influence, though skewed towards sympathetic dominance.

In order to acquire a more reliable index for sympathetic activity, some researchers have proposed it necessary to normalize the LF component (discussed later) where after the normalized HF component can be subtracted to exclude parasympathetic influence.[30] A medium frequency range (MF = 0.08 – 0.15) has been put forth in other studies [23] with LF and HF ranges shifting to 0.01 – 0.08 Hz and 0.15 – 0.5 Hz respectively, allowing deeper interpretations into the baroreflective feedback arising from the MF expanses (0.1 Hz). In addition, MF power relative to that of LF and HF ranges are said to be highly reactive to changes in emotional states.[31]

High frequency (HF) band activity

Unlike the SNS which only truly operates at frequencies lower than 0.1 Hz, the PNS operates at a wider range of frequencies (0.15 – 0.4Hz), implying that the total power of high frequency oscillations, i.e. faster alterations in heart rhythm, is a solitary reflection of vagal activity and operates in phase with the respiratory frequency (RSA).[4, 19, 30] The fact that HF is affected by BR means the spectral power of HF is also affected, however the mean R-R intervals remain nearly constant across all different respiratory frequencies and this consistency can therefore be taken as evidence for the steadiness of vagal-cardiac traffic.[32] Given the fact that HRV is derived from ECG, it is not possible to distinguish between reduced vagal activity arising in the vagal centres of the brain or a reduction in peripheral activity as contributed by the sinus node or afferent/efferent conduction pathways to/from the brain.[32]

2.1.4.3 Filtering of HRV data

It is critically important to the integrity of any data set that adequate artifact removal is performed for unbiased analyses. The most common artifacts that arise in HRV analysis is that of missed beats. Fortunately, by restoring the original R-R series the removal of missed beats results not in any loss of information. However, the removal of any abnormal or ectopic sinus beats does involve loss of information and this is evidently more problematic. By using RR statistics or an autonomic filter the problem can be rectified by inserting upper and lower bounds so that any R-R interval may not differ by more than 20% from its previous intervals. Such methods make it possible to identify and replace or exclude outliers from the data analysis based on estimations of the R-R probability distributions.[5, 30] Detrending methods (e.g. Niskanen et al.[33]) and artifact correction methods make it possible to smooth out erroneous or distorted data end points.

2.2 ELECTROENCEPHALOGRAPHY: FROM CORTEX TO CONDITIONING

2.2.1. Defining electroencephalography

The electroencephalogram (EEG) is a valuable and uniquely developed measuring system of the electrical activity of the brain, first reported in humans by Hans Berger (1873 – 1941) in 1929. The EEG allows one to observe the oscillatory rhythms of electrical activity of the brain often referred to as brainwaves.[34] The brain does not have inherent brainwaves, instead the EEG picks up the stream of electrical activity of neuronal activation on the brain's surface through electrodes (leads) and can be described as a simple method to measure the underlying summed postsynaptic electrical activity of the cortex on the surface of the scalp. It provides a graphic display of brain function by plotting the potential difference between positive, negative and proximal electrode sites (depending on the montage utilised), recorded over time.

Electroencephalography (EEG) is therefore the study of recording such electrical oscillations generated within the brain and can be done either extra- or intracranially. Extracranial EEG produces an across-the-board survey of electrocerebral activity in both hemispheres of the brain by strategically placing electrodes on the scalp (its conductivity enhanced by an electrode paste or other form of conductive medium). Alternatively, intracranial EEG, performed by surgical implantation of electrodes, provides focused recordings from targeted sites directly from the brain.

From the scalp to the electrodes (positive leads), the signal further propagates through the connected wires to an electrode board where it is amplified and routed to a computer or feedback device. In addition, one electrode (negative lead) is placed on either side of the head on an electrically inactive site (customarily the mastoid bone behind the ear or on the earlobes) to serve as reference against which the activity at each of the positive leads can be reflected. The raw waveforms observed through EEG show the wave's morphology (shape), amplitude (height from peak to trough) and frequency (waves per second, measured in Hertz).[35]

It is the clinical application of EEG and its findings that impart its greatest utility, but the EEG is also a practically valuable and inexpensive research tool. Added that it can be set up in a non-medical environment it remains a very useful tool in research and clinical settings to date.

2.2.2 Signal generation and electrophysiology of the brain

2.2.2.1 The neuronal makeup and membrane

At birth approximately $10e^{11}$ neurons exist in the human brain when the central nervous system (CNS) becomes fully functional,[36] averaging at $10e^{4}$ neurons per cubic mm. In the average adult there would exist approximately $5 \times 10e^{14}$ synapses which interconnect neurons with each other to form neural nets.[36] The number of neurons in the brain decreases with age, but the number of synaptic junctions per neuron increases as a person gets older.

Looking at the brain from an anatomical point of view it consists of three main parts: the brainstem, cerebellum and cerebrum. The highly convoluted surface layers of the cerebrum is what is referred to as the cerebral cortex. The cerebrum contains regions related to higher functions such as conscious awareness of sensory input, complex analysis, emotions, behaviour and movement initiation, whereas the brainstem is concerned more with involuntary functions such as heart regulation, respiration biorhythms and hormone secretion. The cerebellum is almost exclusively involved with coordinated voluntary movements of skeletal muscles and balance.

The CNS in general consists of nerve cells (neurons) and glial cells (supporting cells located between neurons) and activities in the CNS relate mainly to currents transferred between the junctions (synapses) of axons and dendrites of these neurons (Figure 4). Each nerve cell consists of a cell body (soma), dendrites (branching processes) and an axon (main process). The cell body of the nerve has a single large nucleus and houses most of the metabolic activity occurring within the cell, especially related to protein synthesis. These proteins (e.g. neurotransmitters) are transported to other parts of the nerve cell by means of tubulin rails which also maintain the shape of the soma.

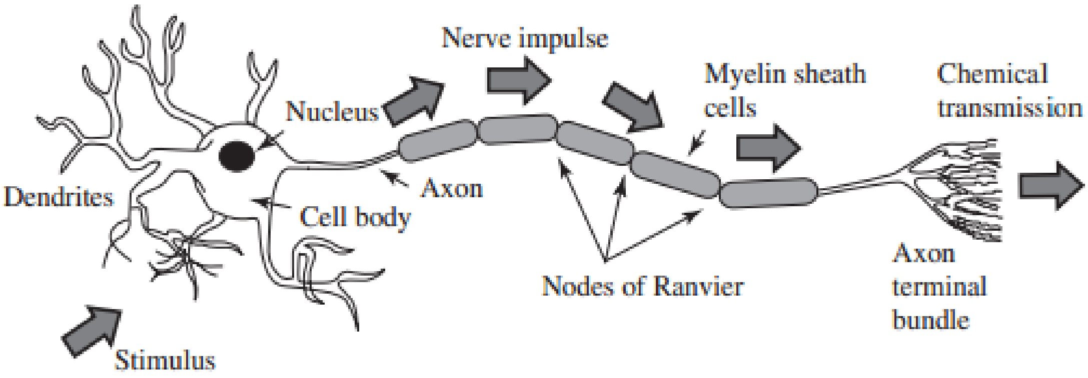

Figure 4: The structure of a neuron.[32]

The axon is cylindrically shaped and carries the purpose of transmitting nerve impulses from the soma to other cells. In humans, the axon can be anything from a percentage of a millimetre to more than a metre in length. The dendrites connect to the axons or dendrites from other cells in order to relay or receive signals. In the human brain a single nerve cell can be connected to upwards of 10,000 other neurons, mostly through such dendritic connections. The large surface area provided by these dendritic connections facilitate the reception and propagation of multiple signals from attached neurons.

Recorded EEGs from the scalp's surface represent pooled electrical activity that is generated from a large number of neurons with modest contribution from the glial cells. The nervous system's intrinsic electrophysiological properties and the time-varying ionic currents generated in the neurons form the origin of cerebral potentials in the brain and can be recorded using electrodes at short distances (local field potentials, LFPs) or longer distances (from the scalp, i.e. the EEG) from the source. These ionic currents are produced at cellular membrane level (transmembrane currents) and it is possible to distinguish between two main forms of neuronal activation [37] namely:

- Fast depolarization of the neuronal membrane – mediated through sodium and potassium voltage-dependent ionic conductance. (Action potentials)
- Slower membrane potentials changes - mediated through synaptic activation by neurotransmitter systems. (Synaptic activation)

2.2.2.2 Fast depolarization of neuronal membranes

Through the efflux of positively charged potassium ions (K^+) the neuronal membrane is able to maintain an electrochemical equilibrium and thus a resting membrane potential at -75 mV. The axon membrane is covered with integral ion channels that allow the passage of ions across its surface. When depolarization occurs, voltage-gated channels within the lipid bilayer of the membrane open[b] and an influx of sodium ions (Na^+) occurs due to the intra- and extracellular ionic gradient, exceeding the normal electrochemical resting state.

If this applied voltage, or stimulus, is high enough to breach threshold the result is a transient reversal of the membrane polarity as the intercellular potential suddenly shifts from negative to positive (depolarization) and rapidly returns to resting potential (1 to 2 ms) allowing the generation of what is called an action potential (Figure 5). The action potential (AP) has the remarkable ability to propagate across dendrites and axons without any loss of amplitude. Furthermore, the shape of this AP and its rate of

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[b] Closure of these channels is time dependant

travel along the axon occur at a rate independent of the initially applied voltage as AP generation is an all-or-nothing event occurring at a distinct threshold. In humans, the amplitude of the AP can lie somewhere in the range of approximately -60 mV to 10 mV.

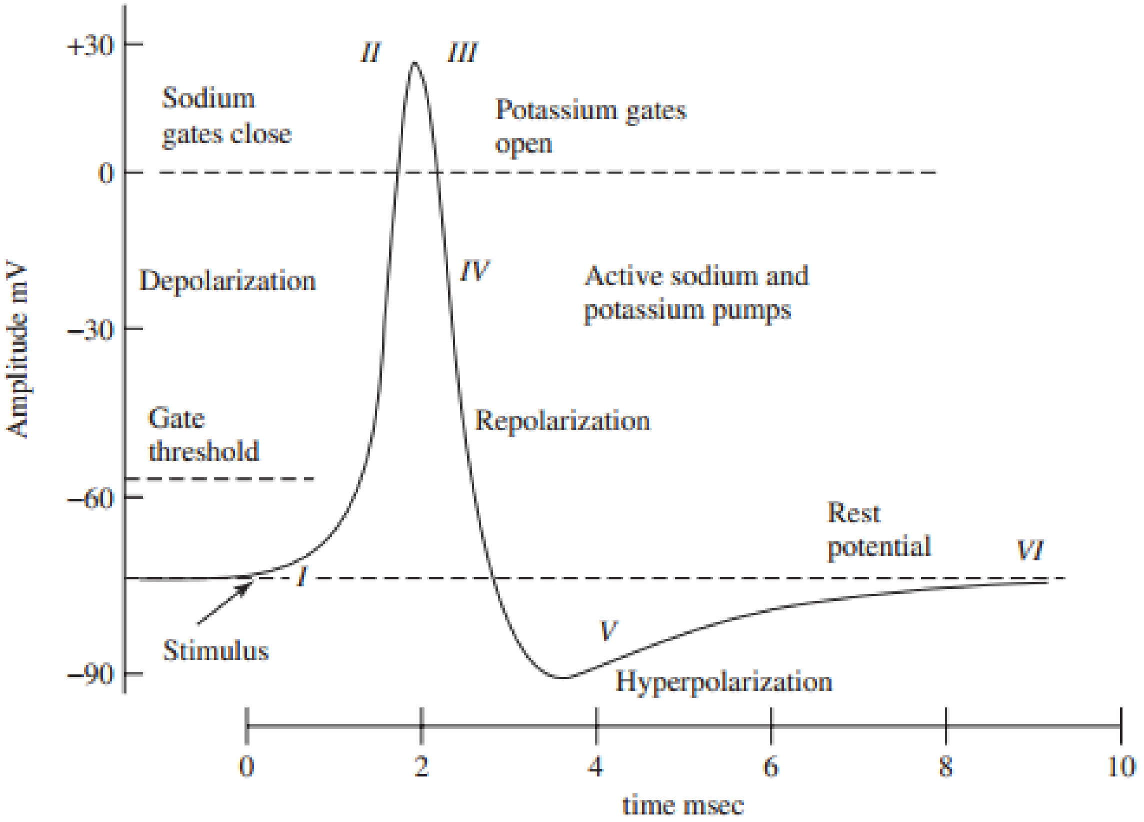

Figure 5: The stages and associated membrane potential fluctuations of an action potential *as measured in a giant squid neuron [adopted from (34)].*

In summary the process of AP generation is as follows: [38]

I. Upon receiving the stimulus Na$^+$ channels in the dendrites open, driving the internal potentials higher. If this opening is enough to raise the membrane potential from -70 mV to -55 mV, the process will continue (threshold).

II. The moment the action threshold is breached, more Na$^+$ channels open, causing an influx of Na$^+$ and raising the interior membrane potential up to 30 mV (depolarization).

III. The subsequent closing of Na$^+$ channels and opening of K$^+$ channels (slower to open) allows completion of the depolarization, while the opening of K$^+$ channels now allows the membrane to repolarize in the direction of its resting potential (repolarization).

IV. During repolarization, these ionic fluxes typically overshoot the resting potential to approximately -90 mV, called hyperpolarization. Hyperpolarization therefore raises the threshold for any immediately following stimuli, preventing the neuron from receiving another stimulus and subsequently generating a new AP. This also prevents any impulse already travelling across an axon from eliciting another AP in the opposite direction.

V. Following hyperpolarization the membrane potential returns to -70 mV by means of Na^+/K^+ pumps re-establishing the ionic gradients collaterally along the membrane.

2.2.2.3 Slower membrane potential changes

Communication between neurons occur by means of synaptic transmission which can be either electrical or chemical. The term synapse refers to the junction between two excitable cells where communication occurs. The greatest percentage of neuronal synapses in the CNS are chemical synapses, which are specialized structures enabling the chemical transfer of information between cells. Typically at these chemical synapses, the terminal of the presynaptic axon swells to form what is called a bouton. A synaptic cleft (gap) exists between termini as the bouton does not physically touch the postsynaptic terminal, but is in extremely close proximity (20nm).

This fluid-filled gap prohibits the direct transmission of the electrical impulse from one cell to the other. Instead, rapid diffusion of neurotransmitters across the synaptic cleft (released into the gap when an action potential travelling across the axon reaches the synapse) is how the nerve impulse is transferred to the postsynaptic cell. This may generate either an excitatory post-synaptic potential (EPSPs) if it ends in an excitatory synapse or inhibitory post-synaptic potentials (IPSPs) if the action potential reaches an inhibitory synapse. If subsequent action potentials, separated by only a short distance, travel along the same fibre a summation of EPSPs occurs.

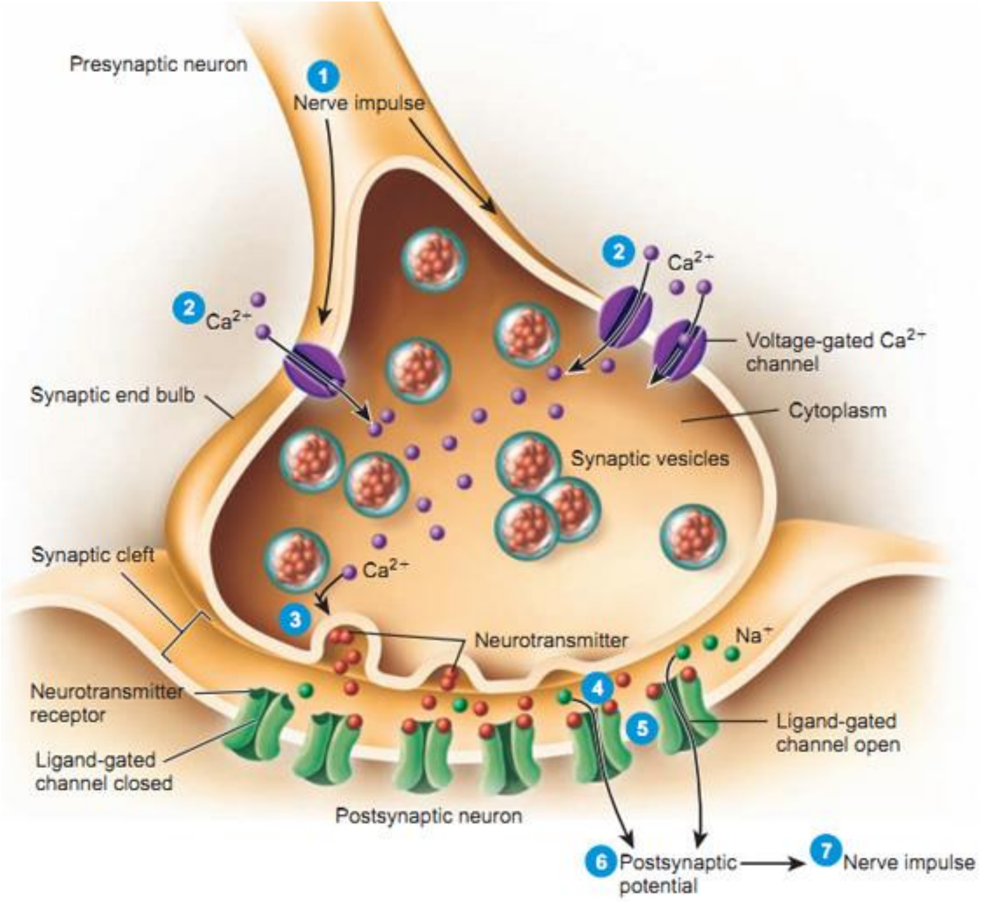

Figure 6: The synaptic junction showing neurotransmitter release into the cleft in propagation of the action potential arriving at the presynaptic terminal to the postsynaptic neuron.[120]

EPSPs flow inwardly (sinks) to other parts of the cell by means of calcium and sodium ions (extracellular to intracellular), whereas IPSPs flow outwardly (source) involving potassium and chloride ions. It is these summed potentials that form the greatest source of extracellular current flow; longer in duration (slower) than action potentials they are responsible for the majority of EEG waveforms of which the major contributor of such synaptic potentials are the pyramidal cells layered in the cortex.

Areas >6cm^2 are required for measurements at the scalp's surface, however due to the attenuating properties of the skull, an area >10cm^2 is required for the scalp EEG to show most IEDs (interictal epileptiform discharges). The thalamus and brainstem act as "*subcortical generators to synchronize populations of neocortical neurons in both normal (i.e., sleep elements) and in abnormal situations (i.e., generalized spike-and-wave complexes*".[39] The term 'volume conduction' hereby describes the process of current flow from the generators in the brain and the recording electrodes and therefore the EEG displays the continuously changing voltage fields across different locations on the scalp.

As described in the previous sections, an EEG signal is therefore a measurement of the current flow occurring during synaptic excitations of neurons, and more specifically their dendrites, in the cerebral cortex. These currents generate electrical fields over the scalp, created by the dipoles between the soma and apical dendrites of the neurons that are caused by such summed postsynaptic graded potentials and are measurable by scalp electrodes.

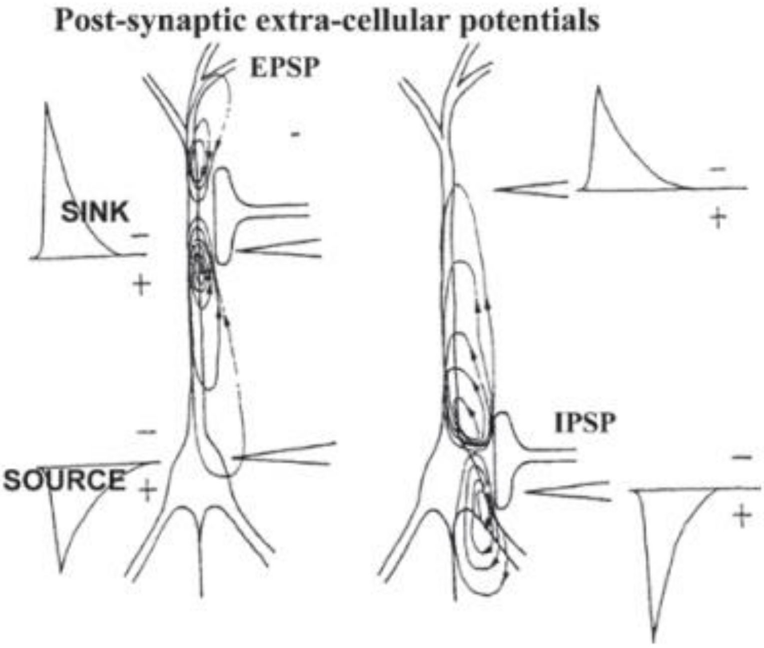

Figure 7: An outline of a cortical pyramidal cell displaying the pattern of current flow caused by excitatory and inhibitory synaptic activation. *The apical dendrites of these cells are typically oriented towards the surface of the cortex. Current flow arising from an activation of an excitatory synapse (EPSP) creates a ‘current sink’ in the extracellular medium surrounding the synapses, showing a negative polarity at the site of the synapse. At the level of the soma however a distributed passive current ‘source’ generates a positive polarity in the extracellular medium. In the event of an IPSP, current flow causes an extracellular ’source’ at the soma and a passive ‘sink’ at the apical/basal dendrites. Note that a source-sink configuration features in both cases.*[37]

2.2.3 EEG signal capture

The first electrical neural activity recordings were made using simple galvanometers, which later evolved the string galvanometer and capillary electrometer in the early 1900’s,[40] using mirrors and coils to register current variations. Modern EEG systems comprise of a number of sensitive electrodes, differential amplifiers and filters, having evolved from pen-type systems (that plotted activity on paper and are still in use today) to more sophisticated computerized systems that can digitize and store signals.

From an empirical standpoint, other perhaps more sophisticated, non-invasive neuroimaging and neuroelectrical technologies exist in addition to EEG, such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET) and single photon emission tomography (SPECT). In a creative task-related study, perhaps more appropriate to the current research context, Bekhtereva et al. [41] compared EEG with PET, finding both systems generally satisfactory. However, the authors disclosed that EEG's spatial resolution and sensitivity for deep brain processes was not adequate. Other authors have also critically expressed that EEG can only be considered a gross correlate of brain activity.[42]

However Fink et al. [43] explain that the primary advantage that EEG has over the high spatial accuracy and neuroanatomical insights of e.g. fMRI resides in the EEG's high temporal resolution which is typically in the range of milliseconds, as well as the availability of many diverse parameters for further analysis. Additional limitations in the application of fMRI when compared to the EEG include: [43]

- Many types of brain disorders, malfunction and typical mental activities of the brain cannot be recorded with fMRI due to the limited effect they have on the level of oxygenated blood;
- Accessibility to fMRI systems are costly and limited, especially in developing countries;
- Temporal (time) resolution of the fMRI is very low, i.e. the image sequences is slow, approximately two frames/s.

Concerning more specifically the current research undertaking:

- Movement on behalf of the individual is a great limitation when using fMRI.[c] As subjects were required to perform using the piano, such movement is not tolerable during fMRI scanning to acquire clear imagery.
- A multitude of cognitive tasks can be conducted during an fMRI scan such as imagination, visualisation or memorising. However, critically such data cannot be accepted as substitute or as accurate representation of real-time brain activity during acts of e.g. art making, music performance or tactile behaviour. A strong motivation for this study.

2.2.3.1 Data montage and recording

The human head comprises of several different layers including the brain, skull and scalp with several other layers of differing tissues existing between them. Signals generated within the brain are attenuated approximately one hundred times more by the skull as compared to the soft tissues, however most of the noise regarding signal processing are produced over the scalp (external noise) or within the brain itself (internal noise). This implies that only large populations of active neurons would be able to generate a large enough potential field to be recordable from the scalp.

Scalp EEG recordings therefore reflect the difference in electrical potentials between two sites overlying the cerebral cortex, representing a two-dimensional projection of the pooled synchronous activity of a large population of neurons at an electrode site. Proper functioning of the EEG electrodes are crucial for the acquisition of high quality data. There are different types of electrodes that can be used for EEG recordings e.g. disposable electrodes (pre-gelled types or gel-less types), reusable disc electrodes (silver, gold, tin or stainless steel), saline-based electrodes, electrode caps and headbands.

A high level of impedance exists between the cortex and the electrode due to attenuation from the skull and it’s lining tissues and might cause distortions or masking of the true EEG signals. Fortunately, most modern commercial EEG systems come

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[c] When head movement of an individual under fMRI testing exceeds two millimetres, no usable data can be collected.[102] Thus, although these technologies are more powerful than EEG, they are also more sensitive to movement artifacts.

with built-in impedance monitors. An effective electrode impedance level lower than 5kΩ, balanced within 1kΩ of each other, is required for satisfactory recording quality.

Once picked up by the electrodes, brain generated electrical signals are amplified for the purpose of display by the EEG, along with the incorporation of waveform analyses of voltage, frequency, morphology and topography. However, due to the two-dimensional nature of these recordings, the layered and spiral structure of the brain, the potential distribution over the cortex is not uniform, [44] posing a problem when trying to localize the signal generator, and/or interictal or ictal sources.

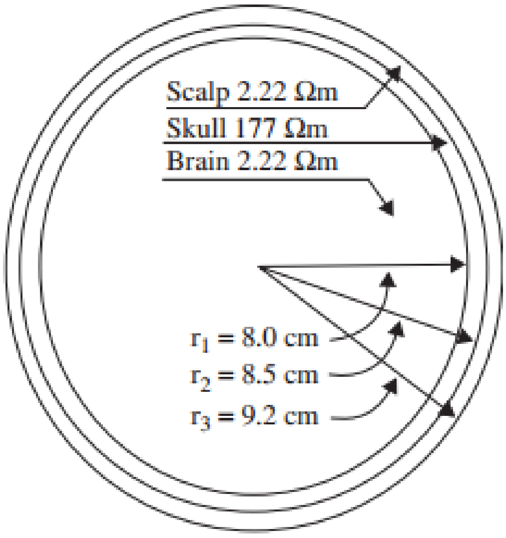

Figure 8: Approximate resistivity and thickness of the three main layers of the head (Ω = *ohm*). [40]

From the original one-channel analogue EEG recordings performed in the late 1920s, the EEG has evolved to sophisticated computerized and digital-based recording devices, offering a wide variety of data presentation for processing and interpretation. Electrode placement has since been standardized to an international 10-20 system that designates the sites where electrodes should be placed based on 10% and 20% interval subdivisions centred on certain anatomical landmarks.

Electrode designations utilized in both the 10-20 and 10-10[d] systems reflect for each electrode the:

- region of the cerebrum – Fp (frontopolar); F (frontal); C (central), P (parietal); T (temporal); and O (occipital);
- side of the head – right (even numbers) or left (odd numbers);
- proximity from the midline – lower numbers indicate a closer proximity to the midline; the midline is indicated by ‘z’ e.g., Cz = central midline).

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[d] The 10-10 system is a newer combinatorial electrode placement system where the intervals between electrodes are much smaller, allowing the use of additional electrodes.

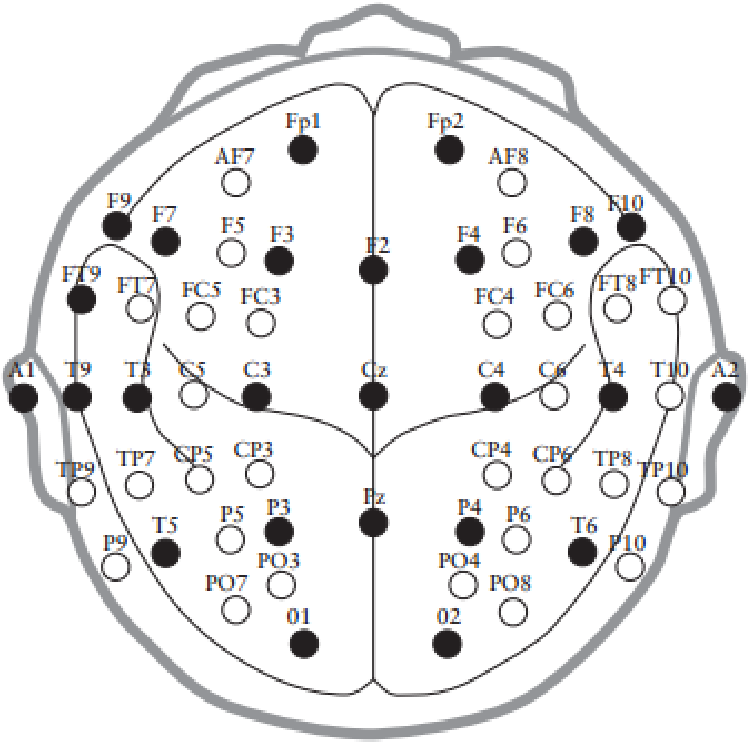

Figure 9: The standardized electrode placement according to the international 10-20 system *(black dots) and the modified combinatorial 10-10 system (black + white dots)*[35]

From the spatial array of recording electrodes, an electrical "map" can be attained known as the montage. Two basic EEG montage types are typically used, monopolar (more often referred to as referential) and the bipolar type. The referential montage depicts absolute voltage through amplitude at different loci by using an active electrode site as initial input and reflecting this measure against one or more 'neutral' electrode/s (placed on an electrically inactive site e.g. the mastoid bone behind the ear, or the earlobes). The greatest advantage of the referential montage is that a common reference allows valid comparisons of activity between many electrode pairings, however there lies a major disadvantage in that no reference site is ideal.[45] Earlobe electrodes might pick up EEG activity from the temporal cortex, whereas other noncephalic reference sites, such as the tip of the nose, angle of the jaw or neck might be subject to EMG artifacts due to activity of the muscles.

Bipolar montage arrangement can take on many different spatial layouts such as circumferential, transverse or longitudinal ("double banana") patterns and compare EEG activity between two active electrode sites. A bipolar montage therefore reflects activity at adjacent active electrode sites with each other, signifying absolute electrographic activity by phase reversals, i.e. activity that both sites have in common are subtracted, rendering only the activity difference. A typical array consists of a chain of electrode placements from anterior to posterior, central and temporal, arranged on both sides of the head.

The major advantage of bipolar montages are that the localization of electrophysiological events are easier. Spikes, or notable EEG patterns or events can be identified by examining sequences of bipolar derivations for phase reversals of electrical signals as one moves spatially (anterior to posterior) or laterally (left to right). However, due to the differential nature of these montages, some information is lost, being the major disadvantage of the bipolar montage.

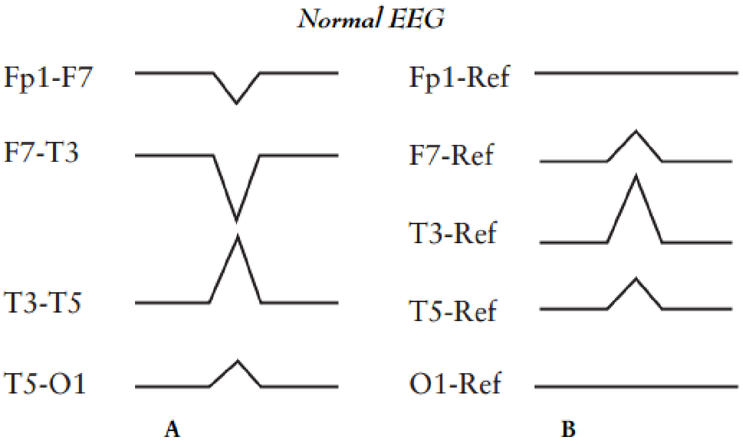

Figure 10: Phase reversal as demonstrated in a bipolar montage (A); absolute voltage as demonstrated in a referential montage (B). *By convention, an upwards deflection in the waveform reflects a more negative voltage difference at electrode 1. compared to electrode 2.*[39]

2.2.4 EEG signal conditioning and mechanics

Analysis of EEG require the sampling of signals, its digital or visual representation and encoding, allowing the signal data to be processed and analysed further. Detecting and understanding brain oscillations from scalp EEGs can prove difficult alongside the definition of back- and foreground EEG, but through the application of advanced signal processing tools it is possible to separate, quantify and analyse waveforms manifestations and abnormalities. Computerized systems typically come equip with simple or advanced signal processing tools, allowing for variable settings, stimulations and sampling frequencies. Conversion from analogues to digital EEG is achieved through multichannel analogue-to-digital converters (ADCs). With a limited effective bandwidth of 100 Hz (although many application may be considered at almost half of this), EEG sampling at 200 samples/s is enough to satisfying the Nyquist's criterion[e].

The raw EEG input comprises of frequency components of up to 300 Hz and amplitudes of the order of μVolts (μV). However, to preserve the operative information the raw signals need to be amplified and filtered in order to reduce noise and make the signal more eligible for processing and visualization. High-pass filters, usually set at a cut-off frequency of <0.5 Hz, are used to remove very low frequency components, such as those associated with breathing, that might cause disturbances in the data. Low-pass filters are also applied in order to mitigate high-frequency noise and are normally set somewhere between 50 – 70 Hz. An additional notch filter is sometimes necessary to ensure the definitive rejection of strong frequencies associated with the power supply, normally set at a null frequency of 50 Hz, although in some countries this might be at 60 Hz.

Filtering as part of the pre-processing stage carries the purpose of removal and mitigation of common occurring artifacts to ensure restoration of informative data. Artifacts can be described as any distortions of the data that might be caused by, but not limited to, e.g. movement. The foremost artifacts can be subdivided into system artifacts and physiological (patient-related) artifacts. System artifacts include 50/60 Hz power supply interference, impedances of the electrodes, cable defects and electrical noise from the electronic components. The physiological (internal) artifacts are mainly related to body or eye movements, ECG and pulsation, ballistocardiogram, and sweating.

A number of factors play a role in the computerized analysis of EEG signals. These factors involve the frequency distribution, amplitude of the signal (voltage), form/shape morphology of the wave, characteristics of the waveform's occurrence (continuous, serial or random), interhemispheric symmetries (voltage frequency, shape and site), reactivity and voltage/frequency regulation.

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[e] *"The statement that when a continuous-time band-limited channel is to be sampled, the sampling process may or may not cause information to be lost according to whether the sampling rate...is less than, greater than, or equal to twice the bandwidth...."* [119]

2.2.4.1 Frequency and amplitude

The term *frequency* refers to the rate at which a waveform repeats within 1 sec, i.e. the number of cycles per second (hertz or Hz). Analysis of the EEG signal in terms of different frequency ranges is known as frequency or spectral analysis and traditionally encompasses two basic approaches: spectral analysis by narrowband filters (typically partitioning the signal into 1 Hz segments or bins) or wideband electronic filtering.[45] Exploring the cyclic or oscillatory patterns or rhythms within the data is the chief concern of spectral analysis, enabling the decomposition of compound and complex time series into a few principal sinusoidal functions of particular wavelengths.

The amplitude of an EEG signal can be defined as the voltage difference (in microvolts, μV) measured from the peak to the trough of the wave and typically falls within the range of 20-50 μV. There is however a great degree of variability, with amplitudes varying from more than 100μV to less than 10μV. The amplitude of an EEG signal is often tempered in response to certain stimulation. An example can be observed when comparing fast activity during an eyes-closed state and how the amplitude of such activity is attenuated when the eyes are opened. The most common method of analysing the frequency distribution within the EEG spectrum is through the use of Fast Fourier Transformation (FFT),[46] resulting in measures of the amount of energy, or power, distributed between different frequency bands of the waveform.

Five major frequency bands or brain rhythms are distinguishable:

- alpha (α; 8 – 13 Hz) and beta (β; 14 – 26 Hz) – originally introduced by Berger in 1929;
- delta (δ; 0.5 – 4 Hz) – initially introduced by Walter in 1936 to designate all frequencies below the range of the alpha rhythms (subsequently changed after the introduction of the theta wave);
- gamma (γ; 30 – 45 Hz) – introduced by Jasper and Andrews in 1938 to described frequencies above 30 Hz;
- theta (Ɵ; 4 – 7.5 Hz) – a notion introduced in 1944 by Wolter and Dovey after the earlier introduction of the delta frequency range as a sort of sub-division of its own.

Activity falling within the delta and theta ranges are often referred to as *slow-wave activity,* whereas *fast-wave activity* refers to the higher frequency band activity in the alpha and beta ranges.

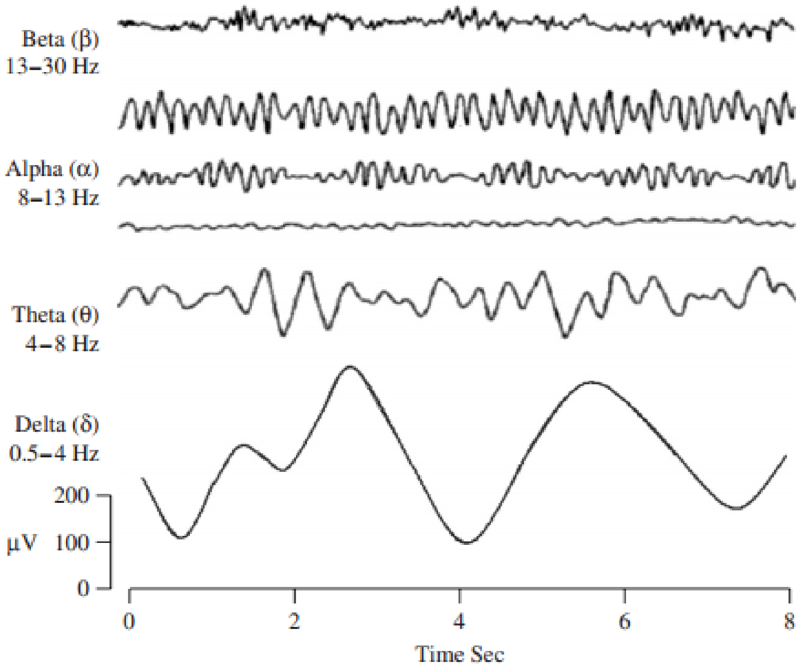

Figure 11: The four most dominant, normal brain rhythms in descending order of frequencies, and at their usual amplitude ranges*. Delta and theta waves are observed in infants and during sleep in adults; alpha waves appear in the occipital regions of the brain during low attention states; beta waves appear at low amplitudes in the frontal and parietal regions.*[40]

Delta waves (0.5 – 4 Hz)

Delta frequencies (δ) are high amplitude rhythms primarily associated with deep sleep (Stage 3 and 4 of NREM), typically arising from the thalamus (coordinating with reticular formation) [47] or cortex (regulated through suprachiasmatic nuclei).[48] Showing right hemispheric lateralization during sleep, it delta rhythms are mediated in part by T-type calcium channels [49] and also stimulates the release of a number of hormones including prolactin and growth hormone releasing hormone (GHRH).

The large muscles in the neck and jaw can sometimes cause artifact signals in the data that might resemble that of delta waves. This is due to these muscles lying close to the skin's surface, causing large signals upon contraction, whereas the genuine delta response, which originate from deeper lying regions in the brain, is severely attenuated as it passes through the skull. Through application of signal analysis methods it is possible to see when these signals are caused by excessive movements to resolve this dilemma.

Theta waves (4 – 7.5 Hz)

It has been put forth that the term theta might have been chosen to refer to its presumed thalamic origin.[40] The theta frequencies (Ɵ) show strong association with deep meditation, creative inspiration and access to unconscious material. It is allied with a person's level of arousal and is often accompanied by other frequencies. Theta oscillations have also been demonstrated in a variety of voluntary and alert behaviours in rats [50] and research suggest that theta might reflect sensorimotor integration.[51] Strong associations have been established between theta rhythms and the hippocampal formations in rats, [52] suggesting its involvement in memory and learning, however hippocampal associations in humans are much harder due to the deeper positioning of the hippocampus in the brain. Cantero et al. [53] did however record theta activity arising from the hippocampus and neocortex in epileptic patients by means of intracranial electrodes and found associations with REM sleep, transition from sleep to waking, and quite wakefulness.

It has been shown that changes in theta occur during meditative exercises [e.g. (54)], alpha/theta neurofeedback enhancement of creative performance, improvisation and anxiety, [55] importance in childhood and infancy, [56] maturation, emotion and various pathological complications in waking adults (e.g. Parkinson's disease [57] and schizophrenia[58]).

Alpha waves (8 – 13 Hz)

Alpha rhythms (α) are most commonly found in the occipital and posterior regions of the brain. These waves often appear as sinusoidal shaped (rounded) signals, but may also appear as sharp waves, although rare. Alpha oscillations are the most prominent rhythms in the brain, thought to reflect a relaxed awareness without overt concentration or attention and may possibly cover a larger range than has been formerly accepted.[40] This is due to regular peaks appearing in the beta wave range that seem to resemble alpha wave morphology more than that of the beta wave.

Alpha waves show greater amplitudes over the occipital regions, normally less than 50 μV. Most subjects show an intensification of alpha activity when their eyes are shut, leading to the supposition that alpha waves are merely a scanning or idling pattern produced by the visual areas in the brain. Opening of the eyes result in a suppression of alpha activity. Therefore, the physiological origin of alpha waves are thought to be in the occipital areas, however speculation of thalamic origination have been suggesed.[59]

Beta waves (14 – 26 Hz)

Beta rhythms (β) represent the usual waking rhythms of the adult brain and shows association with active attention and thinking, problem solving, and focus on the outside world. The normal amplitude of the beta rhythm is usually under 30 μV and are mainly encountered in the central and frontal regions. Beta rhythms may be inhibited by tactile stimulation or motor activity, but may also be enhanced by bone defects, [60] during panic states or around tumour sites.[40]

Gamma waves (30 – 45 Hz)

The gamma range (γ) are also sometimes referred to as fast beta waves, normally arising at much lower amplitude and of very seldom occurrence. However, detection of gamma activity can be used for confirmation of certain brain pathologies. Additionally, the gamma band is also a good indicator of event-related synchronization (ERS) in the brain, having been used to designate the locus for both left and right index finger movement, toes on the dextral side of the body, as well as an expansive and bilateral area associated with tongue movement.[61]

SMR waves (13 – 15 Hz)

The sensorimotor rhythm (SMR) is an idling rhythm observed in sensorimotor areas of the brain during states of immobility. There is typically a decrease in SMR rhythms when a person becomes active, [62] however SMR activation in general is rather poorly understood. Deliberate modification of SMR activity has proven useful in the field of Brain-Computer Interfacing (BCI) [63] in order to control external applications, and have shown utility in the realms of neurofeedback training, learning disabilities and autism. [e.g. (64)].

Other waves of interest

Additional brain oscillatory patterns and rhythms have also been put forth by many researchers including: [40]

a) The **Phi** rhythm (φ; <4 Hz), found to be a possible neuromarker for social engagements and coordination between individuals. [65]
b) The **Tau** rhythm (τ), representing alpha activity in the temporal regions.
c) The **sleep spindle**, occurring during sleep at 11-15 Hz. Often referred to as sigma activity (σ).
d) The **Kappa** rhythm (κ) – alpha-like activity occurring in the anterior temporal regions. Discrete lateral oscillations caused by the eyeballs and considered as an artifact signal.
e) The **Chi** wave (χ) is believed to be a mu-like, rolandic pattern occurring at 11-17 Hz; observed during Hatha Yoga practise.
f) The **Lambda** rhythm (λ) – a rare pattern observed in waking adults; sharp transient signals occurring in the occipital regions during visual exploration of walking subjects. These patterns show varied amplitudes (generally below 90 μV), positive in polarity and time-locked to saccadic eye movement.[66]
g) Frontal artifacts (alpha range) caused by **eyelid flutter** when the eyes are closed.

2.2.4.2 Morphology

Frequency and amplitude components of a signal combine to affect the “shape” or morphology of a waveform. Continuous fluctuations occur within the signal as response to stimuli and towards the subject’s state of consciousness (sleep, awake, drowsy etc.) and certain features of the waveform permit its detection by the recording apparatus. A *transient* form stands out from the background EEG activity and is thus an isolated feature or form like a *spike* (peak duration less than 70 ms) or *sharp wave* (peak duration between 70 – 200 ms). When waves occur together or repeat at periodic intervals they are referred to as *complex* features or forms. A *monomorphic complex* can be described as such waves where subsequent waveforms are similar, whereas *polymorphic complex* waves are dissimilar. Waveforms may also accommodate numerous positive and negative voltage swings and can therefore be of differing phases e.g. nonphasic (either positive or negative), diphasic (positive and negative), triphasic or polyphasic. [40, 62]

2.2.4.3 Symmetry

Waveform amplitude (bilateral) symmetry between homologous electrode sites are often regarded as sensitive to certain neuropathologies and an important consideration within the EEG.[45] Research conducted in the 1970s by Matousek and Petersen [67] revealed that for each of the different frequency bands the symmetry amplitude values were comparable, as well as corresponding to the symmetry of the overall EEG activity. John's [68] neurometric analytic approach published a few years later defined a ratio for amplitude asymmetry of transformed measures at certain electrode sites. EEG symmetry also include the phasic relationship of two waveforms within a certain frequency band, with one of the earliest methods for measuring phasic symmetry applying polarity coincidence correlation (PCC) to calculate phase from a large number of polarity comparisons of two simultaneous signals.[68]

Measures of the phasic relations between signals provide estimates of the lag or lead times between connected systems or generators that are spatially separated. When the sampling of EEG signals is at a high rate (e.g. 10 kHz) the frequency resolution of the correlation exceeds the EEG signal bandwidth, however digital delay circuits allow for the delay of one signal with regards to the other. By quantifying the phase shifts between interhemispheric pairings or from within lateralized hemispheres, it becomes possible to gain information regarding the propagation of neural pathways.[69] Symmetry analysis can furthermore be divided into 'amplitude symmetry within a frequency band' or 'phase and coherence functions within respective frequency bands'.[45]

2.3 LINKING THE BRAIN AND THE HEART

2.3.1 Physiological coherence

In the preceding section it was explained that spectral analysis is a means of examining the oscillatory patterns of the data within respective frequency domains. Cross-spectral analysis is used to compare patterns from two inputs, representing the correlation between two time series at different frequencies. The term *coherence* delineates the symmetry between frequency patterns of two time series, is analogous to cross correlation within the frequency domain and mirrors the strength of connection between spatially distant signal generators. Put differently, coherence can be understood as “the quality of being logically integrated, consistent and intelligible”, as in a coherent argument.[70] When we refer to a person’s speech as coherent, the parts fit together well, whereas if their speech was incoherent, it would not make sense or might be meaningless. For a system of parts, or a sentence of words, the meaning conveyed by the arrangement of these words are greater than each word’s individual meaning, and therefore coherence in this context refers to wholeness and global order.

In signal processing mechanics, the concept of coherence describes the level of coupling or interaction between oscillatory systems. Coherence infers synchronization, which describes the degree to which two oscillatory patterns are frequency or phase locked. Applying this concept to the realm of physiology, coherence analysis can be used similarly to describe the degree of harmonious interaction or coupling between two or more oscillatory systems within the body (cross-coherence), e.g. the heart and brain, or within a single system (auto-coherence), e.g. between regions or electrode sites of the brain. In the case of cross-coherence between two separate systems that may operate at different frequencies, it may be possible that they may become entrained to oscillate at the same frequency or might become phase-locked.

In a beautifully constructed sleep EEG study, Jurysta et al. [71] assessed the phasic relationship and dynamic interactions between the power bands of electroencephalography (EEG) and the high frequency (HF) of the R-R interval variability (RRI; referring to HRV). Using a coherency analysis approach the authors aimed to determine whether specific EEG frequency bands varied greatly in association with HRV. It was found that all EEG bands showed high levels of coherence with high frequency (HF) fluctuations and shifts and changes in cardiac autonomic control showed dynamic relations to all EEG power bands. By determining the gain between changes the authors were able to extrapolate that the delta frequencies of the EEG showed the greatest gain, and hence forth the greatest associated changes with regard to the autonomic regulation of the heart during sleep. Put differently, the ‘modifications in cardiac autonomic regulation are mostly associated with changes in the delta EEG band’ (Figure 12).

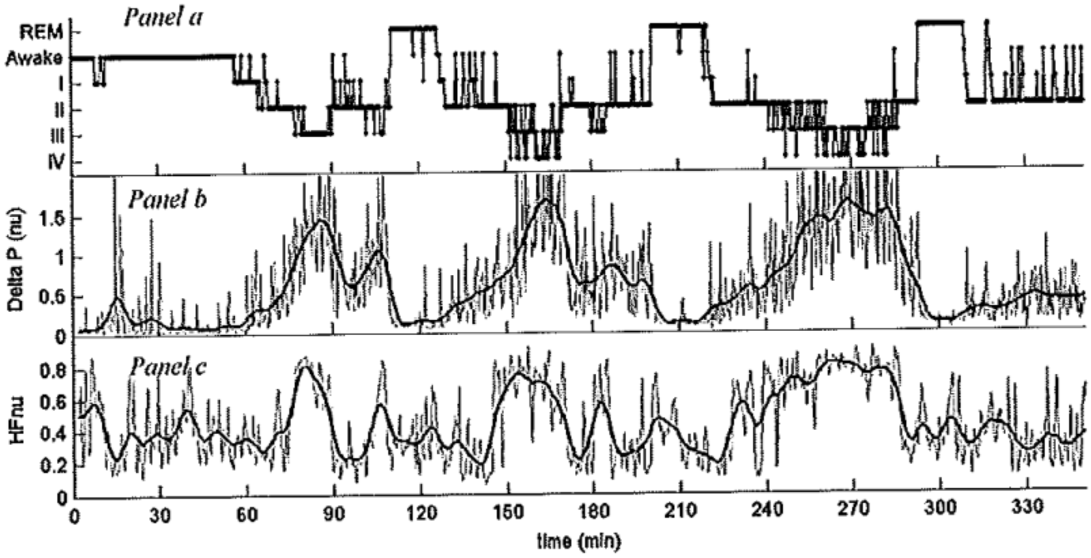

Figure 12: Dynamic interaction between normalised delta EEG power (Panel b) and the high frequency component of HRV (Panel c) across sleep stages (Panel a). *REM, rapid-eye-movement sleep, I, stage I; II, stage II; III, stage III; IV, stage IV of sleep. Note how brain rhythm changes follow slightly after the changes in heart rhythm.*[71]

Interestingly, the authors showed that changes in delta EEG power were preceded by the changes in cardiac vagal activity by a phase shift of 41 ± 14° which corresponded to 12 ± 5 min. Therefore the changes in EEG activity followed about 7 - 15 min after the fluctuations of the HF_{nu}. To simplify this point, changes in synchronization of electrical activity of the brain (inferred by the greater level of slow wave activity) followed *after* coherent changes in the heart's activity. This seems somewhat counterintuitive as one would expect such an increase in the brain's level of synchrony and coherence to perhaps dictate such similar changes in the heart rate and its variability, however these findings show that it is in fact the changes in the heart's variability, brought forth by a slowing of the respiratory rate that prompt a higher state of coherence and synchrony within the brain. Similar studies have shown changes in EEG activity preceding autonomic control of the heart [72] although Jurysta et al. [71] argue that the improved time resolution of their technique could explain the difference.

Additionally it has been put forth that heart coherent states, where an entrainment of the heart and respiratory rates occurs (see respiratory sinus arrhythmia), can facilitate relaxation and cortical reorganization through its functional anatomical pathway in accordance with the polyvagal theory.[23] Vagal afferents from the heart carry forth information to the nucleus in the solitary tract of the medulla oblongata. From this region it projects onto the parabranchial nucleus and the locus coeruleus before branching out to the forebrain, linking with the hypothalamus and amygdala. Thalamic connections to the insula, prefrontal and orbitofrontal areas are also involved, which in turn gives feedback to the anterior cingulate.[73] Although some of these areas lie very deep in the brain and are therefore difficult to probe and quantify, the facilitation of attentional control, meditative states, cortical reorganization through heart coherence and the involvement of the pre/frontal region in the brain are important themes for the current research initiative. An additional dimension to this focus area can be sculpted when looking at more conscious, cognitive functioning such as that of attentional control as opposed to unconscious, sleeping behaviours.

2.3.2 Attentional control

Attentional control (AC) refers to the cognitive ability to regulate attentional distribution and allocation to task-related stimuli or demands.[1] Balle et al. [1] argue that given the evidence that AC could be a trait-like disposition that can not only influence emotional regulatory processes but also influence performance of non-emotional attentional tasks, it would make reasonable sense that self-reported attentional control between individuals could be reflected in specific patterns of cardiac and EEG patterns. As example, an inadequate orienting response and reduced ability to endear attention to task-related stimuli has been reflected in reduced HRV.[1] Therefore, high resting HRV facilitates and maintains sustained attention to discrete impetuses and reduced attentional control has also been positively associated with low resting HRV.[74]

The neurovisceral integration model (alongside other related models) consider vagally-mediated HRV as informative on how the heart-brain bidirectional system works.

> *'In brief, these models consider that a poor tonic inhibition of the amygdala mainly by the medial pre-frontal cortex, and in conjunction with other cortical regions, is associated with… …a disinhibition of sympathoexcitatory circuits… This dysregulated central–peripheral integration results in reduced levels of complex neurogenic rhythms and lower HRV.'* [1]

A meta-analytical review done by Thayer et al. [75] shows that the above statement is supported by neuroimaging studies and a growing body of research according to Balle et al. [1] has identified the amygdala-prefrontal circuit to underlie attentional biases.

Furthermore, poor prefrontal functioning has been associated with worsening attentional control when faced with non-emotionally-laden tasks.[76] The involvement of the frontal regions of the brain during attention related functioning alongside its standing relationship with HRV is relevant to the conduct of this investigation, especially within the context of *flow* (as discussed later).

From the perspective of an integrative physiological and interdisciplinary approach we can recognise that, in order to understand the workings of the brain we need to also acknowledge the impact of factors outside the central system and their influence on the CNS. Studying the deeper lying regions of the brain is extremely difficult, but by combining central and peripheral operatives (brain and body) we can look at brain functioning holistically as there are continuous communication happening between the brain and the peripheries. Such dialogues interaction can lend valuable insights into the control mechanisms, impact stimuli and affective relationships underlying complex behaviours such as creativity, insight, musicality or attentional control.

To serve as an example relevant to this study, meditation studies [22] have yielded valuable insights into the self-regulation of attention and emotional systems by combining the brain and body, showing how e.g. slowing ones breathing can induce cardiovascular changes and subsequently offer insights into the functioning of the brain stem and ANS.

2.4 CREATIVITY, FLOW AND IMPROVISATION

2.4.1 Context and overview

To serve as a contextual overview, creativity research is discussed in the sections following with specific regard to the expression of creative thought, research pertaining to real-time music performance, improvisation and the concept of *flow*, as well as the intrinsic and implicit nature of musical practise and creative expression. The present research undertaking lies rooted in the musical performance of experienced individuals with the aim of extrapolating EEG and HRV information related to their performance and the implicit and intuitive nature of such conduct. Studying the underlining neurocognitive mechanisms and substantiating physiological processes of creativity, innovative thinking and improvisation would bring us ever closer to understanding the elementary nature of our higher cognition and the elusive manner in which our brains are able to give birth to novel ideas and conceptions. The societal benefits that would arise in the wake of understanding such basic underpinnings of innovation and ingenuity would be irrefutable. Alas, to study creative expression, where and how it arises in the brain and the neural basis for such phenomena is a feat almost more abstract and capricious in nature than creativity itself.

Considerable progress has been made in certain areas of creativity research through exploratory investigations and techniques such as surveys, personality inventories and case studies (e.g. Simonton[77]), but laboratory-based research focussed on creativity have been extremely limited up to this point. Up until recent times the greatest research contributions towards the study of creativity have come from psychology-based disciplines and it is only up until very contemporary times that the cognitive sciences (e.g. Ward[78]), neuro- and social psychology (e.g. Hennessey et al.[79]), pedagogy related domains (e.g. Sawyer[80]) and the neurosciences [43, 81, 82, 83] have been able to employ sophisticated neuroimaging techniques for creativity research. Indeed, it is worth noting that the growing interest and attractiveness of creativity across a broad range of scientific disciplines is a field of research still very young in its pursuit of finding underlying cognitive, physiological and neural substrates compared to other mental ability constructs such as intelligence. In 2014, Fink and Benedek [84] found a mere 550 scientific publications relating to creativity and its brain inferences compared to the 19000+ publications on the brain and intelligence.

Perhaps more optimistically, although creativity-focussed experimental research have lacked testability and accession in past, the growing presence of creativity-related research in the neurosciences have yielded a considerable diversity of methodologies, findings and approaches which might serve as a quantifiable consolation. Dissappointingly however, reviews of a large number of these studies have yielded very little clear evidence with Dietrich and Kanso [82] concluding that "…creative thinking does not appear to critically depend on any single mental process or brain region, and it is not especially associated with the right brains, defocused attention, low arousal, or alpha synchronization, as sometimes hypothesized…".

In addition, real-time testing of art or music creation alongside findings grounded in and during the actual performance of music or creative expression seems critically assumptive at best when exploring the literature. The more sophisticated technological involvement in modern times have been ground-breaking but have failed to free creativity research from this bondage. Movement of participants need to be kept to an absolute minimum in order to get good resolution on imaging. Together with the low temporal resolution that such imaging technologies such as fMRI harbour, related methodologies become uncompromisable and equally inadequate to capture the true nature of creative conduct. Thus, there is a very clear gap, but also a strong need for research to move beyond the confines of the laboratory, yet reach still deeper into the mind of the artist, but in an environment and context where creativity can be observed not through visualization or imagination, but through the actual making and performance of art and, in context of this study, music.

It should be noted that creativity is rarely considered as a homogeneous constructs, often being defined in very different paradigms as being a cognitive event or state, as personality disposition, by expertise or achievement, or as cognitive potential. The broad diversity of parameters and neurophysiological measures that have been employed in creativity research may also be partly responsible for no conclusive agreement on potential neural mechanisms underpinning the phenomenon of creativity as of yet.[84] Moreover, considering the multi-facetted nature of creativity and the overlapping findings and interpretations of its inquiry, it becomes pivitol to delineate a clear conceptual definition of which aspects and domains are focussed on when searching for consistent brain mechanisms involved in creativity.[82]

2.4.1.1 Defining creativity in performance

> *"The term creativity, however, seems in constant danger of collapsing under the weight of its own plurality. It is common in everyday parlance, of course, and arts discourse in particular is filled with talk about its importance. To be a great artist, it is said, one must have unusual capacity for creativity, and so create products (in the broadest sense; e.g., compositions, performances, paintings, poems) of the highest quality and utmost originality. The same features of this anecdote that make it so widely appealing – its apparent generality and fervent idealism towards identifying excellence – also suggest why research into creativity is so complex"* [85]

When attempting to define creativity scholars have had great difficulty with almost no success in offering a broadly-agreed upon and unambiguous definition for creativity, partly due to the extreme difficulty of isolating creativity empirically, and partly due to the "deeply entrenched mythology" surrounding creativity within the arts as some mysterious and unknown process.[85] Williamon et al. [85] argue that such perspectives inhibit the progress of creativity research as often researchers might opt to rather focus on more directly traceable issues; a "disappointing state of affairs" given the central importance of creativity in everyday human life. They argue further that it would be a mistake to view creativity in such a light as even the most mundane everyday tasks often require some degree of creativity, alluding to an example of "needing to find the most efficient arrangement for packing shopping bags into the boot of a car". They explain that there are also different degrees of creativity or creative processing requirements and that when we describe a person's idea or action as being 'creative' it might not automatically imply originality or value but rather that is might have been "sufficiently creative as to be relatively unlikely given the experience and knowledge of the person".

Gardner [86] describes a similar distinction between "big C" creativity (e.g. some kind of breakthrough which is rare or only occasionally occurring) and "little c" creativity (e.g. the type of creativity we all demonstrate in our every-day lives). In addition, Gardner's point of view does not only describe the degree of creativity but also the frequency of its occurrence, implying a correlation between the extent of a person's creative ability and the frequency with which they express such creative levels. However, Williamon et al. [85] argue that there might very well be no correlation at all on this front and that the components of 'originality' and 'value' form additional dimensions to creativity that need to be taken into consideration. They go on to explain that the uniqueness of creativity lies not just in a person's ability to think outside the population's norms, but that it is an amalgamation of the manner in which they bring their novel ideas into 'fruition', together with how those ideas and products are appreciated and valued within their society, at the time of production and against the scrutiny of time that follows. This brings together the cultural and societal facet to any creative conduct, with perhaps greater regard to the arts than every day behaviour, and also the ingenuity or creative ideation and, more centrally, the actualisation of those ideas.

From the earlier aesthetics literatures, Götz [87] proposed that creativity shares a direct link with *making,* explicating that "creativity is the process or activity of deliberately concretising insight". He hereby stresses that although the creative process consists of several steps, it is only the one stage – that which occurs between the idea genesis and its actualisation or realisation into a final product or action – that can be regarded as “creative”. Most psychological research of creativity, when viewed in light of this perspective are therefore actually the study of the antecedent stages of creativity and not its central phenomenon.[85] However it is important that such an outlook does not define away the need to disentangle the relationship between originality, value and creativity.[85] Drawn from this point of view, the current research undertaking lies seeded within the promise of gaining much needed insights into authentic experience of creative conduct given the scarcity of literature and research grounded in the actualisation of creative behaviours.

2.4.2 The creative brain

In 2010 an extensive review of neuroelectrical and neuroimaging studies aimed at testing creativity and insight was conducted by Dietrich and Kanso.[82] The authors reviewed 63 articles and 72 experiments published up until Febuary 2010. Seven of these articles were reports on experimental procedures pertaining to visualization or imagination but *none* were constructed for the testing of creative expression in real-time such as painting or musical improvisation. Seven studies revolved around art of which five involved art making but, once more, none involved the real-time testing of art making. Seven of the studies reviewed involved EEG measurements.

In summary, the findings of this review revealed the following (points have been supplemented):

1) Creativity is not an exclusive function of the right hemisphere, but instead involves interhemispheric communication and interactions between multiple regions from both hemispheres.

Hemispheric specialization has been described as early as the 1940’s by authors such as Alajouanine who recognized the hemispheric specialization for music, art and linguistics.[88] Neither hemisphere is ‘dominant’ or ‘recessive’ over the other per se, but the different hemispheres are functionally specialized to handle different tasks or information. Therefore, the workload is subdivided between the hemispheres and each hemisphere is functionally dedicated to certain processes. This distribution of functions between hemispheres in the brain is refered to as *cerebral lateralization*. It is often falsely assumed that creativity and musical ability stem from the right hemisphere (functions related to artistic or musical ability are most often associated with the right hemisphere). It is of general consensus amongst researchers that creativity is a global process, resulting from an intergration between hemispheres [81] and is not limited to a specific hemisphere. Such rigid allocation of functions to one hemisphere or the other is an unfounded and grossly exaggerated misperception.[81]

A multimodal rCBF (regional cerebral blood flow) investigation into the relationship between creativity and hemispheric assymetry conducted by Carlsson *et al.* [89] revealed that hemispheric differences were very prominent in ‘low’ creative participants[f]. Higher creative individuals showed a greater bi-lateral response leading the authors to conclude that creativity is a functional system consisting of the cognitive interaction of hemispheres, as well as the interactions of instructional and executive functioning of the frontal lobes. It has further been supported by other studies [90] that creative individuals are inclined to have abler access to bi-lateral involvement and interaction between hemispheres and have therefore a greater degree of inter-hemispheric communication. Thus, with respect to creativity and music, such activities are of a global nature in the brain, with the cerebral hemispheres complimenting one another to accommodate for such elaborate processing.[91]

2) Activation of multiple areas of the prefrontal cortex was reported in several studies. This included the dorsolateral prefrontal cortex [DLPFC (BA 46)]; frontal gyrus (BA 8 & 9); frontal operculum (BA 44 & 45); and premotor and supplemenatry motor regions (BA 6).

Damasio [92] provides a definition of consciousness as a state of “awareness of self and surroundings” where awareness is designated to ‘core consciousness’ and thereby words such as ‘alert’, ‘awake’, ‘attentive’ and ‘responsive’ are often associated with consciousness. In a later paper by the same author, [93] consciousness is described as being hierarchally ordered where higher cognitive and executive functions such as perception, reasoning, (working) memory and language are fundamental instruments of cognition and consciousness. It has been put forth hereafter that the cerberal cortex, and more specifically the prefrontal

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[f] Rated on the Smith and Carlsson’s Creative Function Test (CFT), designed to measure visual perception.

cortex form the pinnacle of this hierarchy and therefore forms the underlying neural basis for higher cognitive functioning.[94] This is not to say that the cerebral cortex forms the root or foundation of consciousness but instead that the prefrontal cortex contributes the higher-order functions of cognition to the conscious experience, thereby enabling the top-layers of consciousness.[94]

Dietrich explains the development of two neural systems that are anatomically distinct, process information differently and extract different types of information from the environment.[95] One of these systems constructs representations necessary for cognitive processing, whereas the other lies rooted in emotional information extractions (involvement of the limbic system, amygdala and ventromedial prefrontal cortex) and evaluates the ‘biological significance’ of an event. Cognitive processing of such emotional information require additional input from the hippocampus and temporal cortex. In addition, both systems keep record of their activity: for the emotional system, emotional memory, and for the more cognitive system, conceptual memory, are stored in their respective circuitries.[95]

To bring the above mentioned information into context, both information-processing systems (emotional and cognitive) have overlapping structural circuitry but they are only fully integrated once they converge back on the dorsolateral prefrontal cortex (DLPFC), resulting only then in their conscious perception.[95] Therefore, the prefrontal cortex (PFC) is neither directly involved in emotional processing nor long-term memory storage, nor does it receive any direct sensory information but instead it plays a central integrative role and functions as a facilitator of consciousness.

Given the broader functioning of the frontal areas and the disproportionately evolved size and complexity of these frontal regions in humans, it has been suggested that this may explain why humans create art or music, but no other species do.[96] A basic assumption of neuroscience is that the brain is plastic, henceforth learning a skill (such as playing an instrument) and its subsequent practice or repitition - leading eventually to proficiency - will cause the brain to undergo anatomical, physiological and structural changes.[88] Given then the more developed frontal regions in combination with the involvement of these regions with higher cognitive functioning one might be tempted to conclude that perhaps creativity or musical ability as such might therefore reside in these frontal regions. However Dietrich[95] cautions that, once more, the prefrontal cortex contributes higher cognitive integrations to the experience of consciousness. It permits novel combinations and constructs of information, be it science or music, rather than being the ‘seat of creativity’.

3) Activation was also shown outside the frontal regions: several areas of the visual cortex, thalamus, hippocampus, basal ganglia, cerebellum, pons and temporoparietal regions.
4) Wide-spread deactivation of limbic and paralimbic areas (e.g amygdala, hippocampus, entorhinal cortex); parietal and occipital lobes were also observed.

When measuring the manifestation, i.e. creation, and expression of creative thinking one must also recognise that the domain (e.g fine arts or music) as well as the subcomponents of those domains (e.g abilities, training) will be deterministic in what activity occurs in the brain.[97] Many different components can play a part such as the person’s level of education and creative background; the motor areas and activities involved; as well as the type of task at hand. Ward [78] explains how the complex and multidimensional nature of creativity requires a diversified approach of varying metods and perspective to establish its underlying neurocognitive origin. He further suggests that seeing as creative activities rely heavily on accessing stored knowledge, certain ways of accessing this knowledge, when developing original ideas, might be more conducive than others.

Creativity is an integrative process between different locations and functions.[98] Its localisation will never realise, but instead individual results and findings will be dependent upon the methodologies used; the population that are investigated (e.g students, proffessionals), as well as the task that is used as “proxy” (e.g convergent thinking, visualization, piano playing, painting).[83]

5) Significant evidence indicated a strong linkage between creativity and deactivation of the frontal areas (*hypofrontality*) which suggests the downregulation of supervisory processes and metacognition, leading to more intuitive, spontaneous and free flowing actions.

Dietrich [95] postulates that creativity is facilitated by the executive functions and capabilities of the DLPFC which enables still higher cognitive functions such as abstract thinking, planning and self-reflection by integrating information that is already highly processed. An EEG study conducted by Bekhtereva et al. [41] showed both an increase and decrease in frontal cortex activity where this decrease in frontal lobe activity, or *hypofrontality,* during creative exercise is characteristic of *flow*. Therefore, with regards to creative performance such as music creation or improvisation we see a central integrative contribution from the pre-frontal regions, allowing the generation of new ideas and novel association; while simultaneous down-regulation of the cognitive control also vested in the frontal regions allows more spontaneous and intuitive creative expression. This decrease in cognitive control links *flow* to a form of spontaneous or creative thought as described by Christoff et al. [99]

2.4.2.1 Creative versus goal-directed thought

Christoff et al. [99] postulate three types of thought namely ‘goal-directed’, ‘spontaneous’ and a sort of hybrid, ‘creative thought’. Cognitive control is chiefly associated with *goal-directed thought* which can be described as “…representing current and desired states, and linking these representations through a series of actions that attempt to transform the current to the desired state.” [99] This cognitive control is typically localised to the prefrontal cortex, involving the dorso- as well as the rostolateral PFC – which is loosely defined as the lateral portion of that Brodman’s area.[100] Christoff et al. [99] explain that cognitive control refers to the ability of the PFC to override and influence other cortical regions. Research done on creativity and open-ended problem solving have also shown the involvement and activation of the prefrontal cortex during effortful problem-solving tasks.[101]

Spontaneous thought increases when cognitive demands are reduced and is often refered to as ‘mind wandering.’[99] This implies lesser recruitment of prefrontal involvement, i.e hypofrontality (typical of flow) and is explained to transpire along the midline of the brain in areas such as the medial PFC, cingulate cortex (anterior and posterior), posterior parietal lobe and precuneus.[99] Mind wandering have been linked with regions in the temporal lobes (memory processing) as well as a set of areas known as the ‘default network’. The default network is inactive during attention-demanding or novel tasks but becomes active when attention levels are low, in the absence of a task, or during one of high familiarity.[99] It could therefore be said that the capacity for spontaneous thought increases during tasks that have been practised, are familiar to an individual or are done utilising a highly developed skill. Once more a characteristic of flow. Reference is made in the above cited article to neuroimaging studies that have found spontaneous thoughts to carry the same advantages as rest with regard to the consolidation of memories that normally occur while sleeping. Thus, spontaneous thought play an active and important role in human cognition.

Christoff et al. [99] explain that *creative thought* lies somewhere between the two types of thought mentioned above. They explain that the processes of creative thought are similar to spontaneous thought in that it also involves lower cognitive control but during a state of broader attention distribution.

> *"Thus, lowering cognitive control and arousal, as well as shifting attention from a focused state to a wider, defocused attentional state, enables a transition from a relatively goal-directed thinking mode to a more associative, creative mode. This state of defocused attention may be one of the key factors facilitating creative thought…"* [99]

The authors explain how creative thought requires an initial 'generative' phase where novel ideas or concepts are engendered, requiring access to 'remote semantic associations' which seems to share connections with the 'default' and memory networks. In addition, a second phase or aspect to creative thought is one of evaluation strongly associated with lateral prefrontal involvement. The experience of flow is here within described to be a form of creative thought, demanding lesser cognitive control and once more, resulting in hypofrontality.[99]

This state of transitory hypofrontality is a prerequisite to the experience of flow according to Dietrich's primary hypothesis.[95] This allows for temporary suppression of the cognitive control exerted by the prefrontal areas and therefore describes a state of lesser analytic or meta-cognition. In the 1970's Martindale[121] conducted EEG studies on the neurophysiology of creativity, indicating that a reduction in activity of the frontal lobes was associated with creative processes. At the time the concept of flow had not yet been described or identified and this finding might have pointed more towards flow than to creativity per se.[41]

Taken together thus far it seems that creativity and improvisation revolve around a rudimentary integrative process involving the frontal, temporal and parietal lobes (creative axis), the interactive communication between both hemispheres and regional activity is dependant on the task at hand. It seems most likely that the integrations of these creative processes occur in the frontal areas of the brain where sometime a down-regulation in this area occurs which seems to suggest more intuitive performance. A phenomenon related to the concept of ‘flow’. This hypofrontality suggests lesser cognitive control and micromanagement of the actions being perfomed so that it becomes more implicitly driven and intuitive such as occuring during musical improvisation.

Dietrich [95] explains that, as expected, complex behaviours such as art making or musical improvisation involve the prefrontal cortex which is considered the epitomic structure of higher-functioning in the brain. However the involvement of these structures are context-dependant and the manner in which information is being processed in the brain; its acquisition, memorization and representation are attributed to two divergent information-processing systems. These two classifications can be distinguised from one another based on function and anatomy and are refered to as the explicit and implicit systems.[102]

2.4.2.2 Implicit versus explicit information processing

The explicit system requires conscious awareness and handles information that is transmitted and processed globally in the brain. This explicit information can be verbalized, and the recollection of explicit memory is a reconstructive process, consequently being suseptable to misrepresentation.[102] It is also available to other more specialized structures of the brain to utilize accordingly. With regards to the structures and regions involved in the brain, the explicit system is mostly dependant on the prefrontal regions, in particular the PFC. Dietrich [95] hypothesizes that the explicit system can be considered a more recent evolutionary development and better established in animals with higher developed prefrontal cortices; a viewpoint that is consistent with the hierarchical view of higher-cognition and consciousness discussed earlier. This would subsequently localise higher mental actions such as explicit knowledge representation to the the prefrontal cortex.[95]

The implicit system, by contrast, is based on skill and experience and is isolated from conscious intervention. Implicit information cannot be verbalized, but is instead communicated through actions, behaviour and/or task performance. It is more primitive in nature and cannot be made available for exemplification in working memory, consciousness or through the explicit system, i.e the explicit system has no understanding of the implicit knowledge base.[102] The specifics of the neural underpinning of the implicit system still remains unclear.[95]

> *"For implicit knowledge to reach consciousness it must first be explicated, which cannot proceed, due to its concrete-operational organization, through a bottom-up process. We must perform or execute implicit knowledge, which allows the explicit system to observe it and extract its essential components. Because the implicit system refrains from abstractions, it is not burdened by the computational complexity that comes with higher-order thought, and a single brain structure, such as the basal ganglia or cerebellum, can handle all information processing steps. This makes knowledge in the system highly efficient, albeit only to its specific application. Smooth sensory-motor integration leading to purposeful motion must occur in real time and this is the domain of the implicit system, responding to environmental stimuli in a fast and accurate manner."* [102]

Therefore, the main differences lie in that implicit knowledge needs to be performed or expressed through behaviour and cannot be verbalised, where as explicit knowledge requires conscious awareness and can be expressed intellectually and cognitively. Implicit knowledge would represent e.g. practised skillsets or embedded behaviours that can only be expressed through its enactment or actualisation. Tasks typically based in movement such as playing a musical instrument or art making such as drawing, painting or sculpting are taken up much easier by the implicit system.[103]

To draw relations between these two systems of information-processing and the flow experience, Van Heerden[103] explains a kind of trade-off relationship between the explicit and implicit systems during flow. Phenomena such as flow have been described many decades ago and occurs where e.g. artists or musicians become so engrossed in their conduct that creative expression such as improvisation or freestyle painting or drawing becomes effortless, spontaneous and almost completely intuitive, often resulting in peak performance. The intuitive and spontaneous actions associated with flow are therefore the result of implicit representations that are retrieved and translated through actual behaviour such as motor skills and actions. Through the application of such behaviour the explicit system is circumvented to prevent it from micromanaging the skill, which would affect the quality of its execution. This is the hyporfrontality we see during the flow experience.

Dietrich and Audiffren [104] therefore disagree with conceptions that high performance requires equally high concentration or conscious effort directed at that task. In accordance, neural signalling is metabolically very demanding and due to its high energy requirements the cortex employs energy-efficient routes and circuits to compensate for such exhausting metabolic processes.[105] Therefore, it would make sense from an objective point of view, that during enactment of a sufficiently developed skill or highly proficient behaviour the brain would not unneccassarily allocate conscious effort or attention to an already fluent practise. Subjectively, the experience of the individual during the state of flow is exactly that: mental exertion is perceived as almost effortless while performance improves and might even peak.

2.4.3 Flow

The construct of flow is one born from the field of positive psychology during the 1980s. First proposed by Mihaly Csikszentmihalyi [106] as “an almost automatic, effortless, yet highly focused state of consciousness” [107] which often ensues when one becomes so deeply engrossed in a task that it not only feels effortless but is often associated with peak performance. In more colloquial terms flow can be described as a feeling of being ‘in the zone’ or ‘in the moment’. Csikszentmihalyi noticed in painters that, when the painting was going well, the artist tended to persist ‘single-mindedly’ with the task at hand regardless of fatigue, hunger or discomfort, and it was in an attempt to understand such intrinsically motivated states that flow research began. Understanding such autotelic behaviour which is satisfactorily rewarding in itself apart from any extrinsic rewards or the end-product revealed a picture of flow as an absorbed state of effortless attention and ‘optimal experience’.

Some conditions to the experience of flow have been put forward and can be summarised as consisting of:[109] (I) a balance of skill vs challenge – too easy or too difficult could result in feelings of anxiety or boredom; (II) merging of action and awareness where the action feels automatic, with little or no attentional resources are demanded; (III) high concentration; (IV) clear goals; (V) sense of control; (VI) unambiguous feedback; (VII) loss of self-reflective or self-conscious thought such as fear of social evaluation; (VII) distortion in time as being faster/slower than usual; (IX) autotelic experience paired with positive emotions. From these conditions, and the strong correlations found between flow and objective measures of quality of performance in various different domains, [108] flow is therefore a state of energized focus where cognition is driven by implicit processes and free-association rather than self-referential thoughts or explicit rational reasoning.[109]

Flow as a construct often runs parallel with creativity, yet defining creative brain function such as flow remains largely contextual. Despite the rich psychological background to flow research, physiological research on the underlying brain mechanisms involved during flow has only been put forth in recent years. [110, 111, 112] Neurophysiological research on flow is still only in its first decade of testing and have been rather confined to laboratory protocols; however seminal works investigating the neurocognitive processes underlying flow [81, 82, 94, 95] have established strong associations with improvisation, peak performance, creative intuition, spontaneous thought and altered states of consciousness. Dietrich [95] suggests that through the possible identification of the neurocognitive underpinnings of flow "…it becomes feasible to delineate it from other manifestations of exceptional human experience, for instance, creativity."

It is important to clarify at this point that the central focus of this study does not revolve around flow specifically, but that the mental states, attentional distribution and neurophysiological processes associated with its experience shapes a contextual platform to investigate the associated heart and brain functioning of musical performance. As such the current research undertaking does not aim to exemplify flow or its conceptual understanding, but instead 'borrows' from its associated topographies and features to create a focal point for investigation.

2.4.4 Improvisation

De Manzano [109] explains that all creative behaviours have two common features in that they involve the generation of novel ideas that are at the same time both original and meaningful. In this regard, musical improvisation can be seen to involve the continuous and spontanteous extemporization of new and contextually appropriate musical content, while De Manzano [109] also remarks that at the time (2010) only four studies on the musical improvisation and in the neuroscience literature could be found. He does stress however the importance of the DLPFC in three of the four studies.

One of these studies, an fMRI study conducted by Limb and Braun, [113] identified a unique pattern of changes inside the prefrontal cortex that were paired with music improvisation or spontaneous composition. The pattern reflected a wide-spread deactivation of the lateral flanks of the PFC and the convergent activation of the medial PFC.

> *“This unique pattern may offer insights into cognitive dissociations that may be intrinsic to the creative process: the innovative, internally motivated production of novel material (at once rule based and highly structured) that can apparently occur outside of conscious awareness and beyond volitional control.”* [113]

By implication this tells us that improvisation, be it through art or music, can only occur when the fundamental rules for that discipline have been embedded. The process of art making involves continuous improvisation and can be compared to some extent with the improvisation required to play jazz music for example, which lies central to the performance of this art form. This improvisation can truly be considered to be a very subjective interpretation by the artist and is a uniquely individualistic expression. Limb and Braun [113] explain how the construction of ‘autobiographical narrative’ and its association with the medial PFC is apropos to the concept of improvisation. Therefore improvisation is a deeply idiosyncratic expression which, together with its associated activity in the medial PFC, concurs with “…an emerging view that the region plays a role in the neural instantiation of self, organizing internally motivated, self-generated, and stimulus-independent behaviors…” [113] The same authors further explain that the frontal polar cortex (BA 10), which are the regions of the MPFC that are activated during improvisation, are still poorly understood but that it seems to play an integrative role in coalescing cognitive modules aimed at higher behavioural objectives. In particular, utilising sets of rules that chaperon ongoing behaviour, executing behavioural subroutines while still maintaining the governing intentions.

Improvisation (which can also be likened to the spontanteous art making process) is described as involving the deactivation of the DLPFC and lateral orbitofrontal cortex (LOFC) [113] which is consistent with other suppositions on *flow* discussed thus far. The DLPFC is believed to be accountable for the planning, implimentation and real-time adjustment to behaviour related to problem-solving or goal-directed, self-monitoring, focussed and conscious attention. Subfunctions of the DLPFC include attention (to current engagements) and response selection; judgement of allowing or suppressing stereotypical responses and the tracking of preceding actions or steps in working memory.[113]

In a study requiring musicians to improvise and subsequently reproduced that improvised piece from short-term memory, Bengtsson et al. [114] utilised fMRI to identify regions in the brain involved in music creation. What the authors discovered was the involvement of the DLPFC in the creative facet of improvisation and as such, in complex behaviour through its ability to select appropriate responses in tandem with a global objective. Phrased differently, the DLPFC is able to freely select behavioural responses based on a overall goal, which in this case would be the generation of musical constructs or ideas with the aim of producing a musical piece that is aesthetically pleasing or satisfactory.

Limb and Braun [113] postulate that, by implication, if this activity in the MPFC along with the co-occuring decrease of activity in the DLPFC and LOFC is indicative of internally driven behaviour, than such self-engendered behaviour are occuring void of context which is typically provided by the lateral prefrontal capacities. Where activation of the lateral prefrontal regions usually supports focused or self-monitoring attention, herewithin we see that its deactivation, which usually results in de-focussed, non-specific awareness allows for spontaneous and unintentional free association, insight and realizations.

> *"…[C]reative intuition may operate when an attenuated DLPFC no longer regulates the contents of consciousness, allowing unfiltered, unconscious, or random thoughts and sensations to emerge. …[R]ather than operating in accordance with conscious strategies and expectations, musical [or artistic] improvisation may be associated with behaviors that conform to rules implemented by the MPFC outside of conscious awareness..."* [113]

Based on this discussion we can therefore say musical improvisation or other forms of artistic composition or creation is implicitly driven and involves a certain measure of intuition. The above mentioned authors refer to studies in other disciplines that have also shown conscious self-monitoring and dedicated attention to be counterproductive with regards to spontaneity and performance.

With more specific regards to flow and improvisation, Sinnamon et al. [115] report only finding one peer-reviewed article on flow states in adult musicians, while only five article were found pertaining to self-reported flow in any musical domain. Therefore, as stressed before, there is a severe scarcity of research on flow within the context of musical improvisation, which is quite surprising given that music and improvisation are activties that frequently elicit peak performance.[116]

2.5 SUMMARY

In summary therefore, "…musical creativity vis-à-vis improvisation may be a result of the combination of intentional, internally generated self expression (MPFC-mediated) with the suspension of self-monitoring and related processes (LOFC and DLPFC-mediated) that typically regulate conscious control of goal-directed, predictable, or planned actions." [113] The intuitive and spontaneous side to such creative expression is an implicitly driven experience grounded in behaviours and skill sets that have been practised and embedded, thereby circumventing the need for intently focussed attention or micromanagement. Instead such actions can occur 'naturally' and spontaneously, as a result of a decrease in cognitive control and frontal activity associated with flow-like states where performance feels effortless and might even peak. During such a flow state, attention allocation becomes broadly distributed. Subsequently performers can become so engrossed in their actions that they become unaware of things happening around them or might lose track of time. These states could be likened to altered states of consciousness or trance-like states and it was expected that electrophysiological activity in the brain would reflect this. Increased lower band activity has been associated with continuous-attention tasks.[117] During such free flowing performance it is also expected that associated physiological changes would be noticeable in e.g. heart and breathing rate, as well as heart rate variability which has been shown to reflect not only the autonomic regulation of the heart by the brain but a strong association with changes in the brains oscillatory behaviour.

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Chapter 3

Research approach and methodological outline.

It is the tension between creativity and scepticism that has produced the stunning and unexpected findings of science.

Carl Sagan

The primary aim of the study was to do an exploratory, multi-modal physiological investigation of heart and brain operatives during live music improvisation. Hemmed into this leading objective were the ancillary aim of investigating the possible occurrences of flow during performances and its associated psychophysiological characteristics and features within the data. In addition, the study attempted to establish rudimentary correlations and associations between frequency components of the EEG and heart rate variability data captured during improvisation and such flow-like states.

An exploratory investigation of electrophysiological rhythms of the brain and the variability in heart rate was instigated during live sessions of musical improvisation. Wireless EEG measurements were taken from the scalps of professional jazz musicians during performances, while a heart monitoring device measured amount and time variability in heart beats. The aim was to explore potential relationships between variables in order to better understand the physiological processes in operation during a high performance state and the experience of optimal performance associated with flow. The following chapter describes the methodological approach taken in this investigative study. Recruitment of participants are discussed, alongside the testing process and equipment used. The process of data analysis is outlined together with the accompanying analytical perspectives and data pre-processing requirements.

3.1 RESEARCH APPROACH

A combination of quantitative and qualitative methods were used in this observational, exploratory, basic research study. Basic research can be described and contrasted with applied research in that its objective can be considered as "…the primary goal of advancing knowledge and theoretical understanding rather than solving practical problems" as opposed to "…the intention of applying the results to some specific problem" vis-à-vis to applied research.[1] Therefore the study aims to advance the knowledge on the subject matter by determining possible statistically significant relationships between variables, while simultaneously taking a chiefly exploratory and descriptive (observational) approach.

The first phase of the study involved the quantitative testing of heart rate variability and electroencephalographic parameters in professional musicians during a session of continuous improvisation (piano) and was followed by a qualitative phase of semi-structured interviews and informal feedback. This was done in order to gain insight into the artists' subjective experiences, in particular, relating to the experience of flow. This personal feedback was used in combination with video/audio recordings, investigative notes and perceived ease-of-play, and the clarity of data to generate a qualitative perspective on each performance to aid the identification of possible states of flow during each routine.

The quantitative phase involved the preparation of subjects with the recording instruments (EMOTIVE EEG headset; Zephyr BioHarness 3 heart monitor) and the subsequent recording of physiological activity within the heart and brain before, during and after a session of continuous improvisation.

The main limiting factors pertaining to the research were the time lost during replacement of damaged equipment and the subsequent (international) importation of new testing equipment and software, resulting in an unforeseen truncation of time available for testing. In addition, a calculated decision was taken during the testing phase of this study to switch to a more powerful software platform for data analysis, but came at the expense of the data that had been accumulated up to that point. Due to the nature of the study and the sole recruitment of professional musicians, the number and availability of suitable candidates played a restrictive role, while nationwide protests on university campuses caused delays at critical points during the conduction of this study. Further limitations are discussed in Chapter 5.

3.1.1 Ethical Considerations

The research proposal and its outlined protocol was tendered to the Ethics Committee and MSc Committees of the Faculty of Health Sciences (UP), and was approved (S15/2015) by both. In light of the objectives of research ethics as stated by Walton, [2] particular emphasis was given to the health or safety of the subject and no risk existed on the subject's behalf. There was no discomforts associated with the equipment. In order to serve the best interest of the individuals involved, all audio and video recordings of performances were made available to the participants for their own personal use and distribution (e.g. for auditions). Results and findings from this study and individual's performances were reported back to each subject.

Pertaining to the ethical soundness of the testing protocol, informed consent was obtained from all participants, as mentioned, and all persons were briefed on the project endeavours, confidentiality, objectives, benefits and their role and rights in the study. The aim, purpose, procedures and duration of the study was discussed with each participant. All persons and personal information associated with the study was handled with the greatest confidentiality and professionalism. Participants were assigned a subject code and all data, results and biographical information were stored securely and password protected. No personal information of any participant has been made available to any third party or, in the case of currently enrolled postgraduate students, could affect any facet of their academic performance or results.

This study was conducted in compliance with GCP (Good Clinical Practice) which is to say that the scientific goals of the study are secondary to the wellbeing of the research participant. The results of this study was recorded and reported in an objective manner and the limitations, restrictions, shortcomings and constraints have been pertinently noted.

3.2 SAMPLE

All subjects were personally invited to participate and were recruited through their own volition. Senior authorities within the Department of Physiology (UP) and the Department of Music (UP) were consulted regarding the identification, invitation and potential recruitment of musicians that fitted the criteria and level of experience required for the study. Testing was conducted at the Musaion Concert Hall (UP) on different days but all in the morning hours, utilizing the same piano, venue and testing equipment.

The testing population consisted of healthy adults of both sexes, above 21 years of age, right-handed, and were all professional jazz-trained pianists of a performance licentiate standard. This is to say that all tested musicians had advanced levels of performance experience coupled with a pronounced amount of performing hours to ensure that those involved were highly skilled practitioners. With a high level of performance expertise, i.e. advanced skill set paired with experience, engagement with flow and peak performance becomes easier and faster.[3] Additionally, in order to get sufficient volume, good resolution and a greater insight into such volatile and complicated conduct as improvisation it was important that participants would be able to improvise continuously without stopping for at least twenty minutes, while performing unrehearsed and unpractised pieces of music. In light of the demanding nature of the testing procedure it was crucial to recruit individuals with the expertise and the experience to meet the challenge.

Prior to arrival, participants were only informed that they were required to improvise but no further information was shared in order to ensure no premeditation on their part, as the intention was to test improvisation exclusively, making it crucial that they had not practiced or recited parts prior to the testing. Upon arrival, all participants were presented with and required to read and sign an Informed Consent document and Information Leaflet and were subsequently briefed on the testing procedure. Time for warm-up was granted prior to testing, however none of the subjects felt it necessary.

Inclusion Criteria	**Exclusion Criteria**
▪ Aged 21+ ▪ Professional status or advanced level of performance experience ▪ Right hand dominant	▪ Wind Instruments ▪ Left hand dominant ▪ Physical disabilities ▪ Use of chronic medication ▪ Prevalence of epilepsy

3.3 MEASURING HEART RATE VARIABILITY

Heart rate variability (HRV) was measured using the Zephyr BioHarness 3™. The BioHarness is a compact electrocardiography (ECG) monitoring unit attached to a Smart Fabric strap for the monitoring of several heart and breathing modules. It is a wireless, light-weight bio-monitoring apparatus that is worn around the torso and can record and transmit physiological information (in real-time or for future reviewing and analysis) to a PC or laptop.

BioHarness™ 3 modules include: [4]

- Heart rate - 0-240 bpm; ±1bpm;
- Breathing rate – 0-120 bpm ±1bpm;
- Heart rate variability (HRV);
- Posture and positioning (±180˚);
- Estimated core temperature (˚C);
- Movement detection (VMU);
- 3-axis acceleration (up to 16g);
- USB connectivity (for data download and charging);
- Bluetooth and/or 802.15.4 (ECHO) connectivity;
- Galvanic skin response (GSR)
- 500+ hours of data storage.

Component Parts:
1. Main fastener hook
2. Main fastener sleeve
3. Size adjustment slider
4. Internal Breathing Rate Sensor
5. ECG sensors
6. Care label with Size, Serial # & Wash symbols
7. Brand label
8. Strap main body
9. Device receptacle
10. Electrical contacts
11. Shoulder strap (detachable, not visible)
12. Shoulder strap adjuster buckle (not visible)
13. Tension indicator loop
14. Strap (rear)

Figure 13: The Zephyr BioHarness [4]

Validity assessments for the BioHarness™ 3 are well in place. Using a bias and Standard Error (SE) of less than 3 beats, the performance of the BioHarness™ 3 against a 3-lead ECG has been validated [high degree of correlation (>0.98)], showing the device to be an effective practical measure for ECG data reading and collection under common exercise conditions [4] and was therefore more than adequate for the study. In addition, the BioHarness™ 3 has been proven an effective tool in the prediction of high, medium and low mental workload [5] and mental fatigue [6] based on HR features.

3.4 MEASURING ELECTROENCEPHALOGRAPHY

For the measurement of brainwaves and electrophysiological activity within the brain, the Emotiv ® EPOC EEG headset was employed. The EMOTIV EPOC headset is an innovative personal brain-computer interface (BCI) device. It is a wireless, high resolution, 14-channel EEG headset, born from the commercial computer gaming industry and was originally developed to bring the mind into the gaming realm. Allowing users to control the movement of characters and objects in a virtual environment using only their thoughts and expressions, development of such rudimentary, commercially available EEG devices have become a growing trend. The system uses dry electrodes (small cotton pads soaked in saline solution) that are clipped to sockets on a headset frame.

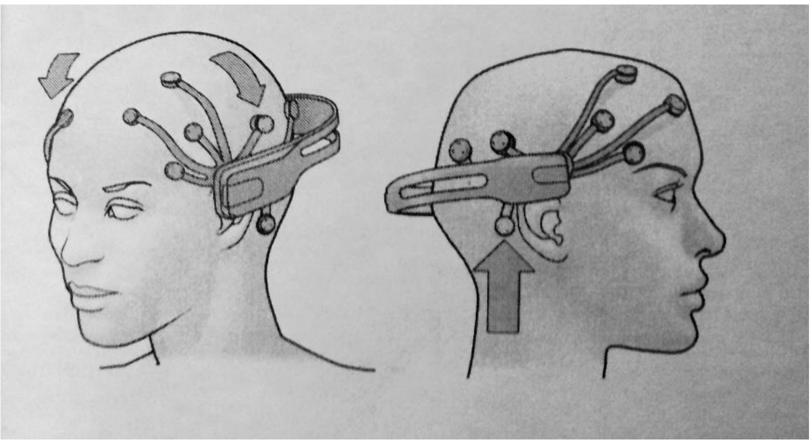

Figure 14: The Emotiv EPOC EEG headset. [15]

The headset frame allows for simple alignment and setup (in accordance with the international 10/20 system), and has a built-in gyroscope for the tracking of head movements. Complimented by a built-in proprietary wireless transmitter (2.4 GHz), real-time EEG data is transmitted over a wireless signal with a bandwidth of 0.2 – 45 Hz (digital notch filters at 50Hz and 60Hz) at a sampling rate of 128 SPS (2048 Hz internal) to a USB receiver.[g] Additionally a USB-rechargeable battery in the headset allows for up to 12 hours of continuous and wireless usage. The 14 EEG channels (excluding 2 reference leads) are positioned as follows: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4 (Figure 15).

The EMOTIV EEG software package includes three detection suites:

1. Expressiv™ suite – Interpretation of the user's facial expressions such as smiling, blinking, winking or frowning.

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[g] A data packet counter in the Testbench™ software interface verifies data transmission integrity and any missing data packets.

2. Affectiv™ suite – Monitoring of user's emotional state, reflecting the user's levels of excitement vs. boredom; attention vs. meditation and focus vs. fatigue.
3. Cognitiv™ suite – Analysis of user's intent and conscious thoughts.[h]

The operational software for this EEG system (Testbench™ SDK) provides real-time streaming of the EEG recordings (5 sec rolling time window), Fast Fourier Transformation (FFT), electrode contact quality and impedance valuation, gyro (head movement), wireless data transmission quality check, event markers and headset battery levels. Raw data can be extracted and exported (.csv format) for analysis. Playback of EEG recordings is also possible at any time.

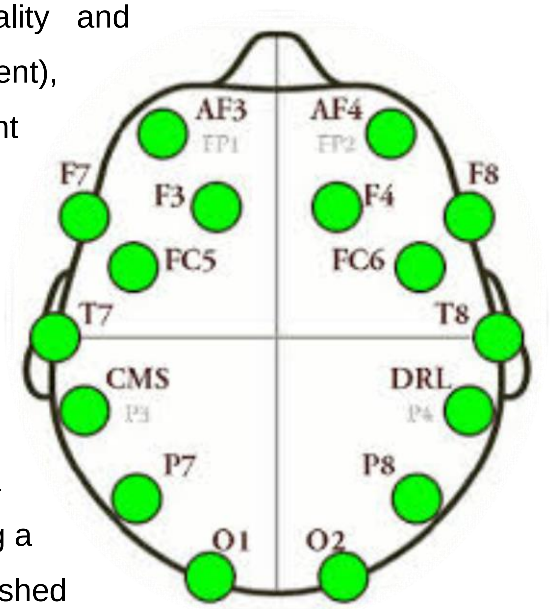

Figure 15: **Electrode placement of the EMOTIV headset**

The validity of the EMOTIV for research purposes have been investigated by only a handful of researchers, most likely due to it being a relatively new research tool. However, all published articles that were consulted were in consensus that EEG data generated by the EMOTIV is comparable to that of conventional EEG standards. [7, 8, 9] In a validity check on the EMOTIV's performance compared to standard EEG systems, Badcock et al. [8] tested the quality of several features of the EMOTIV EEG system in the context of auditory event-related potentials (ERP). Waveform reliability of the EMOTIV system was found to be reliable, though slightly less reliable than the research EEG standard they used. Waveforms amplitude, latency and morphology were found to be analogous to the research EEG and were thereby validated (95% CI; statistically relevant).[i]

Limitations to the EMOTIV system exist due to its expediency, e.g. the drying and fragility of the electrodes, and although the sample rate is not ideal, such wireless systems provide an advantageous autonomy when trying to probe unmapped

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[h] Users can train the module to respond to cognitive input (30 seconds), e.g. when thinking 'rotate clockwise' a user can manipulate a virtual object to rotate accordingly by thinking that instruction. A virtual object can be made to move left, right, up or down; push or pull; rotate along 3 axis or even disappear by thinking such instructions.

[i] Intraclass correlations (ICC) were used in accordance with (13).

scenarios such as real-time creative expression, that have proved difficult in past. Although no published validity checks have been made publicly available by the developers, and access to whitepapers are at this stage limited, non-contextual shortcomings concerning the quality of data, access to raw data and/or its analysis could not be found.

This system does however carry several practical advantages, being a vastly inexpensive alternative to the clinical or laboratory equivalents. Its portability, ease of use, cleaning, wireless capabilities and size/weight proved greatly accommodating given the context of the current study. The system permitted the testing of performers during actual playing while moreover allowing musicians to perform in a natural manner, unrestricted and in a more suitable and conducive environment for such creative expression.

3.5 QUESTIONNAIRE

All subjects were required to complete a short biographical data sheet with the twofold objective of indexing each individuals performance background and expertise, and their basic biographic information. The latter survey centred around physiological and lifestyle factors that might influence HRV such as age, gender, and body mass on one side, while alcohol consumption, smoking habits or sleep abnormalities were also considered. This was a non-standardized questionnaire with the simple aim of eliminating potential perversions and bias within HRV data. The elected questions were grounded in the validation of factors that have been recognised to affect HRV. [10]

3.6 PERIPHERAL RECORDING AND DATA SYNCHING

There was a strong need for the data capturing in this study to be synchronised not only between the different testing modules and equipment, but in a manner that would allow for retrospective analysis. When trying to investigate a phenomenon as volatile as creativity, improvisation or flow it is imperative that high-quality, meaningful peripheral recording methods are set in place during testing, so that performances may be revisited during analysis. Visual recordings of each performance was captured using a GoPro Hero3 camera, mounted peripherally so as to capture each musicians' display. Due to the inimitable fashion and distinctiveness of each performance, playback of visual recordings proved to be a valuable asset during the review process.

Performances were recorded in an acoustically pristine environment and all recordings were made available to participants for their own personal use or distribution.

On the second front, time stamping of events that might negatively or positively influence the subject’s performance were logged during each session. Relevant or potentially relevant events that might cause artifacts within the data (e.g. disruptive movements), impede the occurrence of flow (e.g. distractions or mistakes), or suggest the occurrence of flow (e.g. perceived effortlessness, positive affect) were logged and reflected against the data during the analysis phase.

Time stamping of events and stages of the performances also served an additional purpose in ensuring the synchronicity between the different testing modules. Due to the use of separate systems and software platforms, the synchronicity of the data was of the highest priority and all recording starting/change-over times were logged, and paired relative to a centralized chronograph.

3.7 OUTLINE OF PROCESS

After completion of the biographical questionnaire (Appendix B) and informed consent (Appendix A) participants were briefed and prepared for testing.

3.7.1 Preparation

Preparation consisted of impedance and connectivity checks, together with the physical setup of the testing equipment and took about 10 - 15 minutes. The sponge electrodes of the EEG headset were moistened with common saline solution in advance, while the heart band also needed moistening prior to attachment. Subjects were asked to fit the Zephyr heart band in private following instruction, due to the need for the strap to make contact with the skin around the torso. Subsequently, the EMOTIV EEG headset was placed onto the head of the subject. Alignment and impedance checks were conducted at this point to ensure 100% connectivity, data transfer and absolute signal generation from all electrodes. Both devices were wirelessly connected to the recording laptop (Windows 7 OS) through their respective receivers and once all devices were operational, central and peripheral recordings were initiated and the testing procedure commenced.

3.7.2 Testing procedure

The first stage of testing consisted of a six minute baseline measurement (E1) after which participants were asked to improvise continuously (no stopping) for an undetermined period of time (open frame; OF), followed directly with an inverse replication of the baseline measurement (E2) upon completion.

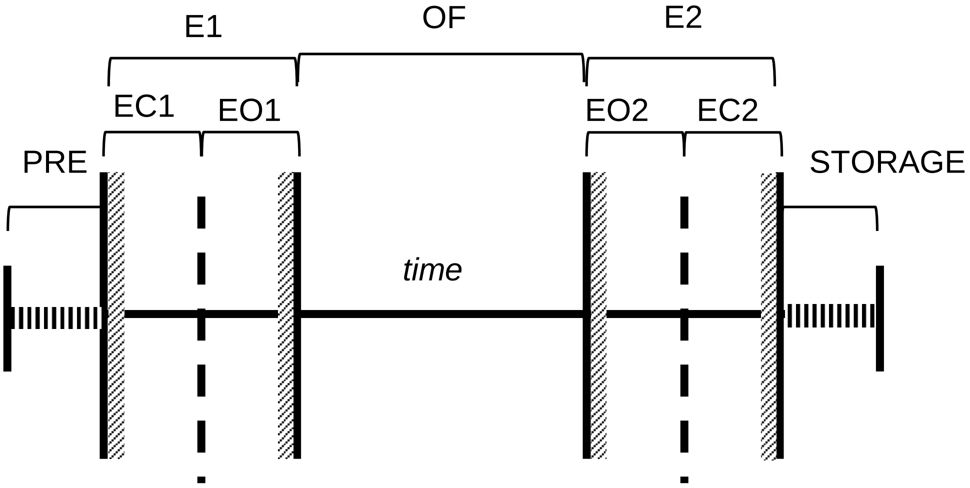

Figure 16: The different phases of the testing procedure. *An initial baseline (E1) is done after preparation (PREP) has been completed, followed by the improvisation performance (OF). Directly after conclusion of the performance, a comparative baseline measurement was performed (E2).EC and EO refer to the eyes-closed and eyes-open divisions of the baseline measurements.*

3.7.2.1 E1 (baseline)

The six minute baseline prior to improvisation required subjects to sit quiet and motionless for 3 minutes with their eyes closed (EC1), followed sequentially by a 3 minute ‘eyes open’ period (EO1). EC1 was conducted as a stabilisation phase to allow participants to become calm, relaxed and alleviate tension from the preparations or prior engagement. EO1 in that regard reflects the true baseline and was used for normalisation and relation during the analysis of each performance.

Phase time: 6 minutes

3.7.2.2 OF (open frame)

Following successful completion of E1, subjects commenced immediately with their performance and continued in a non-stop fashion until completion. Subject were allowed to improvise for any amount of time that they were comfortable with and were not interrupted or distracted.[j] The participant was now allowed to move accordingly, but were reminded to refrain from making noises or overly expressive head movements.

Phase time: 20 – 50 minutes.

3.7.2.3 E2 (comparative baseline)

Directly following the conclusion of performance (OF) an inverse replication of the baseline measurement was conducted. Subjects were required to take their hands off the piano, and sit comfortably with their eyes open for 3 minutes first (EO2) followed by a 3 minute ‘eyes closed’ period (EC2). As in E1 subjects were required to remain quiet and motionless. Here EO2 would represent the stabilisation measure, allowing participants to equalise after their performance, and EC2 could be used to compare before and after baseline values.

Phase time: 6 minutes

Total testing estimate: 35 – 65 minutes

This concludes the testing procedure (quantitative phase). Testing equipment was removed, cleaned and stored. All data was stored and backed up and the informal interview and feedback commenced (qualitative phase). Participants were asked about their performances and how they felt they played, with special focus on flow and its occurrence in order to assist in identifying stages of each performance where subjects felt they reached flow, peak performance, in-the-moment sensations, or any possible distractions or atypical disengagements.

3.8 OUTLINE OF DATA ANALYSIS

For data analysis purposes two supplementary software platforms were employed.

HRV data was captured using the complimentary OmniSense software of the Zephyr BioHarness as mentioned above, and raw data was subsequently exported to Kubios

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[j] The investigation centred on the freedom on the subject’s behalf to play for an undetermined period of time. The rationale here is to allow the subject to perform for as long as they felt comfortable with and remained engaged and focussed on their performance. Having the creative freedom to perform to their own ability and motivation not only generated a greater deal of data, but allowed the free expression of each subject to find their groove, and so reach flow on their own terms. When subjects started disengaging due to fatigue or boredom they could then stop at their own volition. Hereby, the recordings were grounded in the individuals own engagements with the music and their performance, uninterrupted and free of predetermination from the external environment or researcher.

HRV (version 2.2) for analyses. Kubios HRV is an advance heart rate variability analysis tool that provides a wide variety of different analysis options, suitable for both research and clinical purposes. Data was screened for ectopic and missed beats and was rectified using a built-in artifact correction implement. Successive windowing of the data was done so as to generate frequency components and their respective power values for every 30 seconds of data and is outlined in Chapter 4.

EEG data was directly recorded into the BioExplorer 1.6 software platform developed by CyberEvolution [11] and is used for real-time biophysical data processing and display. The software has a comprehensive range of tools, features and investigative outfits for filtering, analyses and graphic representation of the electrophysiological data. Although the platform shows greater utility for the graphical illustration of data captured, tables were generated for the respective spectral analysis and its complimentary power and amplitude outputs for every 30 seconds of data. This too is described further in Chapter 4. Transmitted data from all electrode sites were verified and confirmed to be below the recommended impedances levels (0.5 Ω). Due to the movement involved with playing an instrument it is to be expected that naturally occurring artifacts would be present in the data. During testing data was visually inspected for abnormalities and the greatest of these were noted and time stamped for later consideration.

Pre-processing of the EEG data involved separating the signals from the Emotiv into its respective electrode constituents (sites), and each channel (source) was directed through a filtering component in order to remove unwarranted frequencies and signals falling outside the desired frequency range. A band-pass filter (0.5 – 35Hz) was therefore imposed on the signals from each electrode, allowing only those frequencies to pass through and henceforth eliminating those frequencies that fall outside this range. Amplitude values were calculated, enabling the calculation of spectral power components.

Due to the exorbitant amount of data generated for each subject, the analytical approach was compartmentalised into three diverging perspectives so as to systematically investigate (and explore) the data. These perspectives have the shared aim of describing the shifts and generalisations that were observed within different stages of each individuals' performance but carry dedicated focal areas of investigation. These three perspectives concern primarily the EEG data and can be described as follows:

3.8.1 A Means Perspective

This basic (mean) perspective revolves around the mean values of the different stages, and by calculating such means, this perspective allows for a basic resolution and comparison of the mean spectral values for each stage and subject. The main focus in this perspective revolves around the comparison of baseline stages and whether noteworthy differences are found before and after improvisation.

Research questions that are asked from this perspective involve: How does the overall baseline power means compare to that of the performance? Are there notable differences in the means of the two baselines? Are there noticeable or lingering effects within certain spectral bands following improvisation? Are there consistent changes between individuals?

3.8.2 A Dynamic Perspective

This perspective attempts to give greater insight and focus to the performance stage itself, taking a simpler approach to the means perspective, but instead looking at the global, hemispheric and regional power contributions during the act of improvisation. The approach follows mainly a descriptive valuation of the data and its graphical representations, with the intention of defining trends and shifts in the data rather than robust statistical analysis.

Research questions that are posed from this perspective involve: Are there noteworthy amplitude/power shifts occurring during the performance? Are there important shifts in regional and hemispheric dominance? What are the overall trends in each of the power bands and are is this consistent across subjects?

3.8.3 A Biasing Perspective

This perspective revolves around the subdivision of the testing stages into differing epochs (time intervals) in order to advance a greater resolution on the shifting trends that are taking place during performance. Due to the subjective experience of flow and the idiosyncratic nature of the improving performances of every subject, it was thought valuable to include a biasing or subjective perspective with the objective of describing trends and activity in the data as occurring in and around moments of flow. The ‘bias’ therefore lies simply in the fact that feedback received from subjects in conjunction with subjective investigative measures are combined to pinpoint the incidences of flow. As there are no objective measures for flow, the reliance on subjects to report such occurrences in retrospect constitute this perspective and its partiality. Subject feedback, video review, independent investigator notes, clarity of data, and perceived ease-of-play was all taken into consideration and combined to identify the most likely time periods of each performance where individuals experienced flow. Through adding this bias it was possible to focus the explorative investigation of shifts and trends in the data in and around certain approximated ‘flow zones’.

Research questions asked from this perspective involved: How long into the performance did flow first occur? Are there any noteworthy shifts in overall, regional or hemispheric power during, prior or after windowed flow zones? What are the dominant frequencies, and spectral expression around these times? Is there consistency between individuals concerning the landscape of the data during these times?

3.8.4 Correlating heart and brain

HRV data is described and presented throughout several of the aforementioned perspectives. Through power spectral density (PSD) analysis of HRV data, the high (HF) and low frequency (LF) components could be extracted, allowing the investigation of the autonomic influence from the brain on the heart. Through this frequency-domain analysis, the power and balancing actions of the sympathetic and parasympathetic branches of the ANS could be quantified and described. Frequency components of the HRV data was analysed over a 3minute window and shifted by 30 seconds in order to generate band power values for each half minute of testing. This approach is an altered rendition of an analysis strategy employed by Jurysta et al. [12]

Normalized power values for both HRV and EEG data was employed during all analytical perspectives so as to reflect band power values as ratios of their respective baseline means. Through normalisation of the data it becomes feasible to bridge the gap between such relative power values as calculated for each subject, spectral band and oscillatory system. EEG data, already in the frequency domain, can be processed through Fast Fourier Transformation (FFT) to generate its respective spectral components (i.e. frequency bands namely Alpha, Theta, Delta etc.) in much the same way that HRV is divorced into its high and low frequency components . By normalizing both HRV and EEG data against their respective baseline mean, such separate datasets that operate at different, distinct frequencies and are relative to each subject can be compared or plotted on the same graph for comparison and correlative associations [see (12)].

3.8.5 Statistical implementation

Descriptive statistics surrounding the test population is presented. In combination, bivariate and non-parametric statistical methods were employed in examination of the data, however the small sample size did not lend itself out to further statistical analysis. Amongst other, it is mainly for these reasons that an exploratory study was conducted with a greater descriptive outlook. Statistical approaches as described further in the following chapter.

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Chapter 4

Research outcomes and results.

Creativity itself doesn't care at all about results - the only thing it craves is the process. Learn to love the process and let whatever happens next happen, without fussing too much about it. Work like a monk, or a mule, or some other representative metaphor for diligence. Love the work. Destiny will do what it wants with you, regardless.

Elizabeth Gilbert

4.1 INTRODUCTION TO RESULTS

This chapter presents the results for the current investigation. An exploratory, multi-modal investigation was conducted into the nature of improvisation and flow and its underlying physiological expressions within the heart and brain. Recorded autonomic functioning and electrophysiological activity are presented in this chapter and prominent trends and shifts within the data are described. The occurrence of flow during performances and its associated psychophysiological characteristics and features within the data are explored. Despite being an exploratory investigation, the overall enquiry of this study carries a definitive determination of whether flow induced noticeable physiological events such as a harmonisation of activity between and within oscillatory systems or significant correlates within the data.

By coalescing differing perspectives with specific focal areas, findings and outcomes are compartmentalised through diverging points of view (perspectives) to systematically disentangle the wealth of data generated during the testing phases. These three perspectives are referred to as the (I) Means perspective, (II) Dynamic perspective and (III) Biasing perspective and are put forth in the sections to follow. A general top-down approach was followed in assessing the power spectra associated with each dataset and within each of the aforementioned perspectives, typically starting with the global (overall) impressions. Subsequently, hemispheric (left/right), regional (frontal and temporal expanses specifically) and individual electrode contributions are investigated.

Summarising points after each section alongside a brief concluding discussion of the results at the end of the chapter are provided. An integrated and comprehensive discussion can be found in Chapter 5.

Typically, derivation of spectral power values are reported in Volts-squared per Hz (V2/Hz) or ms squared (ms2) as its units, however due to the number of transformations and rescaling that the data undergoes from the initial voltage measurements (amplitude), values might no longer have a basic linear correlation to Volt units. Instead, none conventional units are ascribed and it should henceforth be clarified that power spectra values have been normalised against each persons’ and each bands respective baseline mean (EO1) or total power. Put differently, all power measures have been reflected against their particular baselines for each subject, thereby reflecting a ratio of the dynamic outputs against the baseline average power. This allows for a better comparison between spectra that naturally carry different amplitudes, but also a more rational comparison between subjects as such normalised units (n.u) therefore convey relative changes of each individual.

As mentioned EO1 serves as the baseline stage in each performance, as EC1 served more stabilising purpose from preceding tensions and exertions leading up to testing. In addition, EO1 is also the eyes open, resting state immediately prior to performance, making it a more appropriate control compared to the eyes-closed state where the person might become somnolent. By normalising the values it becomes possible to compare the magnitude of relative changes within and between separate datasets, and in relation therefore a value of 1n.u would therefore be of equal power magnitude to that of the baseline mean. A power value of 2 n.u for instance would thus be double that of the baseline, and 0.5 n.u would be half.

4.2 TECHNICAL SPECIFICATIONS

In view of the forthcoming exposition, further elucidation is offered on certain technical stipulations and particulars of the study.

4.2.1 EEG specifications and outline

Pertaining to the tech riders and preliminary analysis of the EEG, all electrode signals were visually inspected throughout testing for overt artifacts. Pre-processing involved the mitigation of all electrode signals using low- and high-pass FIR (finite impulse response) filters.[k] This was done to attenuate the data of artifactual signals falling outside the desired range of frequencies caused by e.g. environmental or high-frequency noise. The desired range was from 0.5 – 35 Hz, including therefore the delta, theta, alpha, SMR and beta bands, with the omission of the gamma band (above 35 Hz).

FIR filters carry the advantages of giving stable output signals, due to it being non-recursive, while having a constant delay for all frequency bands implying that the signal shape will not be influenced through phase shifts.[1] A manual adjustment of the default FIR filter offsets were made in order to ensure a flat passband over the sought

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[k] An order of 60 was selected (software maximum). Increased order of FIR filters result in a sharper cut-offs at the boundaries of the specified frequency range.[1]

frequency range as illustrated in Figure 17 and was intentionally made to sharpen the fall-off at the set boundaries without loss of power at the end of the passband (0.5 - 35 Hz). Therefore the high-end offset was extended past 35 Hz to 39 Hz which also altered the pass band to not drop off higher than 0.5 Hz but remain level up to this frequency. Spectral, and thus power analysis of EEG signals are the main analytical approach of the study and a steep roll-off at this passband boundaries are essential. Any premature drop-offs at the passband boundaries would drastically reduce power outputs of any frequencies that fall within these end segments. Therefore, a flat pass band would infer absolute power magnitudes within the desired range with no loss of power towards the offsets.

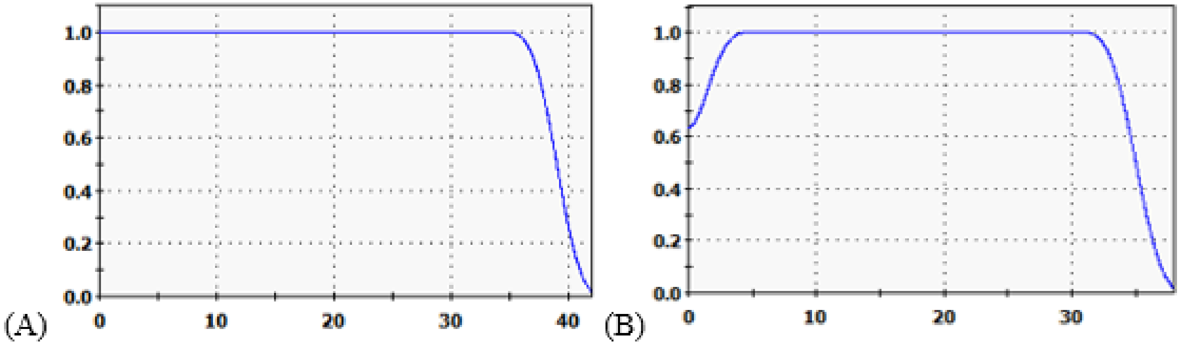

Figure 17: The pass band magnitude of the manually altered FIR offset (A) set at 39 Hz, showing a flat passband from 0.5-35 Hz; versus default offsets set at 0.5-35 Hz (B). *In (B), setting the offsets to the exact values results in an attenuation of the frequencies at the edges of the filters, inferring a increasingly steep loss of power of the frequencies at the edges of the specified range.*

For each subject, the EMOTIV signal was separated out so that each electrode signal was isolated as an independent source. All channels were sampled at 128 Hz. The described filters were applied to all sources, after which spectral components were sequestered and quantified using the BioExplorer software. This is to say that spectral band amplitudes were extracted for the calculation of the relative power of each frequency band at different electrode, regional and hemispheric sites. A quality check was done in comparison with the raw signal to ensure no overlap between filtered bands due to the extension of the upper boundary offset. No additional artifact removal/correction was applied in preservation of the totality of the data, and thus it remains possible for the data to be marginally contaminated by artifacts that fall within the band-pass range.

Conventional frequency bands were stipulated as falling within the specific ranges of 0.5 - 4 Hz (Delta), 4 - 8 Hz (Theta), 8 - 12 Hz (Alpha), 12 - 15 Hz (SMR) and 15 - 25 Hz (Beta), as apportioned by the software platform. Signal amplitudes were quantified and power spectra were estimated for each frequency band through application of Fast Fourier transformation (FFT), and was applied using a rectangular window and averaged for every 30 sec of data. The spectrum power was scaled so that the power of a 50 μV sine-wave was 1250 $(\mu V)^2$. EEG spectral power was normalised against the baseline means for each power band and subject and are consequently expressed in normalised units (n.u).

Concerning the regional demarcations, it should be clarified that due to the particular electrode configuration and montage of the EMOTIV EEG headset, regional investigations orbited around specific combinations of electrode sites. Regional electrode allocations were defined as involving the following electrode sites:

- AF3, F3, F7 (Frontal Left region);
- AF4, F4, F8 (Frontal Right region);
- F7, FC5, T7 (Temporal Left region);
- F8, FC6, T8 (Temporal Right region).

Parietal and occipital regions were disqualified due to the shortage of electrode sites in these regions (one parietal site; one occipital site) and preliminary acumens from the data preparation.

4.2.2 HRV specifications and outline

The ECG was recorded at a sensor sampling rate of 1000 Hz and reporting frequency of 250 Hz. A built-in automated algorithm was used to detect the QRS complexes, so that RRI time intervals and series could be calculated. Ectopic beats, artifacts and premature ventricular contractions were detected using the criteria RRI < 350 ms and RRI > 1500 ms. A quality check was imposed to assess the percentage of contaminated data and revealed less than 0.97% (mean) of the data to contain ectopic or artifactual beats (min= 0.54%; max= 1.24%). Due to the low percentage of 'abnormal' values, a low artifact correction method was imposed on the data, set at a threshold of 0.35s from the local mean RR interval. The RR series was interpolated using a cubic-spline interpolation method (2), sampled at 4 Hz and the power spectrum values were calculated for each 30 sec in a 180 sec window.[l]

Each analysed window contained 180 sec of RRI data over which HRV frequency components were calculated, and the window was shifted by 30 sec interludes, resulting in the obtainment of data values for each 30 sec of data.[m] Spectral components for the HRV were computed: LF (0.04 Hz < f < 0.45 Hz); HF (0.15 < f < 0.4 Hz), alongside the LF to HF ratio (LF/HF). Power values were normalised against the total power, thus LFnu = LF/(LF + HF), and HFnu = HF/(LF + HF). Consequently, power spectral density (PSD) was used with a spectrogram algorithm using FFT on 180 sec of data (sampled at 4 Hz) to generate a 256 points PSD with 50 % window overlap. LF and HF power and normalised power values could be obtained for each 30 sec of the data set.[n]

4.2.3 Statistical specifications and outline

As is evident from the research approach, an exploratory investigation was piloted here due to the complexity of not only the task at hand, but by the same token that of the data generated from this enterprise too. Testing of individuals during real-time creative expression, let alone improvisation on such a specialized level presents with many difficulties and limitation. An exorbitant amount of multifaceted data was recorded for each individual performance which comprised of a large number of variables, each pertaining to various different localities, exacting modifications and implications, and on a large scale of processing and consolidation. In addition, given the duration of each performance, i.e. the size of each data set, the number of processing steps and the subdivisions of analytical perspectives and testing phases, robust statistical analysis is challenging.

It is for these same reasons and, in addition and perhaps more significantly, the small sample size that an exploratory statistical approach was implemented as such multivariate data paired with a small testing population restricts the use of vigorous statistical strategies. Instead a more descriptive line of attack was taken, graphically

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[l] All power spectra analysis of the RRI time series was performed in accordance with the recommendations of the Task Force of the European Society of Cardiology. [14]

[m] This is a modified approach similar to that used by Jurysta, et al. [12]

[n] 30 sec intervals allow for the same number of power estimates for both ECG and EEG.

illustrating prominent trends and features in the data, and supplemented with a basic correlative, non-parametric statistical approach.

Correlation matrices were constructed for intersubjective, inter-spectral and time based comparisons in the form of Spearman’s Rank Order Correlations analysis in order to investigate any significant (P<0.05) relationships within the data. Any such findings were then reflected back against the graphical depictions so as to get a rounded interpretation of the presented findings and stated where applicable.

In supplementation of these statistics and given the small sample size, bootstrapping techniques was incorporated to support and verify findings of significance. Bootstrapping is a resampling technique used to generate random “copies” of a sample statistic in order to assign measures of accuracy to sample estimates (e.g. bias, confidence intervals, variance or error prediction). By random resampling (1000 samples) the sample size is therefore exaggerated and lends additional support to the correlative tests performed by establishing whether such correlations fall within a confidence interval (95%). In this regards significant correlations and differences were only reported if both Spearman and Bootstrapped correlation matrices showed corresponding significance.

In addition, a Friedman test was performed as a non-parametric alternative used to test the same sample of cases at different conditions or times. Here it was used to assess the differences of power spectra at designated time intervals in order to compare the mean ranks of spectral power during continued performances. The findings from this analysis are presented and explained further in a separate section below (section 4.6.1.1).

Ideally, cross correlative measures were sought after in order to assess the level of coherence between HRV and EEG power spectra within a concluding perspective. Comparing the level of coherence between the normalised values of these two time series would have proved ideal but statistical resources for such advanced methodologies proved problematic. One method suggesting the comparison of the slopes of each series within designated windows was rejected due to the lack of objective measures of flow and its duration, as the intention behind such cross coherence analysis lied with establishing whether a level of synchronicity between brain and heart activity arose during flow.

None the less, exploratory statistical support and correlations are presented where found within the confines of such a descriptive and exploratory approach, and appropriate findings are expressed where applicable. All statistical analysis were performed using SPSS (version 23).

4.3 SAMPLE DEMOGRAPHICS AND DESCRIPTORS

4.3.1 Demographic descriptors

Upon invitation, eleven individuals responded and nine subjects volunteered for the study. Due to the replacement of the preliminary analytical software (Chapter 2), two datasets were consequently excluded due to compatibility issues between the captured data and the altered software platform. In addition, two more subjects had to be disregarded due to data quality inadequacies. The sample therefore consisted of three males and two females (N=5), with the mean age = 25.8 years (SD = 1.6; range = 24 – 27 years). Some demographic characteristics of the sample are summarized in Table 4.1.

Table 1: Demographics of the sample

Variable	Mean	SD	Minimum	Maximum
Age (years)	25.8	1.6	24	27
Height (cm)	172.4	11.9	155	182
Mass (kg)	68.6	13.3	54	90
Hours of sleep (night before)	6.4	1.14	5	8

The sample comprised of three African and two Caucasian individuals. Two individuals admitted to being smokers, however both participants reported smoking on average no more than 5-7 cigarettes per day. No alcohol consumption was reported for the evening prior to testing. Likewise, no chronic illnesses or medication needs were reported, however one subject did report experiencing slight insomnia in the days preceding testing. No other sleep abnormalities were reported.

Individual testing was conducted on separate occasions over two weeks, but all between 9.30 – 11.30 am. The sample population boasted three Master’s degrees (MMus), with all participants having finished at least their Bachelor’s degree in Music (BMus). Two subjects were piano teachers at tertiary level and all participants performed frequently, both recreationally and professionally, and were therefore of a very high performance licentiate standard.

4.3.2 Performance descriptors

As described earlier each performance consisted of an initial baseline measurement (E1) that consisted of a 3 minute eyes-closed (EC1) and subsequent 3 minute eyes-open (EO1) inactive period. Following the baseline measurement, subjects commenced their performance (OF) and improvised continuously for a self-determined period, followed by an inverse repetition of the baseline measurement (E2).

The comparative baseline (E2) involved a 3 minute eyes-open (EO2) phase followed immediately with a 3 minute eyes-closed period (EC2). Both baselines were conducted in motionless silence with the individual looking at a blank wall in front of them with no visual or auditory stimulations or distractions present.

Between subjects the mean performance phase (OF) length was 28.8 minutes (mean) with the total testing times (E1+OF+E2) rendered at a mean of 40.8 minutes (SD = 8.89; Range = 30 – 51 minutes). Participants were allocated a code-letter as alias and are henceforth referred to as Subject A – E from this point onwards.

Table 2: Performance times for each subject

	E1 (min)	OF (min)	E2 (min)
Subject A	3 + 3	33	3 + 3
Subject B	3 + 3	51	3 + 3
Subject C	3 + 3	30	3 + 3
Subject D	3 + 3	45	3 + 3
Subject E	3 + 3	45	3 + 3

4.4 A MEANS PERSPECTIVE

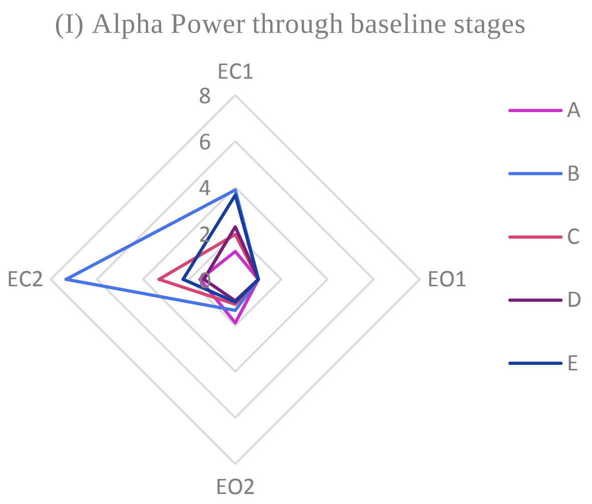
This preliminary perspective can be considered one of basic resolution with the rudimentary objective of assessing whether there were substantial differences and/or prominent shifts occurring between the two baseline measurements – i.e. before and after improvisation. The assessment involved comparison of band power means between the two baseline measurements. Global and hemispheric means are reported, alongside a more progressive surveying of the particular outputs from regional and electrode sites across the baseline phases. Both the original (E1) and comparative (E2) baselines consist of an eyes-closed (ECx) and eyes-open (EOx) component. As described EO1 acts as normalising reference, while EO2 serves also to stabilise the subject immediately after performance. Hereby the comparison of EO1 and EC2 are of greater importance and represent a truer comparison of the baselines.

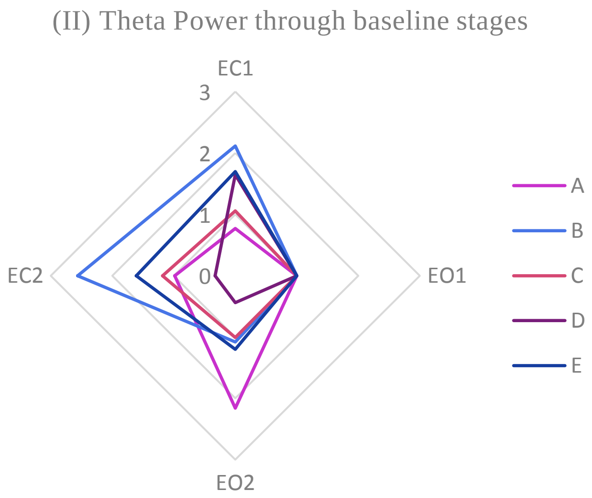
4.4.1 Global EEG Means

Figures 18 and 19 represent the different frequency bands and their relative, normalised power for the baseline stages of each performance. Note that EO1 is always 1 n.u, while the other stages reflect the ratios of their means against that of EO1. In general summation of the global mean power differences, a comparison between subjects showed greater variation within the Alpha and Theta bands (I & II, Figure 18). Beta and SMR bands (III, Figure 18; V, Figure 19) showed greater consistency between subjects, while individualistic outliers are most prevalent within the Delta (A & E) band and therefore shows the lesser consistency. Such inconsistent variations (Alpha and Theta) could imply greater recruitment of those frequencies during improvisation as there are greater differences before and after its execution, versus the steady out puts of SMR and Beta compared to the original baseline. However, it is well known that Alpha power increases when the eyes are closed, and the Alpha band power shows such typical increases when looking at the EC stages. There is thus a general trend for Alpha power to increase once the eyes close and therefore needs deeper enquiry, also given that EC2 generally shows greater strength compared to EC1.

Focussing on the Theta spectral band, subjects show very dissimilar responses. As stated, such inordinate variation could infer greater involvement and utility of theta activity during performance, as one might expect perhaps that were improvisation not engaging the brain within this frequency range, that subjects would show uniform responses after the performances. Such uniformity presents in the Beta (III) and SMR (V) bands, where subjects show more similar and consistent responses at baseline.

Figure 20 illustrates the averaged means from all subjects, and therefore a composite comparison for each power band at baseline. Both alpha and theta bands showed significant positive correlations between EO1 and EC2 (P=.037, 95% CI) supporting the notion that there was significant differences before and after improvisation within these bands. Additionally, alpha also showed correlation between the two eyes-closed stages (P=.037; 95% CI). Beta and SMR once more show consistency between stages with very little differences between stages. Both these bands showed various significant differences between EC1 and the other stages (see table 4), which again strengthens the necessity for the inclusion of a stabilising baseline phase as was included. Delta showed no significant correlations, however a positive non-significant correlation was found between EO1 and EC2 (P=.188), showing therefore an association between before and after measures in delta. Major shifts in


(I) Alpha Power through baseline stages


(II) Theta Power through baseline stages

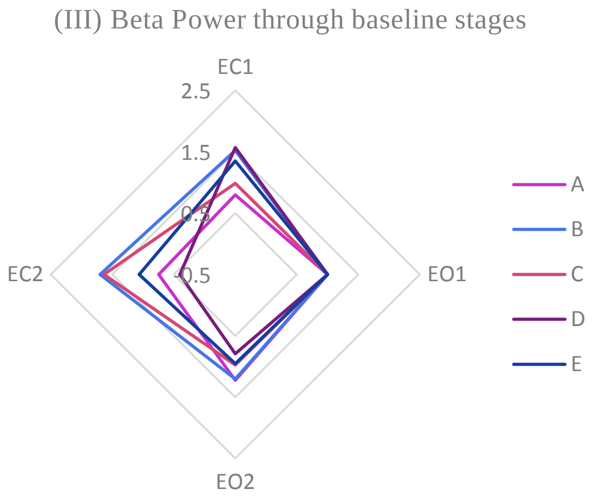
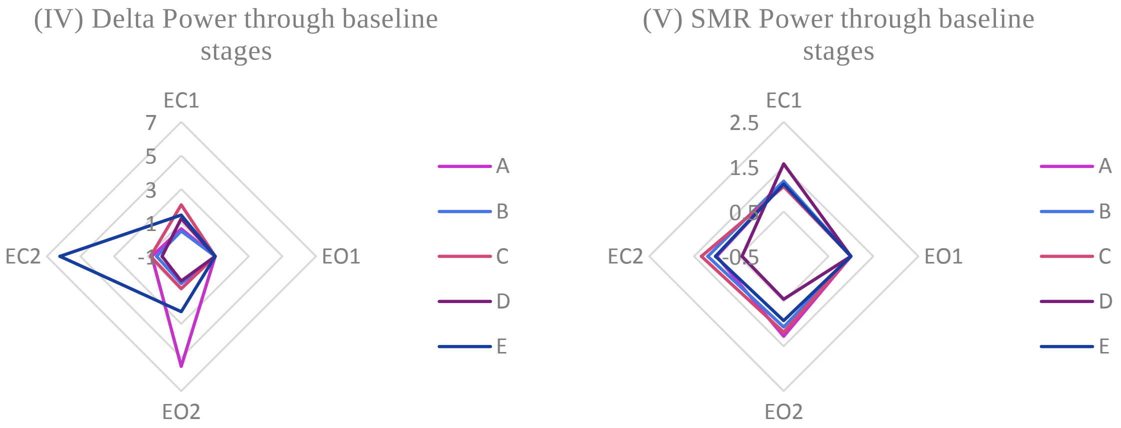

(III) Beta Power through baseline stages

Figure 18: (I) Alpha, (II) Theta and (III) Beta band power baseline means per subject. *Comparisons between EO1 and EC2 form the main points of interest. Normalised units (n.u.).*

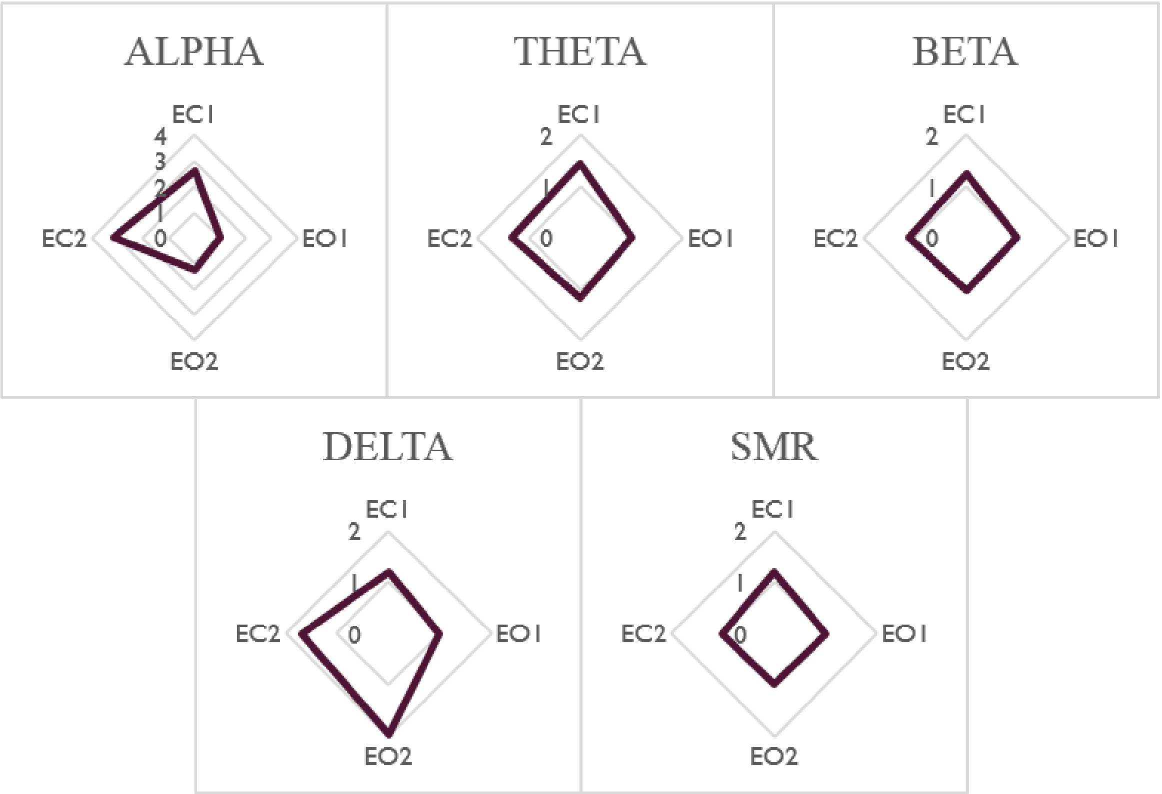
Delta in Figure 20 may therefore likely be misleading due to the massive differences by two particular subjects, as shown in Figure 19.



(IV) Delta Power through baseline stages

(V) SMR Power through baseline stages

Figure 19: (IV) Delta and (V) SMR band power baseline means per subject. *Normalised units (n.u).*



ALPHA

THETA

BETA

DELTA

SMR

Figure 20: Composite power distributions for each frequency band and stage of baseline measurements.

Table 3: Notable and significant correlations at baseline stages for the population means – Spearman's Rho

		DELTA				THETA				ALPHA				SMR				BETA			
		EC1	EO1	EO2	EC2	EC1	EO1	EO2	EC2	EC1	EO1	EO2	EC2	EC1	EO1	EO2	EC2	EC1	EO1	EO2	EC2
EC1	CC		-	-	-		.900*	-	-			.700	.900*		-	-	.900*		.900*	.900*	.900*
	Sig.		-	-	-		.037	-	-		-	.188	.037		-	-	.037		.037	.037	.037
	N		-	-	-		5	-	-			5	5		-	-	5		5	5	5
	Bias		-	-	-		-.055	-	-			-.036	-.036		-	-	-.066		-.037	-.037	-.047
	Std.Err		-	-	-		.303	-	-			.434	.434		-	-	.313		.24	.24	.295
EO1	CC	-		-	-	.900*		.700	.900*			.700	.900*	-		-	.900*	.900*		-	.800
	Sig.	-		-	-	.037		.188	.037	-		.188	.037	-		-	.037	.037		-	.104
	N	-		-	-	5		5	5			5	5	-		-	5	5		-	5
	Bias	-		-	-	-.055		-.035	-.055			-.054	-.054	-		-	-.066	-.037		-	-.084
	Std.Err	-		-	-	.303		.442	.303			.297	.297	-		-	.313	.24		-	.332
EO2	CC	-	-		-	-	.700		-	.700	.700		-	-	-		.900*	.900*	-		.800
	Sig.	-	-		-	-	.188		-	.188	.188		-	-	-		.037	.037	-		.104
	N	-	-		-	-	5		-	5	5		-	-	-		5	5	-		5
	Bias	-	-		-	-	-.035		-	-.036	-.054		-	-	-		-.066	-.037	-		-.084
	Std.Err	-	-		-	-	.442		-	.434	.297		-	-	-		.313	.24	-		.332
EC2	CC	-	-	-		-	.900*	-		.900*	.900*	-		.900*	.900*	.900*		.900*	.800	.800	
	Sig.	-	-	-		-	.037	-		.037	.037	-		.037	.037	.037		.037	.104	.104	
	N	-	-	-		-	5	-		5	5	-		5	5	5		5	5	5	
	Bias	-	-	-		-	-.055	-		-.036	-.054	-		-.066	-.066	-.066		-.047	-.084	-.084	
	Std.Err	-	-	-		-	.303	-		.434	.297	-		.313	.313	.313		.295	.332	.332	

*. Correlation is significant at the 0.05 level (2-tailed).

For HRV analysis for each of the baseline stages:

Table 4: HF power and LF/HF ratio at baseline stages

	Mean HF power (ms^2)	Range	Mean HF power (n.u)	Mean LF/HF
EC1	929.6	250-1170	41.04 ± 20.4	2.64
EO1	840.6	110 – 1925	42.48 ± 20.5	2.12
EO2	750.1	106 – 2690	28.98 ± 16.1	3.82
EC2	1244.3	146 – 4260	41.49 ± 18.6	3.00

No significant correlations between stages were found, however the table above can be interpreted to mirror that HF power is typically higher in the comparative baseline. Through the increased LF/HF ratio and declining HF normalised power however we can see that this is misleading as LF is also higher at this stage (LF/HF) and therefore reflects a higher level of sympathetic dominance after performances despite higher HF power.

Summarising point: The overall impression is that globally Alpha and Theta bands show greater variation between individuals, as well as respective significant differences before and after improvisation. This might infer a greater recruitment of these frequency bands during creative expression and more so than that of Beta and SMR bands which show equal power outputs at both baseline measures. The Delta response proves ambiguous and non-conclusive while no significant differences or correlations were found between the original and comparative baselines.

4.4.2 Hemispheric EEG Means

Hemispheric band power means were calculated for laterally designated electrode sites with the aim of examining the contributions from each hemisphere towards the global power laid out in the previous section. Within the same perspective, baseline values are compared, described and correlated for each power band respectively.

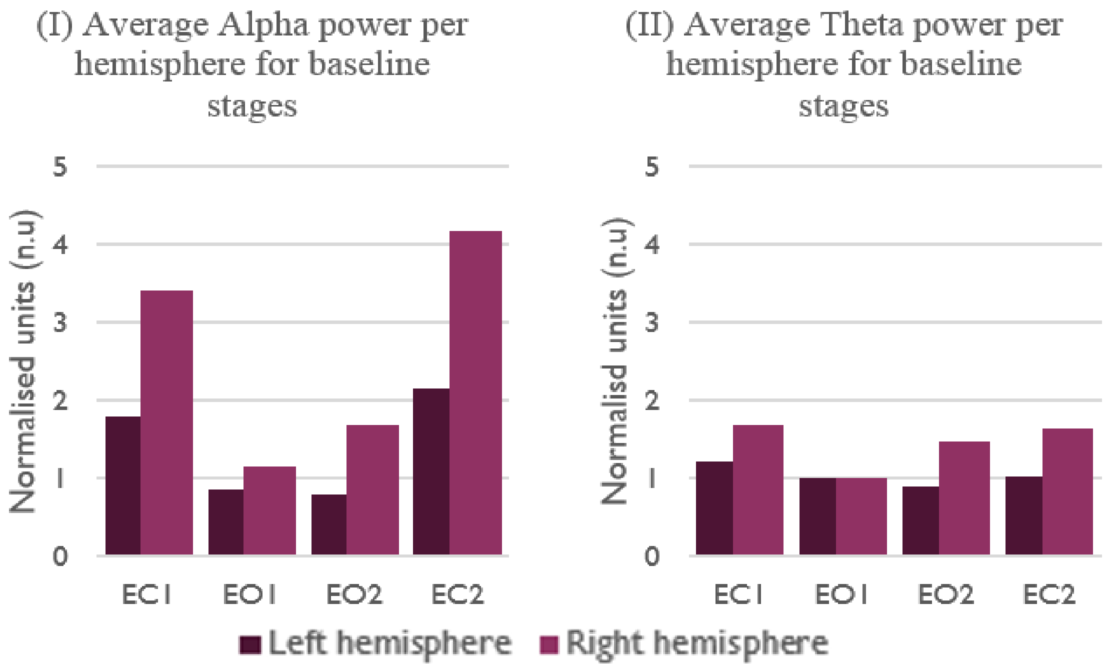


Figure 21: (I) Alpha and (II) Theta averaged baseline powers for each hemisphere across subjects.
In normalised units(n.u).

A more generalizable trend is noticeable when examining the hemispheric power contributions. Interestingly, all frequency bands show the right hemisphere to have greater power (if any differences are apparent) during all stages of both baseline measures. Therefore, even prior to improvisation all individuals showed a greater power output arising from the right hemisphere across all spectra. It would be interesting to investigate whether such lateralized activity is perhaps a consistent feature for higher creative individuals or musicians specifically, compared to persons of averaged creative inclination or non-musicians. In conjunction with this all power bands show very little if any hemispheric dissimilarities in power once the eyes are opened prior to performance (baseline). However, upon completion hemispheric divergences are much greater and persists through both eyes-open and eyes-closed stages. Thus, there is a consistent and obstinate difference in power output between hemispheres immediately after improvisation, with only the Delta power seemingly stabilising during EC2, despite showing elevated power levels in EO2.

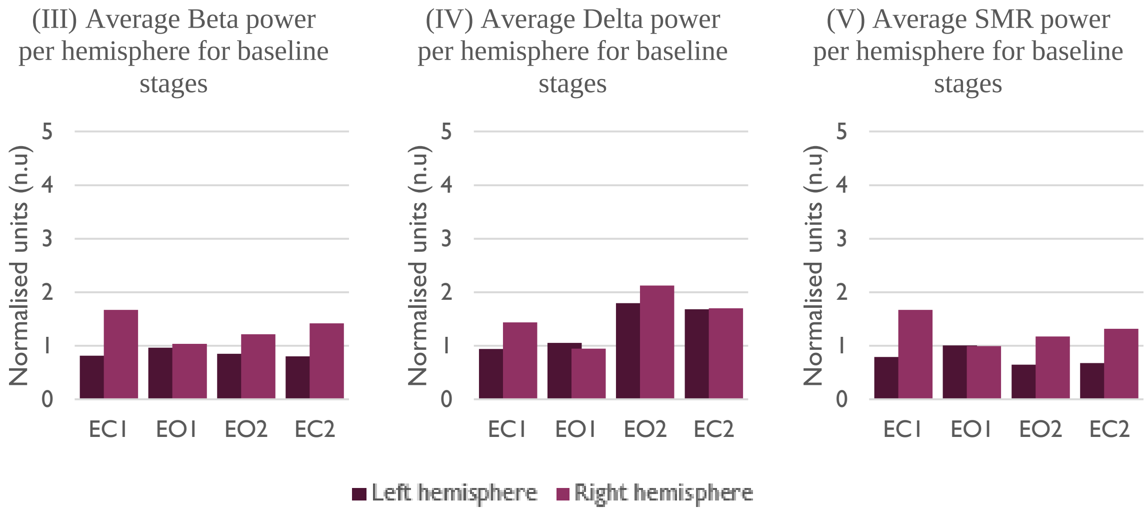


Figure 22: (III) Beta, (IV) Delta and (V) SMR averaged baseline power for each hemisphere across all participants. *In normalised units (n.u).*

A bivariate Spearman's correlation revealed no significant differences between right and left hemispheres for the spectral bands at the original baseline, but significant differences (P=.037; 95% CI) at the comparative baseline within theta, delta and SMR bands. This is to say that following improvisation, lower band activity showed persistent and significant hemispheric differences even 6 minutes after completion. Furthermore, alpha and beta bands showed significant differences at the EO2 stage directly following improvisation, but not at the EC2 stage. Therefore these differences might be the residual consequence of the performance and the high state of focus associated with it.

Summarising point: The right hemisphere consistently shows greater power outputs before and after performances within all power spectra. A general trend is observable whereby hemispheric differences exist when the eyes are closed, but equalise during the eyes-open baseline prior to performance. However, after improvisation hemispheric differences are more stubborn and persist during both eyes open and closed stages, proving significant in the SMR and lower bands (delta & theta). Alpha and beta activity show significant differences from the other baseline stages immediately succeeding performances.

4.4.3 Regional EEG Means

The reader is reminded that only the frontal and temporal expanses were investigated due to the shortage of electrode sites in the parietal and occipital regions. The section following assesses the specific contributions of these two regions specifically and can be broken up into four hemispheric variants namely the left frontal (FL), right frontal (FR), left temporal (TL), and right temporal (TR) regions.

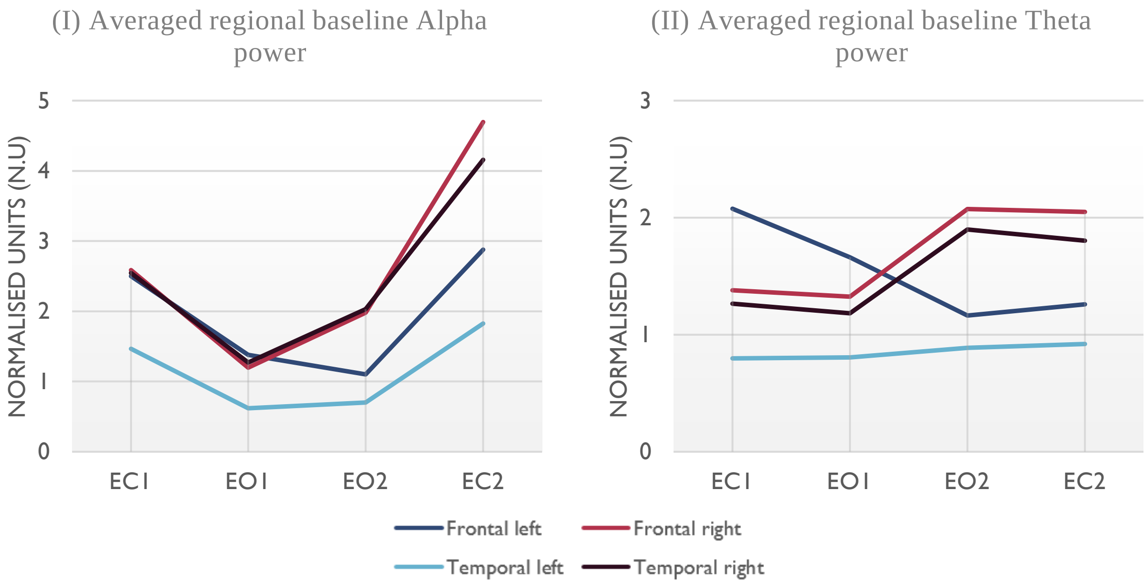


Figure 23: Regional baseline power means for Alpha (I) and Theta (II) power bands. *In normalised units (n.u).*

Figure 23 and 24 depicts the subject power means at each baseline stage within all five frequency spectra. At first noticeable is the seemingly strong association between FR and TR present in all of the power bands. In fact, taking the averages of all four baseline stages from all subjects, a bootstrapped correlation matrix comparing the right frontal and right temporal power bands, reveal extremely significant correlations. TR and FR baselines values showed remarkable correlations, all significant at the 0.01 level (2-tailed). Although this statistics need to be considered with caution corresponding TR and FR baseline means for each of the frequency bands showed significant correlation (P<.01). This high level of correlation exists during all every stage of the baseline and power band. While it is certain that TR and FR show continuous association, TL shows constantly lower power outputs compared to the other regions in all power spectra, while the FL response in all the graphs show unpredictability and inconsistency between stages.

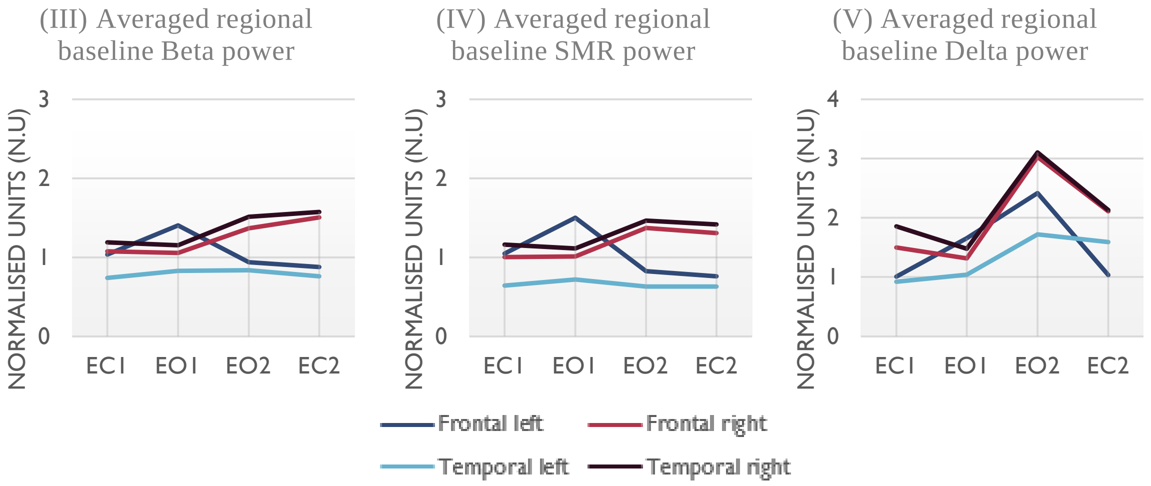


Figure 24: Regional baseline power means for the Beta (III), SMR (IV) and Delta (V) power bands. *In normalised units (n.u).*

What is clear however is that there is a very clear and prominent divorce of power between the regions on a hemispheric level, and is evident when in all the graphs. Right brain regions (FR and TR) show sustained higher power in following improvisation compared to the regions on the left (FL and TL). During the comparative baseline it is clear that there is a distinct difference in hemispheric power output across all power bands, with those areas on the left showing greater association after performance but all lower power.

In addition, a general pattern is observable whereby the areas located in the right hemisphere typically show elevated power in all bands in the comparative baseline compared to the original baseline, with the power of those areas on the left generally about the same or lower than initial baseline means following performance. Furthermore, significant correlations between baselines (EO1/EC2) were found for the TR region within Alpha and Theta bands (P=.037; 95% CI), FR region within the SMR band (P=.037; 95% CI), and the TL region in the Theta band (P=.037; 95% CI).

Summarising point: There exists an exceedingly strong relationship between FR and TR across all spectra and stages (P<.01; 95% CI). The right hemisphere again shows consistently greater power outputs, especially after improvisation, at which point there is typically also a better association between left-brain regions but at distinctly lower power outputs. Therefore, after improvisation frontal and temporal regions show strong lateral associations but at markedly different power. The temporal region on the left shows a rise in slow-wave power following improvisation and shows correlation within the Theta band when baselines are compared.

4.5 A DYNAMIC PERSPECTIVE

The Dynamic perspective carries the particular objective of examining the related shifts and trends of the set out parameters during the actual performance stage (improvisation). Unlike the Means perspective results are much less generalizable, as each performance is very subjective and personally expressive, effected possibly by subjects' playing style, level of engagement, expertise and the duration of performance. To draw consistency between the baseline measures and that of the performance (OF), datasets were spliced into 30 sec epochs, and power estimates were averaged over a 180 sec windows. This 3 minute window corresponds with the length of each baseline stage, thereby maintaining consistent intervals throughout each dataset. A similar top-down modus operandi is employed to the outcomes of this perspective, starting with the global epoch power normalisations, and refined to assess both hemispheric and regional power shifts and contributions.

Therefore, the focus within this point of view lies in assessing the performance phase means with that of the baselines. An investigation of the diverse nature of outcomes yielded by individually-driven performances that carry little more commonality than the instrument and genre of music, proved difficult. Data arrays show large differences and the idiosyncratic core to such doings therefore forces a measure of subtly when probing the data for cohesive similarities.

4.5.1 Global EEG Dynamics

In order to assess the global undercurrents of performance, each frequency band's overall (mean) power was calculated for the improvising performance (OF) and is reflected in Figures 25 - 26 next to the inactive baselines before and after the session (EO1 and EO2). Frequency bands have been chronologically ordered from 0 – 35 Hz and each graph therefore demonstrates the global power distribution (n.u) of each subject and power band.

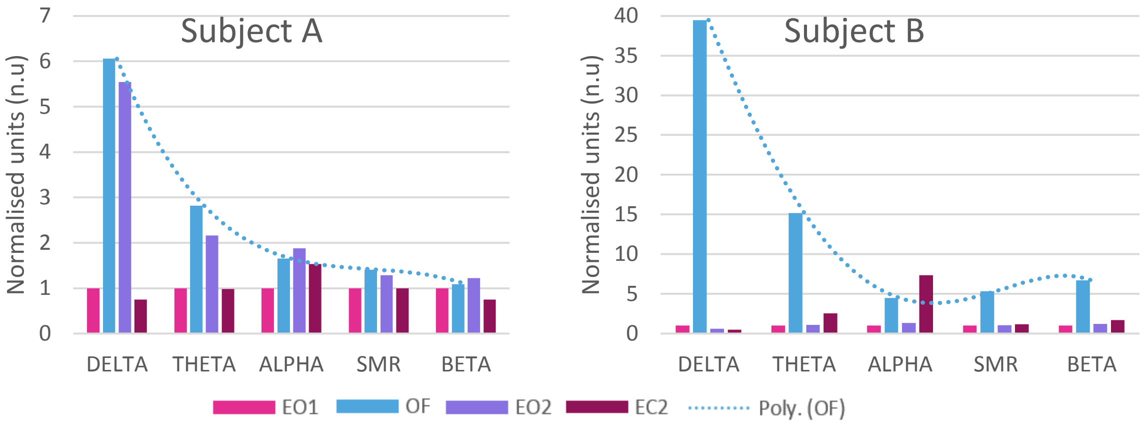


Figure 25: Band power means for performances (OF) in relation baseline measures for subjects A and B.

Alpha, theta and SMR bands showed significant correlations (P<.04; 95% CI) between the EO1 and EC2 baselines, while delta and beta bands showed notable positive but not significant correlations too (P=.104).

There are no immediately obvious similarities between individuals, but there are however major increases in power across all frequency bands in all subjects (with the exception of Subject D) compared to baseline. It can therefore be said that a definite increase in global power is evident during the creative endeavour of improvisation. These increases vary greatly, with some subjects showing power increase of a 5x magnitude, whilst others show in excess of 40x greater power fluxes. Most noticeable are the extremely high increases in the Delta and Theta bands. Taking into account that EEG signals are generated by the underlying electrical activity of firing neurons, amplitude, and therefore power, is directly proportionate to the number of firing neurons. More neurons firing at the same time results in a greater energy output, resulting in greater amplitude and power. Henceforth, as we see in sleep and meditative states, low frequency waves with their correspondingly higher amplitudes become predominant, inferring also a greater synchronicity between firing neurons that leads to higher energy outputs.

Sleep and deeper levels of meditation and awareness are associated strongly with delta activity, [3] while theta activity has been shown to be protuberant in daydreaming, creativity, spontaneity;[4] visualization, association and peak performance.[5] Both show great power increases here, which might be in part due to their naturally higher amplitudes, but the degree to which these lower frequency increase in magnitude, suggests a greater prominence of slow-wave activity during the improvisation stages, and therefore a greater level of synchronicity between active neurons in the brain.

Increased Alpha power has widely been reported as being an important marker for creativity and creative conducts. Wise [6] describes a state of strong simultaneous presence of all power bands during creative inspiration and peak mental awareness. After testing a great number of artists, athletes, high-performing businessmen and spiritual teachers, Wise found a distinctive wave pattern that she refers to as the "awakened mind", showing strong expression in all bands from delta to beta. This 'state' is described as having both intellectual processing (as governed by beta frequencies), and deeper meditative and unconscious connections to memory resources (as overseen by the theta and delta waves). High alpha acts as a bridge connecting the conscious and unconscious, and may explain the relationship between creativity and flow. [3]

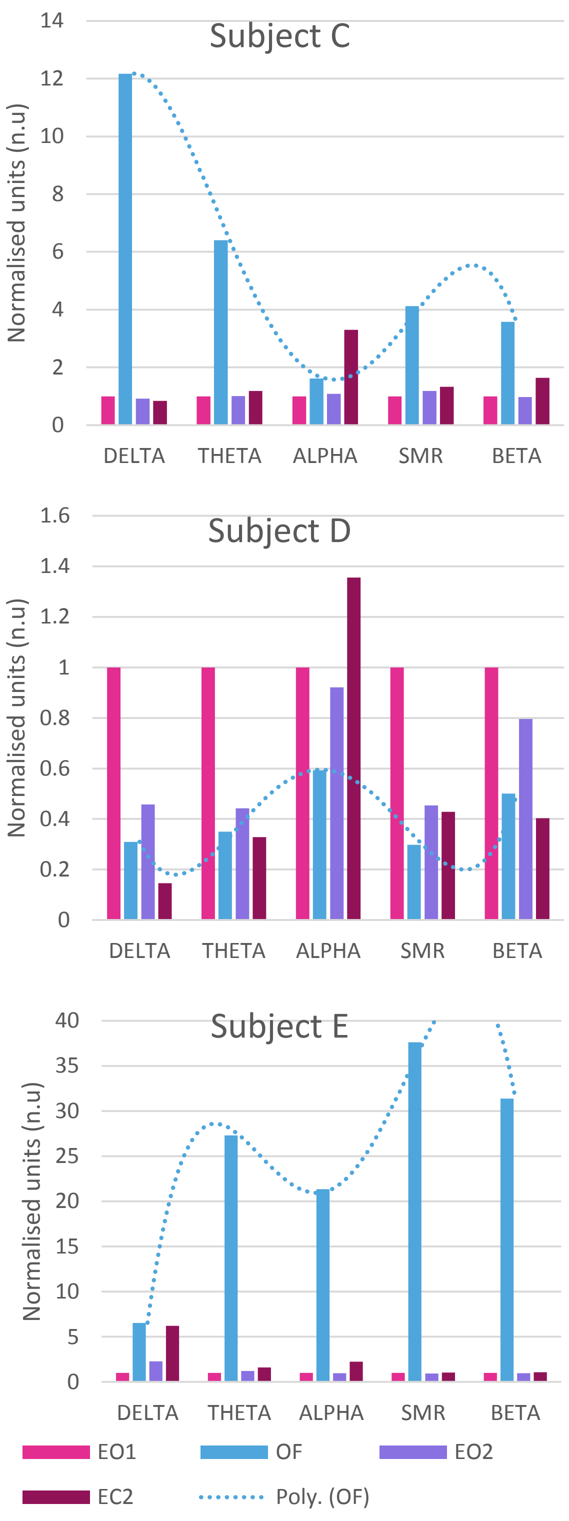


Figure 26: Band power means for performances (OF) in relation to baseline measures for subjects C, D and E.

In light of such findings, Alpha power shows a definite increase from baseline during these all presented creative sessions and in all subjects show a definite increase in the comparative baseline (EC2) compared to pre-performance (EO1). The significance of higher alpha activity resides with the strong relationships that have been established between higher alpha activity and relaxed awareness (viewed as 'cortical idling'), shifts in consciousness, deeper creativity, prevention of external disturbance of internal processing states, visualization and lack of cognitive processing. [3, 4, 5, 7, 8] The fact that heightened alpha activity endures into the inactive measurements directly after performance could have significant therapeutic consequences and are explored later.

Summarising point: Global power increases are observable across all power spectra, showing large power increases in all but one individual during the performance phase. The lower spectral bands (Delta and Theta) show the greatest power increases during performance which is typically associated with accessing unconscious information processing systems in the brain and might play an important factor in the flow experience. Although not as high as the lower bands, Alpha power also shows definitive increases across subjects during improvisation and remained still elevated even 6 minutes after completion, at increased levels compared to pre-performance. Elevated levels in the comparative baseline might be due to the closing of eyes and its paired rise in alpha activity.

The dramatically elevated lower bands activity, in conjunction with the elevated alpha activity during improvisation are the leading findings from this section.

4.5.2 Hemispheric EEG Dynamics

Divorcing the data representation into its synergic hemispheric interaction reveals a strong slant towards the right hemisphere once again. According to Figure 27 all power bands show stronger power contributions arising from the right hemisphere, except peculiarly again for one subject. Creative conduct such as music and art have been misleadingly ascribed as an exclusive right-brain phenomenon, and it is much better understood today that creativity is a global phenomenon. However, hemispheric specialization does describe the designation different functions to each hemisphere.

These graphs represent the power contributions from each hemisphere during improvisation and therefore not where hemispheric activity is symmetrical or not which is often important for creative conduct. The proclivity of the right hemisphere to show greater power outputs might be explained by the trade-off between the hemispheres during flow states, but is not an uncommon theme in creative research. The left brain has often been linked to more cognitive activities like sequential thinking, logic, sense of time, detail orientation and analytical thinking, [3,9] all of which are doings that become diminished during flow. The right brain however shows attributes of associations, symbolism, holistic inclinations, aesthetic senses and intuition. Concurrently, these are all trade mark of flow states and creative ideation. Therefore, the strong power arising in the right hemisphere may stem from the moderation of left brain tendencies to process information in a more cognitive manner, leading to a greater freedom of the right brain to express these skills in a non-verbal and more spontaneous and intuitive manner.

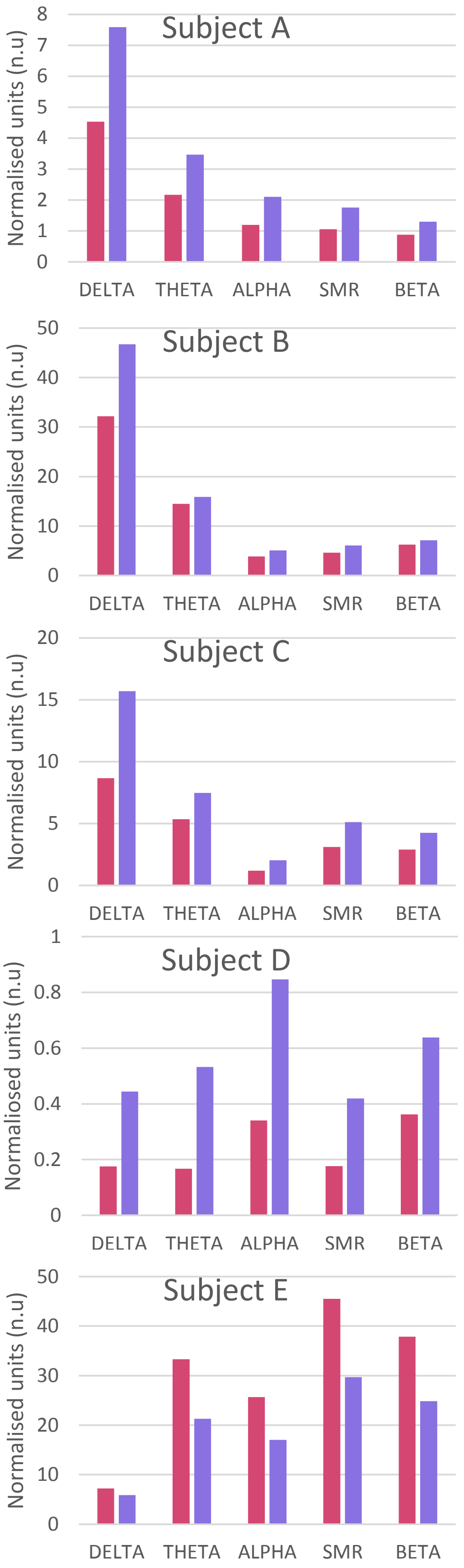


Figure 27: Hemispheric power distribution for OF per subject and spectral band.
(Pink = left; Purple = right)

Summarising point: The right hemisphere consistently shows greater power yields across spectra during improvisation in all but one subject. This partiality of the right brain to express greater power and energy might be due to the information processing inclinations of this hemisphere. Such preferential tendencies might be a product of flow or the nature of improvisation itself.

4.5.3 Regional EEG Dynamics

As we move systematically closer to the consideration of flow within the data, the reader is reminded of the brain architecture and recruitment pertaining to flow and more generally creative expression, as described in Chapter 2. Regions in the prefrontal cortex are “involved in making novelty fully conscious, evaluating its appropriateness, and ultimately implementing its creative expression,” [10] with the dorsolateral prefrontal regions providing the cognitive input for novelty generation. The medial prefrontal areas also play a role in spontaneous thought which is more related to creative thought and increases when cognitive demands decrease. However, even though the prefrontal region are crucial in processing such already highly-processed information, flow recruits different brain circuitries that result in a transient hypofrontality which empowers implicitly driven skills like improvisation to occur at maximum efficiency without ‘micro-management’ from these frontal regions.

The temporal regions in the brain are strongly associated with auditory functioning and processing, and it is common knowledge that musicality requires auditory feedback for effective execution. Additionally, temporal regions border association with the Broca’s and Wernicke’s areas involved in language, speech, singing and other areas of communication which are often used to research creative drive and ideations (e.g. Flatherty[11]).

At first glance Table 5 (below) might be perplexing. In order to investigate the regional contributions throughout each performance, it was thought valuable to investigate each electrode site individually to establish underlying dominance between lead positions. Scaling the individual electrode power outputs yielded insight into which sites were expressing higher and lower power returns during improvisation. Power bands have been grouped (right of table) and cross divided into electrode site (header row) and subject (first column). For each subject within each band, electrode site mean power values have been highlighted in a grading colour scale from highest (red) to lowest (blue). Middle values have no colour (white). Through this assemblage of all fourteen electrode positions, for each of the five subjects, into the five allocated power spectra, power distributions from all sites can be visualised as a 'heat map' to identify which regions were most active during the improvising performance (OF) in general.

Furthermore, the table has been schematized so that all electrode sites associated with the left hemisphere are situated in the left half of the table, and the right hemispheric sites in the right half. Sequentially all sites in the left brain have been arranged from rostral to caudal position, starting with the prefrontal site (AF3) and ending with the occipital site (O1). From here the reverse is true for the right brain sites which continues from the neighbouring occipital (O2) site and continues to the prefrontal (AF4) position. Power bands have also been organized from lowest frequency (delta) to highest frequency (beta).

Immediately visible from the table is again greater power (red) flaring in more cells on the right half of the table compared to the left, signifying the higher power output from the right hemisphere as described earlier. Electrode sites F7, F8 and T8 can easily be identified as showing a uniformly stronger power output across subjects and bands. Equally, T7, P7 and O1 can be recognised as those sites expressing the lowest power (blue). This pattern of activation is illustrated in Figure 28, which is a live screenshot taken from the Emotiv 3D brain activity map during recording. Although this is a stationary imaging it serves to illustrate the heightened activity (red) at the electrode sites just mentioned. Equally at the same time, turning the 3D model around shows lower activity (yellow) in the left temporal, parietal and occipital regions, as identified from the electrode heat map below. This pattern of activation was discernible for all subjects deep into their respective performances. From the image, low (green) level of activity are also observable in the prefrontal areas, consistent with flow conditions.

Table 5: A 'heat map' of each electrode site and its global power mean for the performance stage (OF) of each participant (A-E) as normalised against the baselines (EO1).

DELTA

	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4
A	3760	23638	1825	3309	2153	943	1241	2005	4278	17407	7447	2201	22279	6078
B	9602	78720	8658	12502	13095	13219	10638	23540	22660	32578	17805	21903	67917	26106
C	39636	74492	7266	18817	84113	14173	3925	6574	25117	151542	55157	6705	131581	62660
D	4935	19086	803	2693	1428	1465	2045	937	1209	15114	5938	1629	52982	4103
E	30830	22870	18100	30087	10071	11721	5688	18530	1304	6054	2142	10799	26034	40610

THETA

	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4
A	344	887	206	206	89	56	131	202	253	478	433	206	1029	464
B	403	3290	362	506	695	277	359	488	629	1128	1004	694	1971	552
C	949	1712	1253	341	976	228	118	342	681	3121	607	333	2211	511
D	538	625	155	202	140	109	112	245	273	490	521	311	3568	583
E	15079	10092	9156	10682	225	216	557	1824	78	224	443	2355	904	23569

ALPHA

	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4
A	122	201	89	73	59	37	80	127	149	233	159	94	256	139
B	282	731	226	253	396	163	313	402	432	478	391	322	691	391
C	282	398	595	176	327	161	149	381	516	1166	380	222	630	270
D	687	410	298	261	137	121	143	459	442	578	578	558	1769	737
E	7961	5302	3797	5610	76	97	334	849	71	124	231	1287	353	12425

SMR

	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4
A	56	75	43	38	41	25	44	73	88	102	70	46	93	60
B	144	265	114	119	316	115	235	250	297	278	209	169	303	206
C	133	195	311	141	239	105	75	191	324	661	237	130	282	149
D	102	86	33	46	86	34	34	96	84	130	83	60	466	83
E	4451	2920	1804	3110	36	42	154	459	39	65	113	677	127	6685

BETA

	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4
A	112	123	79	82	123	55	68	116	182	189	124	84	145	103
B	270	302	180	237	801	239	449	445	548	488	345	254	428	323
C	304	493	617	462	634	311	208	458	800	1146	645	369	640	401
D	191	171	58	93	277	72	66	178	178	272	156	100	605	146
E	4645	2961	1627	3183	59	63	188	470	60	102	134	689	146	6754

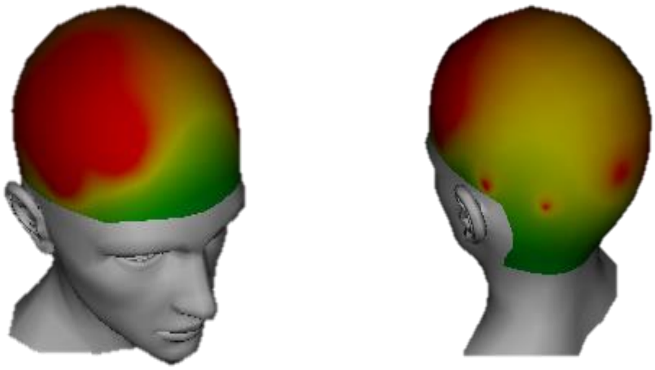


Figure 28: A snapshot taken from the Emotiv EPOC 3D brain activity map during recording.
High activity in the frontal and right temporal regions. Low activity in the left temporal, parietal and occipital regions can be seen in the image.

Summarising point: Electrode sites F7, F8 and T8 show greatest power outputs across participants, especially in the lower range frequencies. These sites stand in strong contrast with that of the T7, P7 and O1 which show the lowest power yields. This hints towards the lateral frontal and right temporal regions playing a much more significant role during improvisation. Likewise, left temporal, parietal and occipital regions show lower power yields and might therefore be recruited less or are not so much involved within this domain of creative expression. Medial frontal (F3 & F4), together with prefrontal (AF3 & AF4) show moderate to moderately low power outputs which is consistent with the conception of a hypofrontality occurring during creative peak performance.

4.5.4 HRV dynamics

Figure 29 & 30 shows the HF and LF values for each subject over the duration of each performance, including baseline values (first and last 6 min). Normalised HF and LF (primary vertical axis) and LF/HF (secondary vertical axis) have been plotted over time (horizontal axis). Trend lines were ascribed to each dataset and were based on a polynomial trend of order = 6.

HF represents an almost pure indicator of parasympathetic influence from the ANS on the heart, which typically slows the heart response and rate. LF is not a pure indicator of sympathetic activity however, but rather a mix of both para- and sympathetic effects, though slanted towards sympathetic influence. LF/HF is therefore a simple ratio of the interactive relationship between these synergistic branches of the ANS.

Similar trends were observe in most participant and were not atypical to what would be expected from the testing situation. Two subjects (Subject C & D) did however reported feelings of anxiety and have been grouped together in Figure 30 as we therefore see two groups of very different HRV responses.

During baseline stages, where the subject would be sitting in a passive and resting state, the normal grouping showed expectantly higher levels of HF power. HF power showed higher or equal measures (mean= 1305.3 ms2) to that of LF where the mean LF/HF ratio was 0.93 (SD=0.39). In the anxious subjects however the ratio of LF/HF averaged around 4.5 (SD= 1.7) for baseline stages (mean HF power= 254.7 ms2). Therefore, even prior to performance the anxious subjects were already in a highly sympathetic state, and from Figure 30 we can see that this hardly changed during performance with these subjects showing continuously

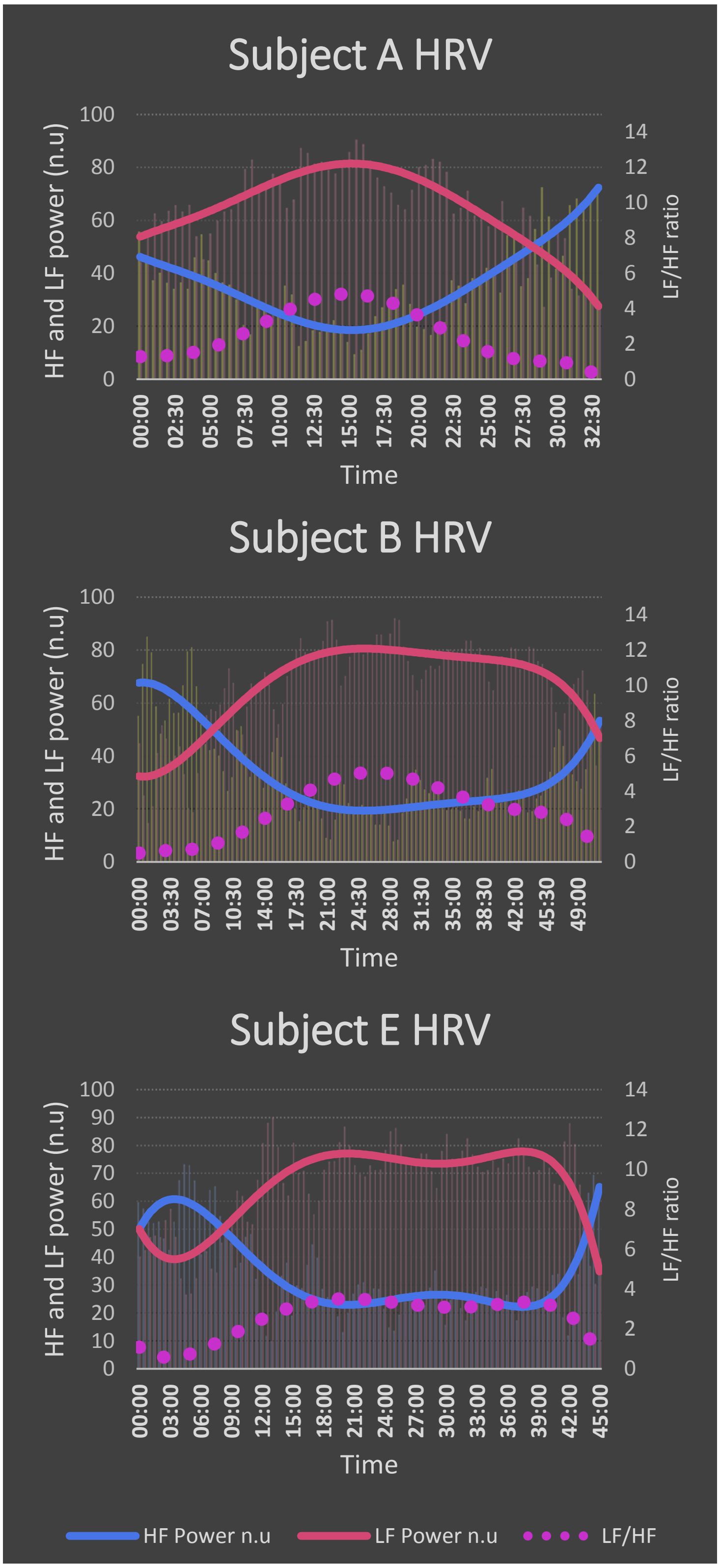


Figure 29: HRV data for Subjects A, B & E (normal). *High frequency (HF), low frequency (LF) components & the ratio of LF/HF for each 30 sec of each performance are shown. All values are normalised*

low HF power throughout. Low parasympathetic influence in these individuals might impact on their performances as feelings of nervousness, and therefore elevated sympathetic influence could affect focus, breathing rates, emotions and flow.

In the normal subjects, slight shifts occur during performances compared to prior and following baseline measurements. Typically, as mentioned, a LF/HF ratio lower or equal to 1 is measure prior to performance, with a rapid declined in HF power occurring when improvisation is commenced, followed by a steady increase in HF power towards the latter half of performance and the subsequent measures at rest following its conclusion. The LF/HF trend line demonstrates such changes quite clearly. Upon initiation of performance, the LF/HF ratio shifts quite sternly in favour of LF power (sympathetic activation) as would be expected from a person moving and actively engaging the task at hand, typically peaks around 15 – 25 minutes into all performances. However, after peaking there is a gradual decline in LF power, showing a growing influence in parasympathetic stimuli the heart. The growing presence of the parasympathetic system as the performances continues on might carry significance and is readdressed later.

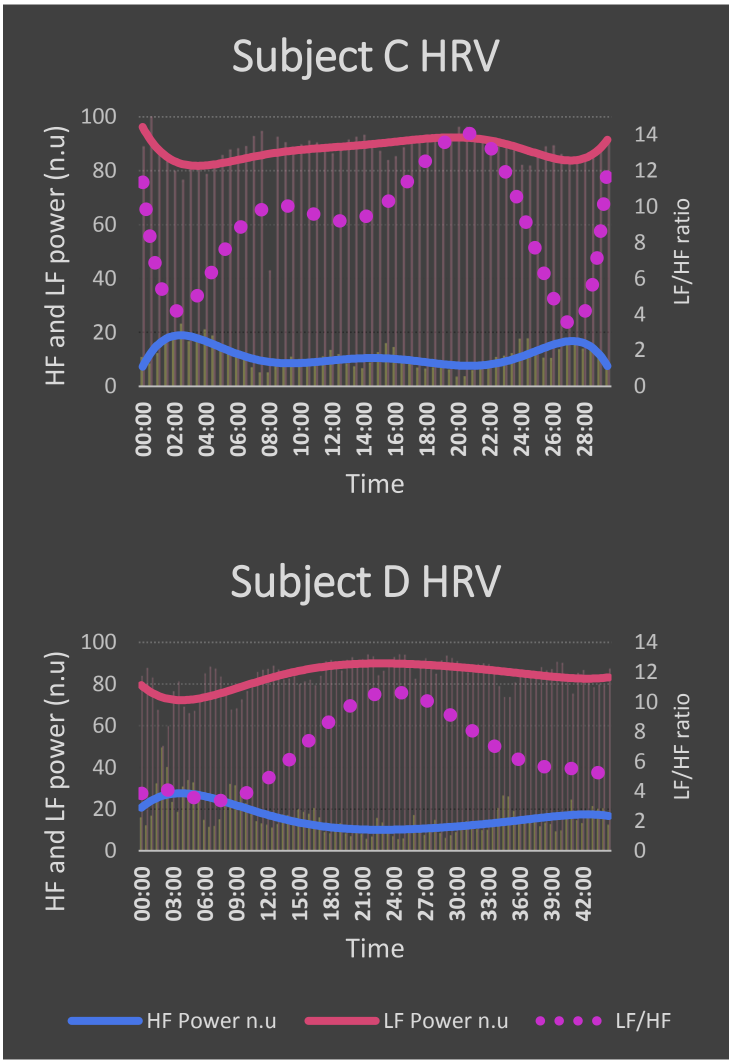


Figure 30: HRV data for Subjects C & D (anxious). *High frequency (HF), low frequency (LF) components and the ratio of LF/HF for each 30 sec of each performance are shown.*

Table 6: Mean HF power and standard deviations for all participants

Table key	E1	OF	E2

LF/HF		**HF_{power} (ms^2)**		**LF/HF**		**HF_{power} (ms^2)**		**LF/HF**		**HF_{power} (ms^2)**	
Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
0.93	0.4	1305	602	4.56	1.7	255	104	2.38	2.2	885	746
3.24	0.3	264	113	9.30	2.6	48.2	.03	5.66	3.6	177	142
1.63	1.0	1571	1588	6.09	0.8	137	33	3.41	2.5	997	1407
Normal subjects				Anxious subjects				All subjects			

4.6 A BIASING PERSPECTIVE

Flow is a very subjective experience of strongly positive emotions paired with heightened creativity, peak performance and sharp focus. Its meditative and trancelike properties allow the individual to become so engrossed in their conduct that their behaviour becomes almost automated and intuitive. An implicitly driven state that allows for the maximal expression of embedded and highly practised skills without the need for higher executive cognition.

It is for these highly idiosyncratic qualities of flow that a biasing perspective was built into this investigation. The 'bias', however, lies only in approximating where in each performance the subject experienced flow, i.e. the locus for investigation, and was never biased in its interpretation. Subjects were asked after each performance about their feelings toward their performances and whether and when they had experienced flow or flow-like states while playing. Their feedback was combined with notes taken by the investigator regarding the perceived ease-of-play, sense of enjoyment, noticeable positive affect in facial and body language, and predicted flow occurrence scores. Collectively the subject feedback, and subjective investigator assessment notes were combined with data clarity and audio/video reviews to isolate segments of each performance that carried the strongest possibility of flow. The objective in this regard was to evaluate these windowed or designated 'flow-zones' for trends and comparable differences in interpretation of whether flow might present with quantifiable or discernible fluxes in spectral power. The areas were marked for each performance, and developments in the data in, and around the windowed flow-zones were described.

It should be stressed once more that the bias here lied only with designating at what points in time assessment should be conducted based on subjective and qualitative information sources. Identifying these moments in time was done prior to any examination or preparation of the data. If no significant or discernible changes or difference were observable, the selection stood and findings were reported as is. No alterations or tempering of these designated areas were done to better suite the data, salient events in it or any preconceived notions of what the data was supposed to reflect. In essence therefore, a few markers in the data were demarcated based on individual feedback and qualitative investigator notes during/after improvisation and subsequently investigated and described. These areas were surveyed for potential events or fluctuations in brain activity that could have been caused by the flow experience. This perspective carries the aim of bridging the subjective experience on behalf of both the subject and researcher, with the empirical and objectively presentable data and never to highlight the data that best suited the conditions, prerequisites and ideologies of flow. Such a bias would be intolerable and critically damaging to the integrity of both this study and flow research in general.

A dynamic and progressive trending of the real-time data is presented here that accurately reflects the moving averages of brain waves and HRV powers at 30 second and 180 second frames. The need for such a dynamic representation of the data is motivated from a critical viewpoint. Due to the high temporal resolution of the EEG it is deceivingly easy to be misled into trusting a snapshot or freeze-frame image (moment in time of a given dataset) as an accurate representation of the totality of a dataset. Therefore, the biasing outlook presented here aims to capture the full performance with all the changes happening across spectra, over time, and in turn to focus on the identified flow-zones to assess whether there are noteworthy changes surrounding these moments in time.

During each performance, events that could be important or of value in assessing the data were marked and time stamped. These events included contextual events, such as possible distractions, excessive movements or vocal noises; subjective events like perceived ease-of-play or noticeable positive affect and body language that might portray positive emotions (like smiles, or enjoyment); and data specific events like visible amplitude shifts in the real-time windowing, spindle-like waveforms or noise. Spindle-like waveforms that are typically present during sleep was noticed by the investigator in more than one subjects during performances, and could be investigated in future.

In Figure 31 (below) events and markers indicative of the potential occurrence of flow were plotted for each minute, as noted, marked and reported through individual feedback during/after each performance. A summation of these events were used to identify moments during each performance that subjects might have been in flow. Along these lines, determination of flow zones were not purely advocated by feedback received from participants. The main reason for this is that it is difficult to quantify with accuracy, the duration that a participant is in a flow state. One of the traits of flow is the perceptive loss of time on behalf of the individual and therefore participants were often able to approximate when they were in flow but not for how long. In consideration of this, subjective feedback was amended with supporting evidence from notes made by the investigator, events in the data (e.g. spindle-like waveforms) and contextual markers (e.g. possible distractions; noticeable positive affect), as already mentioned. No objective measurement of flow exists at present and a combination therefore of subjective and investigative comments were used to define flow-zones.

Peaks portrayed in Figure 31 were again weighed against subjective feedback and visual/audio recordings, and were concurrently highlighted and windowed in Figure 32. To particularised this matter, Figure 31 set out a mixed criteria whereby flow-like characteristics and experiences were identified during performances and thereby constituting the biasing focal point for investigation. These windows were then highlighted in the graphs of Figure 32 that represent a dynamic outlook of each power band over time within each participant. Values were averaged for every 180 seconds as recorded during each subjects’ improvising performance. Values have been normalised against the baseline values for each band and hypothetical flow zones shaded in purple.

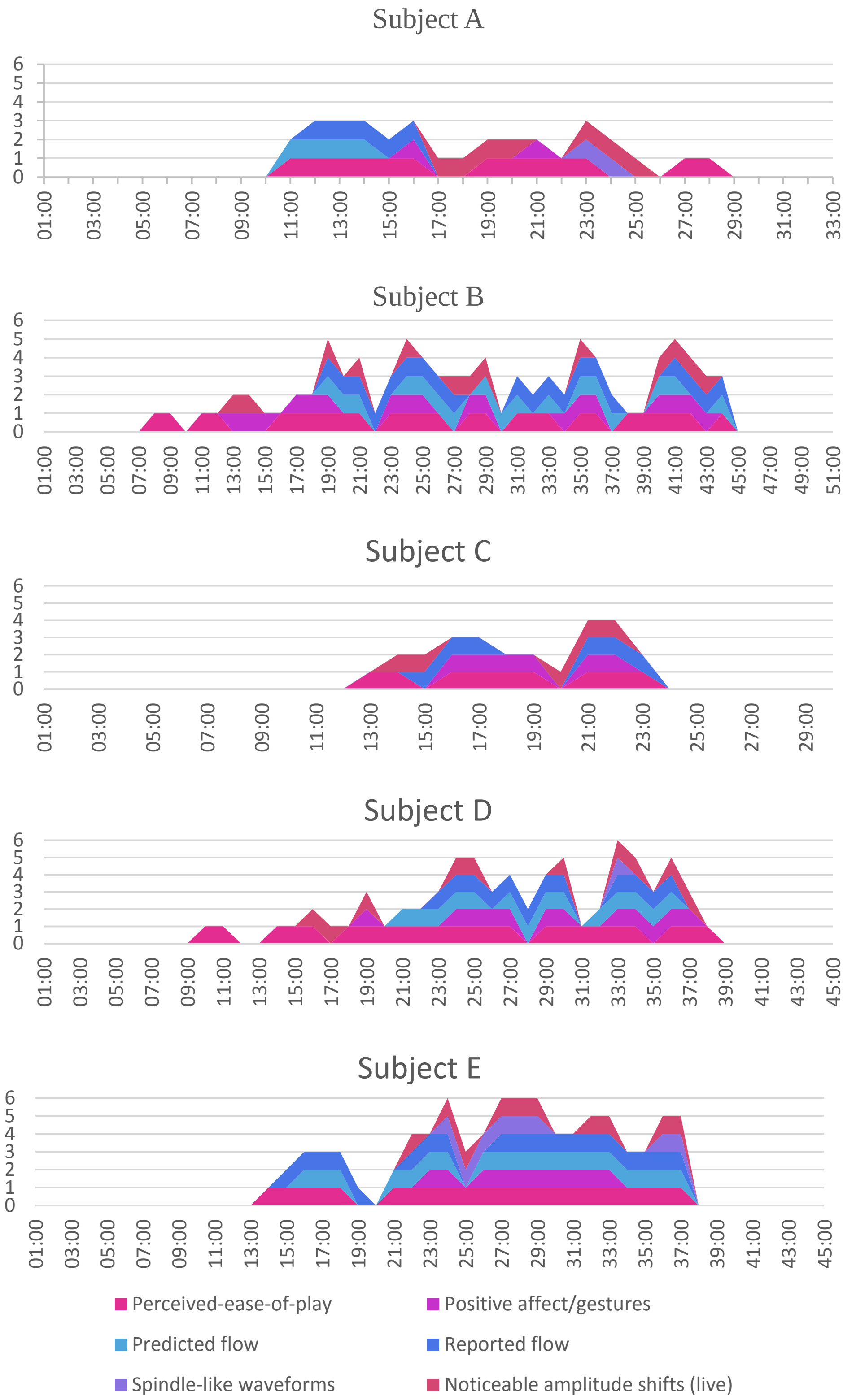


Figure 31: Summation of contextual, subjective and data-specific events as noted and reported by both subject and investigator for each performance.

Based on the narrative thus far, the windowed zones highlighted in Figure 32 thereby serve as indicators of when flow was encountered, but the width of each window is thus not directly proportionate to its duration. These windowed flow zones might have been longer/shorter, overlap with neighbouring zones or be part of the same continuous flow experience were they pure indicators of the complete experience. As already motivated, a statistical analyses approach of correlating the slopes of each power band with each other and that of HRV within these flow windows was considered and rejected for the above mentioned reason. In this regard, it makes more sense to objectively look at the overall trends that are happening within the data at these moments in time, rather than describing the data that fall only within the bounds of each window.

Composite graphs are presented with both EEG and HRV data depicted on them. The statistical method incorporated here are based on correlative matrices again along the Spearman Rank Order correlations. Two sets of matrices had specifically been constructed for this section based on time and within-subject data sets. The corresponding graphs presented in this section are plotted on 3 minute intervals however in order to make the statistical data more functionally valid only the first 30 minutes of each dataset, excluding baseline, was used.[o] In addition, constructing matrices based on each 30 second intervals proved to be too great and a condensation around every 6 minutes of data was prepared instead. Therefore, the data was averaged at five intervals (at 6, 12, 18, 24 and 30 min) and the spectral elements for each subject were correlated against each other at these interludes.

In much the same manner, subjective matrices involved the cross correlation of spectral bands for the total duration of each performance within each subject's dataset. Given how many variables were at play, variables were reduced to the five different spectral elements of the EEG (delta, theta, alpha, SMR, and beta power) and only the high frequency (HF) component of HRV. HF was targeted as the primary locus for investigation of HRV due to the facts that HF is a pure indicator of parasympathetic influence on the heart,[p] its previous correlation with EEG power bands in other

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[o] Some performances continued for longer, but later times would therefore not reflect all datasets, reducing the N score and therefore its reliability as being representative of the total population.

[p] LF was excluded due to it not being a pure indicator but rather under mixed influence from bot parasympathetic and sympathetic outflow.

research, [12] and the hypothesised notion that its intensification demonstrate the occurrence of flow.

4.6.1 Global trends

As clarified above, each subject’s full performance (including EO1) have been graphically illustrated in Figure 32. Windowed ‘flow-zones’ have been shaded in purple and all spectral bands including HF (HRV) data are plotted. These graphs illustrate the variables at 6 minute intervals as was used in the statistical analysis, with the exception of the baseline (EO1) which is labelled at 3min. Due to the fact that some performances were longer than others, only the first 30 minutes of each were used for statistical purposes, however the full duration from each subject has been graphically illustrate d. As all graphs are represented in normalised values, EO1 is a 1 n.u values for all parameters including HF (secondary axis).

Figures 32 can clearly be seen to demonstrate a high level of variance between individuals with very little commonality or similarity. Essentially however, all graphs show substantial peaks across spectra, especially within the delta and theta bands. These peaks attest to major power increases that arise from equally great amplitudes upsurges within these frequency bands. In some cases these increases are of magnitude greater than 100 fold and in the case of one subject (D), power values across performance are lower than the baseline means (as was apparent in section 4.5.1). Therefore it is clear, at least off the bat, that improvisation resulted, on some level, in an upsurge in cross spectral power especially within the lower power bands.

Focussing then on the highlighted flow zones, general trends of overall increases can be observed across all bands, however delta and theta show greatest intensifications through these windows. When observing Subject A, B and C, these intensifications are most evident. The indicated flow-zones show great concomitance with these chief peaks and the most major amplitude shifts throughout each of the five performances. On this front, one could be led to believe that perhaps the flow-states experienced at those moments in time evoked such major increases, which in some cases correspond to more than an 80 fold increase in power (Subject B & E in particular).

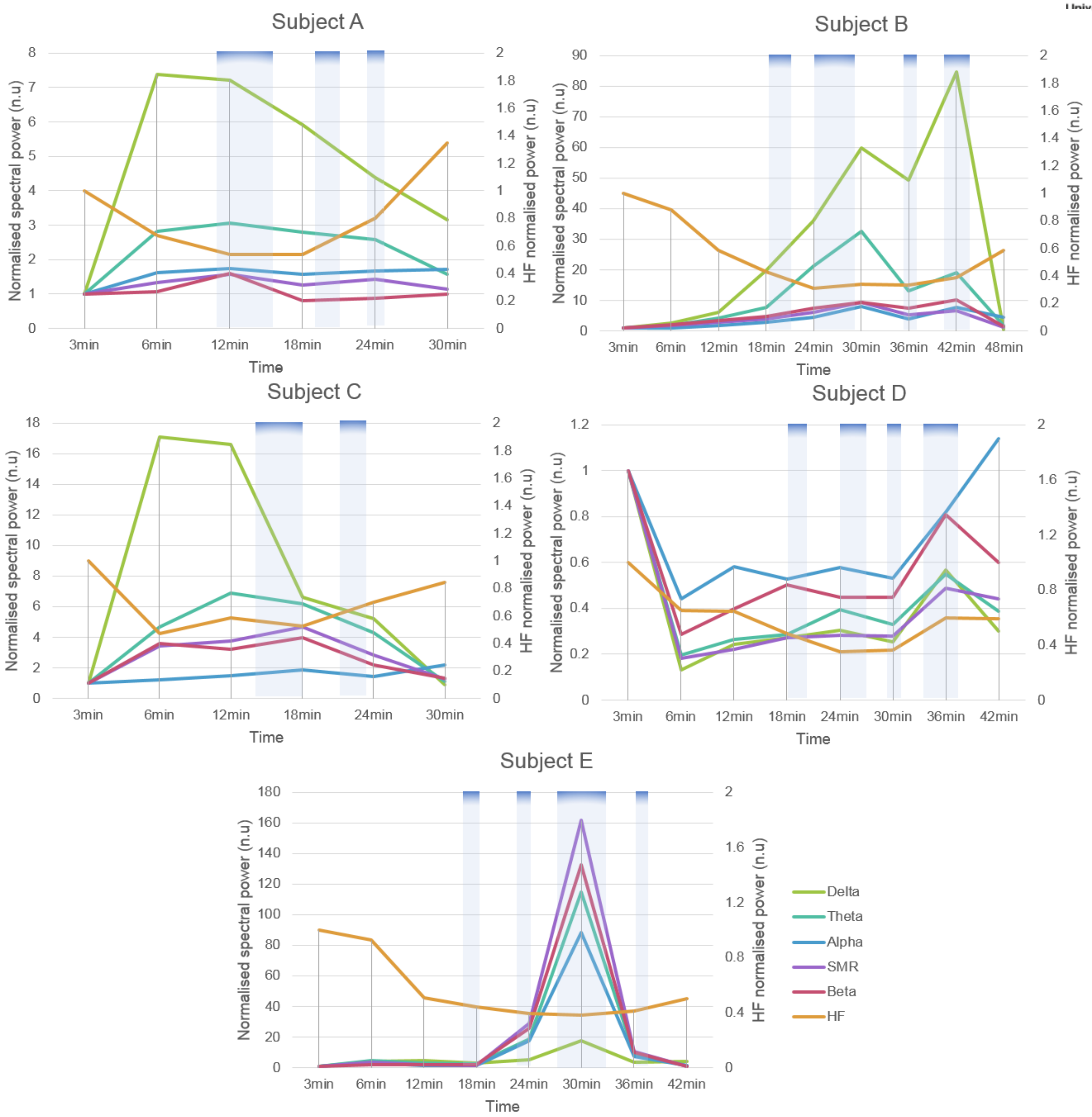


Figure 32: Composite graphs for all subjects showing power spectra over time and each individuals approximated 'flow-zones'. *Each graph illustrates the mean power within the delta (green), theta (light blue), alpha (darker blue), SMR (purple), beta (pink) EEG spectra (primary axis), alongside the HF (orange) power (secondary axis) for that individual. All values have been normalised against the respective baseline mean for that band and subject (EO1).*

Reader note: *Due to continuous reference to this figure throughout this section, a copy of the graphs presented here have been added as Appendix at the back of this document for cross referencing.*

Were it the case that flow was responsible for major increases in amplitude across spectra, such findings could prove to be of great significance. The reader is reminded that there is an expected difference in amplitude across the differing frequency ranges, with lower frequencies typically showing higher amplitudes by default. However in the resulting graphs posed here, values have been normalised against the respective baseline mean, which in basic terms implies that the values on display are ratios of that baseline, qualifying bands with naturally different amplitudes to be comparable. Additional, a 1 n.u increase translates to a 1-fold increase. Therefore, the fact that individuals are producing power shifts of such magnitude, which is directly comparable to the inactive baseline, must carry meaning.

As mentioned also, slower wave activity is chiefly generated during more unconscious states of awareness like sleeping (delta) and deeper meditative states (theta). Activity manifested in the delta and theta ranges infer greater synchronicity amongst active neuronal responses as would be the case where an individual was sleeping, as opposed to the erratic higher frequency signals generated by more active, conscious states of awareness. Therefore, these principal increases in the low frequency bands during identified flow zones could be interpreted as greater global synchronicity of brain activity occurring at these moments. In and around most of the highlighted flow windows there are either already elevated power or an escalating gradients noticeable in most bands, with the lower frequency bands generally showing the greatest upturns.

It can further be remarked that the tendencies of cross spectral power increases during these chief peaks in each graph reflects an upturn in frequency power associated with both conscious and unconscious processing. Such collective augmentation across spectra and its association with peak mental performance and creative inspiration has been put forth by Wise, [6] during a state which the author refers to as the “awakened mind”. Such a state is described as having a distinct configuration of joint increases across all bands and was shown to over hundreds of EEG recording of individuals during high performance states. Such a specific configuration was hard to isolate in our findings but global increase across all bands are positively discernible in most cases reported here.

A bootstrapped correlation matrix was constructed based on the power within each band across participants at a given time. This was done in order to assess whether there were significant relationships across the population at each time interval. Table 7 puts forth all significant correlations found for the sampling population.

Corroborating these correlations with the graphs in Figure 32 reveals a few apparent underlying patterns. The first 12 minutes of data shows the same correlations, namely the significant associations between delta and theta, theta and SMR, and SMR and beta (p=.037; 95% CI). Reflecting this finding against Figure 32, it is easy to see this relationship. During the initial 12 minutes delta and theta show similar trending increases, while SMR and beta show similar responses. Here within we see a correlative relationship between the lower and higher spectral ends.

Interestingly, over the next 12 minutes (i.e. 12 – 24) there are significant correlations between beta and all the other EEG band at the 18 minute mark, which is mirrored again at 24 minutes, except here SMR shows correlation with all other bands too (beta excluded). Towards the half hour mark, theta shows correlation with all other power bands. No significant relationships were found to pair with the HF components.

In order to better understand these seemingly arbitrary relationship, a hypothetical, simple stacked area chart was conceived graphically illustrate these findings. Although the chart has no meaning per say, it helps to visualise these findings in a manner that help describe the underlying shifts. By ascribing an imaginary value of 1 unit to each of the bands for every significant relationship found, the chart (Figure 33) brings forth interesting possibilities.

Table 7: Significant correlations between power spectral at specific time intervals during improvisation – Spearman's Rho

		6 minutes					12 minutes					18 minutes					24 minutes					30 minutes				
		δ	θ	α	S	β	δ	θ	α	S	β	δ	θ	α	S	β	δ	θ	α	S	β	δ	θ	α	S	β
δ	CC		.900	-	-	-		.900*	-	-	-		-	-	-	.900*		-	-	.900*	.900*		.900*	-	-	-
	Sig.		.037	-	-	-		.037	-	-	-		-	-	-	.037		-	-	.037	.037		.037	-	-	-
	N		5	-	-	-		5	-	-	-		-	-	-	5		-	-	5	5		5	-	-	-
	Std.Err		.297	-	-	-		.273^d	-	-	-		-	-	-	.268^d		-	-	.313^d	.313^d		.320^d	-	-	-
θ	CC	.900		-	.900	-	.900*		-	.900*	-	-		-	-	.900*	-		-	.900*	.900*	.900*		.900*	.900*	.900*
	Sig.	.037		-	.037	-	.037		-	.037	-	-		-	-	.037	-		-	.037	.037	.037		.037	.037	.037
	N	5		-	5	-	5		-	5	-	-		-	-	5	-		-	5	5	5		5	5	5
	Std.Err	.297		-	.306	-	.273^d		-	.284^d	-	-		-	-	.268^d	-		-	.313^d	.313^d	.320^d		.301^d	.301^d	.301^d
α	CC	-	-		-	-	-	-								.900*				-	.900*	-	.900*		-	-
	Sig.	-	-		-	-	-	-								.037				-	.037	-	.037		-	-
	N	-	-		-	-	-	-								5				-	5	-	5		-	-
	Std.Err	-	-		-	-	-	-								.268^d				-	.276^d	-	.301^d		-	-
S	CC	-	-	-		.900	-	.900*	-		.900*					.900*	.900*	.900*	.900*			-	.900*	-		-
	Sig.	-	-	-		.037	-	.037	-		.037					.037	.037	.037	.037			-	.037	-		-
	N	-	-	-		5	-	5	-		5					5	5	5	5			-	5	-		-
	Std.Err	-	-	-		.269	-	.284^d	-		.295^d					.306^d	.313^d	.313^d	.276^d			-	.301^d	-		-
β	CC	-	-	-	.900		-	-	-	.900*		.900*	.900*	.900*	.900*		.900*	.900*	.900*	-		-	.900*	-	-	
	Sig.	-	-	-	.037		-	-	-	.037		.037	.037	.037	.037		.037	.037	.037	-		-	.037	-	-	
	N	-	-	-	5		-	-	-	5		5	5	5	5		5	5	5	-		-	5	-	-	
	Std.Er	-	-	-	.269		-	-	-	.295^d		.268^d	.268^d	.268^d	.306^d		.313^d	.313^d	.276^d	-		-	.301^d	-	-	

*. Correlation is significant at the 0.05 level (2-tailed).

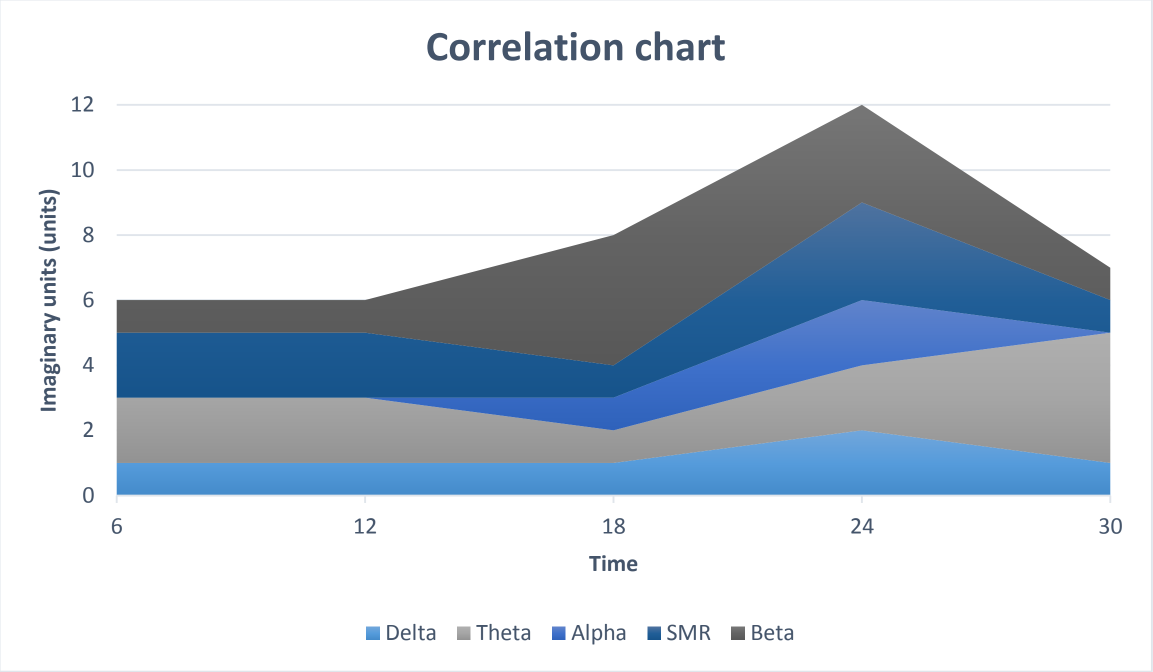


Figure 33: A fictitious, stacked area chart visually illustrating the number of significant correlations found per spectral band at different time intervals (6 minutes).

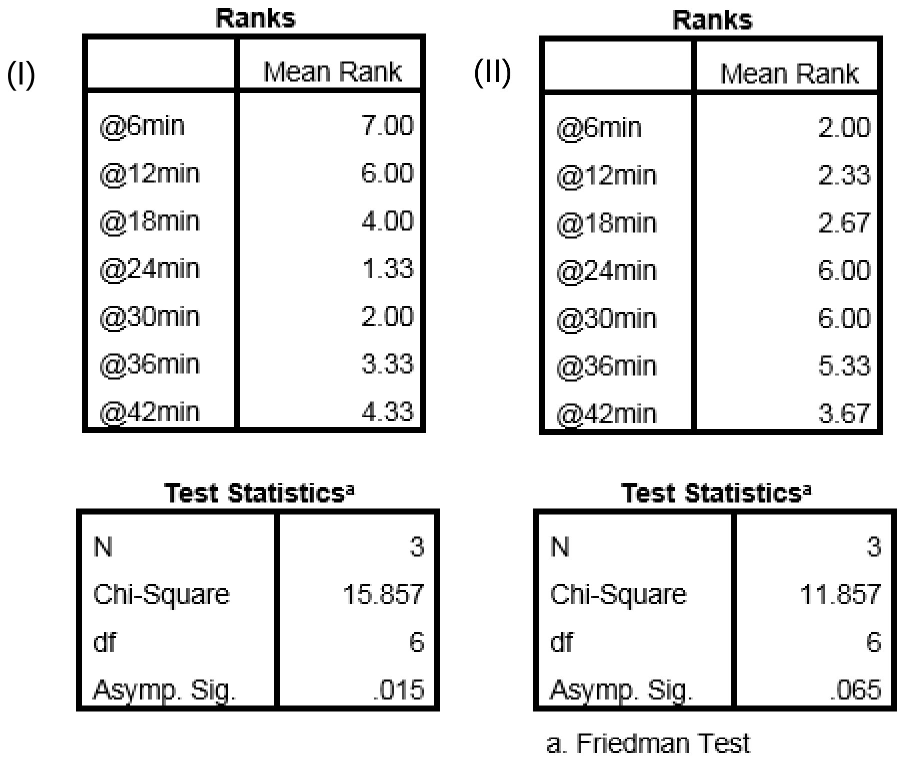
In the fabricated chart above an imaginary value of 1 unit was allocated to each power band for every significant correlation that was found linked to it. What the chart illustrates is firstly, the increased number of correlative relationships over time, implying that the longer improvisation went on, the more cross band activity started showing significant relationships. Secondly, following the timeline we can see that between 12 -24 minutes beta activity showed more correlations than any other band (correlation found with all other bands). In light of this, it does not make sense to think of it as one entity (beta) correlating with several completely different arrays of data, but instead that the reverse was true and that the other bands' activities were in fact correlating with beta between these times. Therefore, beta activity might the governing frequency during this time. Along the same lines, we see the growing presence of alpha within this midterm period, however towards the half hour mark theta band activity starts showing much greater prominence, exemplified by the amount of correlations involving theta. Therefore, perhaps the chart suggests that during the first 10 - 15 minutes of performance we have a predominance arising from the higher frequencies (beta and SMR), associated with high focus, cognitive processing, creative ideation and sensorimotor integration. Succeeding this is the growing presence of alpha, often described as a bridge between high and low end activity and diversely pronounced in the creativity research literatures, around 15 - 20 minutes. Building on this then, the dominance continues to shift lower towards the theta frequency range as lower band activity starts showing greater significant influence on the other bands, hinting towards a more unconscious, trance-like perspective experience that we might describe as flow. Such a relationship between the different spectral bands are most likely not of a linear nature, however in all except one subject theta does show a strong presence progressively build in power as the performance continues. Alas, the correlations above are based on the population's means and are less pragmatic when applied directly to any individual dataset.

There is however perhaps some support to be found from the individual graphs put forth in Figure 32, in that subjects typically show the first occurrences of flow arising around the 18 minute mark and manifesting sporadically thereafter over the 24 – 30 minutes intervals. Furthermore, in section 4.5.4 it was put forth that LF/HF ratios peaked for all subjects between 15 -25 minutes before declining for an unknown reason. Therefore, at the same time that theta band shows greater correlative significance, subjective flow was reported while simultaneously a decline in LF/HF (i.e. rising HF, declining LF) was observed. The matter is particularised in the integrated discussion of Chapter 5.

4.6.1.1 Friedman analysis

When considering the high amount of processing and processing steps incorporated in the study, especially given the small sample size and the need to average out large quantities of data points in order to detrend and break the data down into more manageable chunks, any statistical interpretation needs to be considered with caution. Simple correlation methods have been employed to substantiate the descriptive exploratory approach taken by this study, and for this reason a Friedman test was also included as a non-parametric alternative to assess the level of variance between time intervals given the small sample size.

From the Friedman Mean Rank only two bands showed meaningful or notable significance between their respective periods. The HF component for HRV showed asymmetrical significance at P=.015, while the Theta bands showed notable mathematical differences just above the significance cut-off (P=.065).



(I)

Ranks

	Mean Rank
@6min	7.00
@12min	6.00
@18min	4.00
@24min	1.33
@30min	2.00
@36min	3.33
@42min	4.33

Test Statistics[a]

N	3
Chi-Square	15.857
df	6
Asymp. Sig.	.015

(II)

Ranks

	Mean Rank
@6min	2.00
@12min	2.33
@18min	2.67
@24min	6.00
@30min	6.00
@36min	5.33
@42min	3.67

Test Statistics[a]

N	3
Chi-Square	11.857
df	6
Asymp. Sig.	.065

a. Friedman Test

Figure 34: Friedman Mean Ranks tables with test statistics for HF (I) and Theta (II).

In order to assess where the significance lied within the ranks, i.e. which intervals contributed the most variance, a post hoc analysis in the form of a Wilcoxon Signed rank was calculated. However, the post hoc analysis was unable to reveal where, due to high number of variables. This is to say that due to the high amount of time intervals considered, the Bonferroni adjustment resulted in a very small P-value (0.005/7 = .0007) and consequently could not reveal between which ranks the significance lied. Although not significant and inconclusive, the Wilcoxon Signed Rank seemed to suggest (based on the lowest significance scores) that the greatest variations lied between 6 and 18 minutes, 12 and 18 minutes, and 24 and 30 minutes for HF (P=.188); and between 18 -24 minutes, and 18 – 30 minutes for the theta band (P=.188).

Were this the case, and more specifically towards that of the theta band, if it were true that the greatest variation, and therefore most significant variation for theta occurred between 18 and 24 minutes, this would coincide not only with most subjects' approximated flow-zones but also concur with most of the findings put forwards up to this point. This could lend valuable insight into theta band activity playing a prominent role in the conduction and manifestation of flow during improvisation and higher creative behaviour.

Summarising point: The dynamic power graphs above revealed salient power shifts within each separate dataset. These major power peaks directly translated to massive amplitude upsurges over those periods in time and such increases were typically found across all power bands, though more so in the lower frequency ranges (delta and theta). Approximated flow-zones show high concomitance with the biggest observable peaks in all subjects, leading to the consideration that these chief amplitude shifts might be a product of the flow and its trance-like properties. In addition, an exploration of the correlative relationships between the power bands values across the population at different time intervals revealed the possibility of flow being induced by the high numbers of correlational and perhaps coherent engagement with the theta band. Unfortunately no correlations were found between the EEG and HRV spectra, however significant correlations were found between theta and HF in two individuals (P=.037). Moreover, a Friedman test revealed significant variations within the HF band (P=.015) with the differences between 6 and 18 minutes, 12 and 18 minutes, and 24 and 30 minutes seemingly showing the greatest variations. In much the same manner, although not significant, a high degree of variance within the Theta band (P=.065) was also detected, and seemed to lie chiefly around the 18 – 24 minute interval, hinting once more at the Theta band playing an important role in the transmission of the flow state. Furthermore, the aforementioned findings coincide with a decline in LF/HF as reported in section 4.5.4.

4.6.2 Regional trends

Ensuing examination of the frontal and temporal regional power contributions in and around the designated flow-zones revealed some interesting trends. In light of the limited number of electrode sites in other areas on the headset configuration, the frontal and temporal regions continue to be the main focal areas, and therefore remains a gross correlate to these specified regions. From the earlier deliberations in section 4.5.3 it was evident that the F7, F8 and T8 sites contributed the largest amounts to the major power shifts and themes in the data. In context of the biasing inquisition of this perspective, these findings prompted the examination of these regions and whether their prominence could be associated with the drifts in these flow-related time frames.

Examining the regional contributions in all power bands and individuals during the designated flow-zones revealed, foremost, the predominance of the right temporal region in all bands and also across all participants. In this regards, the dextral temporal region generated higher power outputs compared to any of the frontal or other regions in almost all power bands and was consistent across all participants except Subject E. This individual also showed an elevated power output in this region but it was not the higher and other regions showed superior power.

Examination of the individual regions for all spectral arrays in each participants yielded a generous amount of graphs, all of which did not carry noteworthy revelations and the most relevant findings are therefore presented in bullet point form below instead.

The main finding are as follow:

- In all individuals, the right temporal (TR) region shows higher power outputs in almost all bands compared to the other regions.
- TR shows peak power outputs in concomitance with the highlighted flow zones. Thus, there is an association between flow-zones and major amplitude shifts in the TR region across subjects.
- All individuals show raised theta levels in all frontal and temporal regions, showing hemispheric convergences during flow-zones, especially in the left hemisphere. Such convergence infers that activity shows strongly similar patterns in its peaks and valleys.
- Alpha band shows consistent peaks with approximated flow zones across the frontal and temporal regions in all subjects.
- SMR and beta bands show very similar activity patterns.
- Delta band power is strongest again in TR and shows mixed responses in subjects.
- Subject C typically shows looser associations between hemispheric regions compared to the other subjects. Higher frequency bands in this subject show greater cohesiveness than lower bands. Objectively Subject C was also the lesser experienced performer in the sample group. This might point to some aspects of expertise.

Summarising point: In all individuals, the right temporal (TR) region shows higher power outputs compared to the other regions. The greatest of these amplitude shifts within the TR region tend to occur around close to the approximated flow-zones within each respective subject subset. Alpha activity also shows trending elevations during flow-zones in the frontotemporal regions, while elevated theta levels are also observed in these regions. Differences between the temporal and laterofrontal regions seem to equalise on both sides of the brain during flow-zones. This is to say that the possibility exists that there is an entrainment of activity in these regions during flow, especially in the left hemisphere, but such a notion would be assumptive. In addition, there seems to be a level of entrainment occurring between regions in the delta band in and around the windowed flow-zones. Findings suggest expertise and experience might play a role in the strength of associations between frontotemporal regions.

4.7 OVERALL FINDINGS

The analytical approach taken in this exploratory, investigative study was one that embodied just that. In a top-down manner the global, hemispheric and regional contributions to the spectral power generated during improvisation and the baseline measures made before and after, were assessed. This hierarchical approach was maintain through three divergent perspectives that helped to compartmentalise and systematised the complex and generous amount of data generated during testing. The complexity of the data captured, processed and presented, together with the small sample size constituted a more descriptive outlook, and statistically found correlations were presented where found. In this chapter many findings have been reported, some statistical and some purely of descriptive nature, but taken together the main observations and overall findings of the study can be made as follow:

- The right hemisphere was found to elicit consistently and significantly higher power during the original baseline, improvisation phase and during the comparative baseline following performance. This elevated power was unfailing in all power spectra of the EEG and was found in all but one of our subjects. Therefore, the sustained prominence and stable presence of the right hemisphere during creative behaviours such as musical creativity and improvisation is once more found and supported.

- The theta band did not just show elevated power across all participants during improvisation but was found to show significant differences between several parameters before and after performances. These included significance correlations and associations found between theta power levels (a) in the right hemisphere before and after performances; (b) in the frontal and temporal regions on both sides of the brain following performance; and (c) in the most active electrode sites identified (F7, F8, T8). Moreover, theta power showed continuously elevated levels in and around the approximated flow-zones, and showed increased correlations with other band activity around the 18 – 24 minute intervals. During this time period, a Friedman analysis of the variability within theta band, and an unsuccessful post hoc analysis showed possibly significant variations around this same point in time. HRV data also reflected an increase in parasympathetic influence on the heart during this interval. Therefore, findings suggest the greater importance of theta band activity during improvisation, and perhaps more specifically the flow experience and its trance-like experiential, and unconscious processing characteristics.
- Frontal and temporal regions on the right of the brain showed exceedingly strong associations and there was a convergence of the activity within these regions following improvisation, especially in the lower bands. The right temporal electrode site (T8) showed the greatest power contributions of all electrode sites, while the lateral frontal sites (F7 and F8) showed highest power next to that of T8. During low-zones there was also typically good associations found between the right temporal and right frontal regions, especially in the theta band. Therefore, the convergence of activity in the right frontotemporal region stands out as the most active areas during improvisation.

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Chapter 5

Integrated discussion, conclusion and prospective research directions

The greatest athletes are the ones who 'make it look easy'...The athletes and others in peak performance states are not 'wanting' to perform well but are engaged in the flow of doing.

Michael Hutchison

Flow can only truly be achieved when we are willing to let go of the outcome and just play.

Sandra Taylor Hedges

5.1 RESEARCH CONTEXT AND RELATIVITY

The study of flow and its underlying physiological mechanisms is a modern day quandary. For half a century psychology and its related disciplines have attempted to contextualise this state of peak performance that carries an almost uncanny mystic whilst at the same time being an every-day human feat. A state of implicitly driven behaviour that needs no superior directive, often occurring void of context and freeing the individual from internal incitements so that action becomes the ordinance. Yet, our comprehension of the underpinning neurological functions that governs such behaviour is not well-founded, with only a handful of researchers making reforming advances in the field. However, despite being an enormously challenging field of research, neurophysiological research on the topic of flow is still only in its embryonic phase, dating back merely a decade. There exists a large body of qualitative research on flow and creativity, from many different standpoints and in many research fields, however quantitative perspectives are scarce. In the initial chapters it was discussed that numerous publications and sources on the topic of flow revolve around retrospective analysis or self-report surveys, with practically no studies found that conducted active, real-time investigations of creative conduct during its actualisation and transference. This renders the current research undertaking novel.

The study was designed in a bold attempt to grab the bull by the horns, investigating the higher states of creativity and peak performance in the context of jazz improvisation. Highly experienced professionals were tested during a live session of continuous improvisation by using wireless systems as a new-fangled approach to get to the heart of the matter, as opposed to more classic methods. The difficulties face here however boil down to a few key issues. The first issue is one of quality control and is perhaps the greatest restriction to the progress of flow and creativity research within a live, real-time setting. An ideal could be conceptualised whereby the researcher would be able to test, with great accuracy, whichever parameters are of interest, in an actively engaging individual whilst performing their respective art. Therefore the two cornerstones holding up such an ideal would be the accuracy of measurement on the one side and the actual, real-time engagement of the subject on the other. Meeting the latter ideal is in essence the core to the current investigation as most research strategies in the literature involve retrospective feedback, self-report, or intervention during the creative endeavour, as was contested in Chapter 2.

This is an important point in motivation of this study as it is the opinion of the investigator that retrospectively captured data can only be deemed marginally correlative of the actual act. In addition strategies involving intervention, or prompting of the performer at time interval during their performances in order to report on their current experience of flow-related parameters, can also be misrepresentative. The problem resides with the intervention from the researcher or research equipment. In a state of conduct such as improvisation or free-styling in whichever art form, interrupting the process for feedback or measurements draws in the consequence of interrupting the persons focus and thus rendering the flow state terminated. It is for these reasons that a protocol design was attempted that would not rely on borderline or interceptive data acquisition, but would instead take continuous real-time measurements throughout the act of improvisation and any occurrences of flow during that process.

The idealist theory on the creative process maintains that the process is complete once the creative idea has been generated, whilst action theory pinpoints the execution of such ideas as indispensable to the creative process.[1] Action theory has proven to be the preferred viewpoint amongst researchers in the field of creative research [2] and the deportment of this study stands in agreement. As an original approach, the study would yield insight into the ongoing conduct and physiological responses of the individual, generating novel data directly linked and translatable from the creative endeavour. Individuals could perform unimpeded, in an environment that suited the art form with far less intervention from the researcher or research equipment. And, as described before, lending us a privileged insight into the mind of the artist submerged in their creative on-goings and during an ever elusive state of optimal performance that we call flow.

However, as fate would have, with resolution comes compensation, and data quality remains a concern. Some of the reasons why real-time investigations are so difficult (and often abandoned) is due to accuracy of data. Until recently EEG monitoring involve a large amount of parts, connectors and wiring that was designed for the laboratory or hospital environments, restricting movement of the individual and proximity of the research equipment. Artifactual complications is the main concern, arising as a consequence of e.g. head or other sudden movements, while the use of sophisticated technologies such as fMRI and PET scans could not tolerate even the smallest amount of movement, let alone the costs involved with conducting such testing.

However, in recent times more affordable, practical and portable alternatives have been developed, giving rise a multitude of new commercially available EEG devices that are easy to set up, expedient and programmable. It has become increasingly conceivable to do research in scenarios that might previously not have been up for consideration. The growing trend within the industries of wireless EEG and brain-computer interfacing (BCI) means that technologies are being developed and improved at a more than respectable rate, and developing protocols such as this one will carry much greater accuracy within the immediate future. As things stand at present, such technologies as used in this study (EMOTIV) are still novelty research tools and is thus a modest alternative to its clinical counterparts, but offers the added advantages that is needed to pursue the objectives of this investigation. In this regard, the balancing of priorities in the study design prompted as original line of attack in addressing the issue of real-time research on creative behaviour. Granting the reduced sampling quality an exploratory investigation was thus piloted.

5.2 INVESTIGATIVE UNDERTAKING

To date, no complete definition of creativity exists that can be fully applied to any and all disciplines of creative conduct including the arts (e.g. painting, dancing), music, architecture, science, medicine, film and literature. Empirically difficult to test in human subjects, creativity research is also not easily translatable in animal models, and hinges on a strong "cultural relativity" in many frameworks.[3] Distinguishing the truly creative from the simply eccentric; the correlating relationships between creativity and features of psychopathy, and the imperative differentiation between insight, originality and novelty aspects to creativity is perplexing. From an integrated physiological standpoint, research on creativity is equally confounding and sometimes even contradictory, while the physiological study of flow, a non-exclusive manifestation of highly creative behaviour has already been highlighted as still only in an incubation phase. The study aimed to shed light on such phenomena as flow and its physiological underpinnings while contributing valuable research to the narrow existing body of knowledge pertaining to EEG and HRV evidence within the sphere of music and neuroscience.

The study began with the investigation of heart rate variability and electroencephalography parameters in a volunteer-based sample of 5 professional jazz musicians. All volunteers filled in a short biographical questionnaire, signed an informed consent leaflet and were fitted with the Zephyr BioHarness heart monitor and EMOTIV EEG headset. A baseline recording was conducted at a state of relaxed inactivity with the eyes closed where after the eyes were opened and another continuous measurement (true baseline) was done. Each subject then improvised continuously without stopping for an unanticipated period of time after which a stabilising (eyes-open) and comparative (eyes-closed) inactive baseline repetition was measured. During improvisation there was no interaction or intervention with the subject and participants were allowed to perform for a self-determined period, only instructed to remain quiet and motionless upon completion.

Analysis of the data captured during improvisation was approached from three divergent perspectives that carried distinct objectives in order to firstly compartmentalise the exorbitant amount of data generated from each performance, but also to systematise the analysis. Normalisation of the spectral analysis of both EEG and HRV data was done in order to relatively standardise the magnitude differentials between the two systems, but also between individuals.

5.3 PALLIATIVE ASSOCIATIONS AND CONTEXTUAL IMPACT OF THE STUDY

According to Arden et al. [4] the neuroscientific theories of creativity, at present at least, can be broadly categorized into four groups that are based on the hypothetical associations of creativity with: (a) right brain activity dominance, (b) higher levels of neural connectivity, (c) low cortex arousal, and (d) functioning of the prefrontal and frontal brain regions. Given the scope of this study, and the associative importance of the frontal brain regions in both novelty generation and flow, findings are discussed within the greater context of creativity and flow research. In an effort to liaise these two entities within the current framework, Burzik [5] is cited, summarising flow as compromising of:

1. Largely symmetrical brain activity;
2. The presence of strong delta, theta and alpha waves which might be the bridge between creativity, flow and its spiritual constituents, as well as explaining the trance-like properties of flow;
3. An economisation of brain activity in the form of “cerebral microsleep” which might explain the ease and efficiency of the flow experience;
4. The paradoxical activation patterns of a partially passive mind and active body.

These arguments will serve as guiding principles for the ensuing discussion.

5.3.1 Regarding symmetry and lateralization

During the 1970’s, early neuroscientific conceptions of creativity lay rooted in the idea of “hemispheric specialisation”. Transection surgery for intractable epilepsy led scientist to believe that the right hemisphere (non-dominant) was specialised for creativity and holistic pattern recognition. [6, 7] However, the model of lateralization applies poorly to creative language and other creative activities, and later evidence pointed to the greater importance of bilateral recruitment for maximizing creativity. [8]

A meta-analysis by Mihov et al. [9] on hemispheric specialization and creativity affirms the lack of evidence to suggest a partiality of right brain activation during creative thinking. However, early EEG studies have added greater dimension to the issue of lateralisation and the ubiquitous presence of the right brain, showing that highly creative individuals differ from lesser creative persons in that they show:

1. Greater activity in the parieto-temporal areas in the right hemisphere;
2. Heightened alpha activity during spells of inspiration, and
3. Tendencies of greater physiological over-responses. [10, 11]

Later EEG studies illustrated a significant correlation between EEG coherence levels in the right brain with higher creative scores during “rest.” [12] In addition, one study showed greater interconnectivity in the right hemisphere of higher creative male subjects, [13] along with associations found between right temporal epilepsy and de novo artistic expression.[14]

In light of such associations, our findings proved consistent. Prior to improvisation all subjects showed fairly equal power output arising from the both hemispheres during the true baseline. Upon initiation of the performance there was continually greater strength in power arising from the right hemisphere in all but one subject. This elevated right brain power persisted throughout each performance and showed consistently higher activity in all spectral bands. Moreover, we also found exceedingly strong associations between the activity of the frontal and temporal areas in the right hemisphere. Following completion of the performance phase, the comparative baseline revealed continued supremacy of the right hemisphere, typically showing even greater differences between left and right brain activity. Put differently, all frequency bands of the EEG showed greater power (thus amplitudes) in the right hemisphere during and after improvisation in all but one of our five pianists.

It could be possible that a greater power expression in the right brain can be a product of the information processing tendencies of the right hemisphere within the creative context. To grossly simplify, the processing inclinations of the left hemisphere involves more sequential, logical thinking and is more detail orientated, whereas the right brain involves more holistic, symbolic (associative) thinking and is more intuitive.[15] The flow state and its associative propensities as a subjective experience, encompasses a lot of these ‘right brain tendencies’. It could therefore perhaps be said that such lateralization of processing predispositions could, at least in part, explain the prominence of the right hemisphere, however other research has also found greater right brain activity in higher creative subjects during creative tasks.[16]

A study by Crews [17] involving golfers putting under stressful conditions revealed that those who were successful exhibited the same levels of anxiety as those who ‘choked’ under the pressure, but that a determining factor existed in the EEG activity measured from these subjects. Failed golfers showed much greater activation of the left hemisphere, associated with higher cognitive and self-conscious behaviour; mentally trying to control their actions by analysing or intellectualising the action. On the contrary, the successful golfers showed greater activation in the right brain which would involve greater measures of visualisation or focussing on the smoothness of the action and senses rather than sequentially deconstructing the action. These golfers displayed greater co-lateral symmetry in activation too, which once more lends credit to the notion of equal activation of both hemispheres during high-performance states.

In our study, all participants consistently showed greater activity arising from the right hemisphere during improvisation, however the activity from both hemispheres showed symmetry. What we observed was consistently symmetrical responses from both hemispheres within all of the power bands, but more often than not the right hemisphere would exhibit greater power magnitudes compared to the left. In other words, there is symmetry between the activities of both hemispheres, whereby amplitudes showed closely similar fluctuations in both hemispheres, except fluxes in the right hemisphere would occur at greater magnitude. PET studies performed by Chávez-Eakle [18] support these findings, stating that the creative performance involves "a bilaterally distributed brain system" but that most elevated activity arises from the right hemisphere.

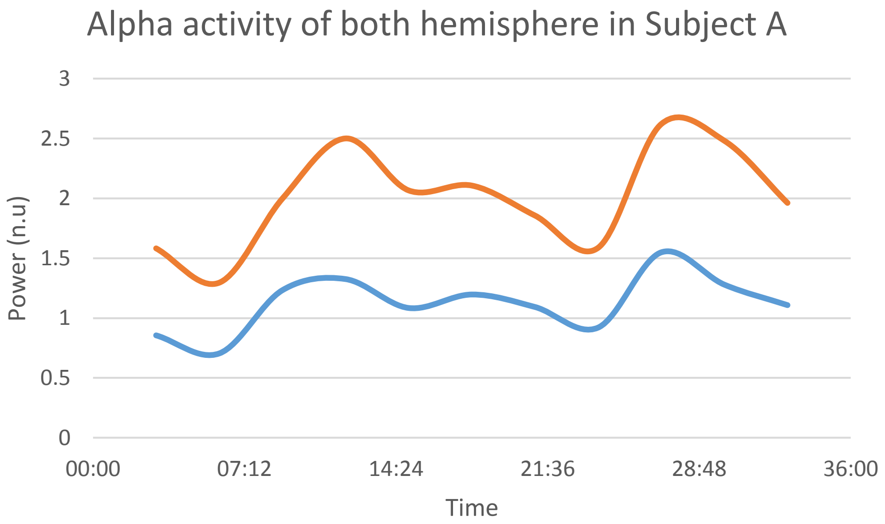

Figure 35 - An example of the symmetrical activity expressed in a subject at different power magnitudes throughout the testing phase.

Therefore, our findings show accuracy and agreement with Burzik [5] and Arden et al. [4] more specifically showing significant differences (P=.037) between the right and left brain activity in the delta, theta and SMR bands following improvisation.

5.3.2 Regarding spectral density and state of mind

One of the most apparent and rousing observations of this study was the pre-eminence of theta band relations throughout the findings. Looking at theta activity in isolation our findings revealed globally significant differences (P=.037) between the true and comparative baseline measures (EO1/EC2) for theta. Together with this, the means perspective revealed that there existed a significant difference (P=.037) between the hemispheres when comparing the baseline theta power measures. Regional means contributed to these initial findings by showing that there were significant differences (P=.037) in baseline theta power within temporal regions on both sides of the brain. Significantly therefore, global theta activity was different before and after improvisation and was also different between the hemispheres, with the right brain consistently showing higher power. Theta activity in both temporal regions (left and right) were also difference before and after improvisation too.

During improvisation, dramatic increases in theta and delta power constituted the greatest recorded amplitude shifts in all but one participant. Theta power magnitudes showed increases varying from 3 – 100 times that measured at baseline and was also found to be highly expressive in the F7, F8 and T8 sites which were isolated as the most active electrode positions during improvisation. Therefore, the fact that theta activity shows prevalence in the most active sites during improvisation, paired with the considerably higher mean power outputs of the lower bands (theta and delta) during improvisation hints at a state of lower band dominance during the performance phase. This slower wave activity predominance can be said to reflect a state of greater unconscious processing associated with accessing memories and other unconscious material, transition between sleep and waking, and integration of sensorimotor information. It should also be taken into consideration that heightened slow-wave activity does not infer slow or less activity, but on the contrary a greater level of synchronicity between firing neurons operating at these frequencies. When more neurons are firing in syncopation (together) the pooled energy is greater, which is reflected in the amplitude of that frequency range and therefore directly related to its power output. Thus higher power translates to higher amplitudes which translates to higher energy output which translates to neurons firing in a harmonised and coordinated manner (rhythmic pulsations versus erratic arbitrary firing of neurons).

Such activity is typically seen while sleeping or meditating, however here we see elevated slow-wave activity occurring in alert, highly focussed individuals actively engaged in very complex, highly skilled creative behaviour. The Royal College of Music, London, demonstrated enhanced musical understanding, quality of performance, stylistic accuracy and interpretative imagination through improved theta activity in students using neurofeedback protocols.[19] The authors explain that alpha/theta feedback is used so that the subject can enter a "theta cross-over" whereby theta activity surmounts that of alpha activity. Entering such a mental state implicates "a transient entering and re-entering of dreamlike states while staying awake, enabling a fluent retrieval of memories into conscious awareness and working memory." [5]

Even more, trance EEG studies have shown elevated theta activity during states of intense physical and mental engagement.[20] EEG recordings conducted on fakirs in deep trance states - during which these individuals would stick swords through their tongues and other areas on their body – revealed, once more, the presence of high theta activity.[20] Larbig [20] explains that such elevated theta activity during intense physical, and thus wakeful engagement could be interpreted as an "economisation of the brain by temporary synchronisation of those parts of the brain which are not included in the processing of the task at hand." What this means is that it is possible for the brain to switch areas that are not actively engaged in an activity into a "microsleep" [20] which would therefore give rise to such elevated theta presence. Described as a paradoxical state of mind-body activation referred to as "passive mind – active body", the author did not specifically refer to flow, most likely because the idea of flow was only introduced around the same time (late 1970's) it is evident that such trance states and its accompanying brain activity resembles that of flow to a great extent. Flow has in fact been described as a trance state before ("meditation in action")[5] and our study provides further evidence for such views.

From the biasing perspective it was shown that theta band activity showed an increased number of correlations with other bands as improvisation continued. Significant positive correlations (CC=0.9; P=.037) were found between theta and all other spectral bands, arising from about 18 minutes into performances. In addition, consistently elevated or rising theta power was observed in close proximity to approximated flow-zones in all subjects. Flow-zones were probability estimates based on subjective feedback and investigative notes taken from each performance and not only showed great concomitance with raised or rising theta power, but all subjects also showed flow encounters starting in or around the 18 minute mark. Moreover, a Friedman test showed almost significant (P=.065) variation within the theta band over time and despite being inconclusive, the post hoc analysis seemed to suggest that the greater contribution to this variation centred around the 18 – 24, and 18 – 30 minutes interval. Therefore, given the already elevated theta levels during flow-zones, paired with the occurrences of flow overlapping within the time frame that all spectral bands show improving correlation with the theta band; and the Friedman analysis which, though not significant suggests the greatest intraspectrum variation in theta seems to occur around the same time, the notion of flow as a high theta state seems plausible.

In even further support of this idea, HRV data showed LF/HF peaking at 15 – 25 minutes, followed by a steady decline in this ratio. What this signifies is the gradual decline of LF strength and the consequent rise in HF power. This suggests the decay of a sympathetic dominated state into one that is by no means parasympathetic dominant but where parasympathetic influence is rising, slowing the heart and breathing rates. During sleep or meditation parasympathetic, or vagal tone dominates due to the lowered breathing rates, coupled with the heart rhythms (respiratory sinus arrhythmia) and therefore reflects high HF power. EEG studies have also already been put forth showing the coherent relationship between HF and the lower spectral bands of the EEG as occurring during sleep, [21] and two subjects were found to express correlating relationships between theta and HF power over 30 minutes (Subject A & B; P=.037). Thus, given the theta related results discussed up to this point, the overlapping statistical findings of elevated theta during and after improvisation, its correlations with other band activity and intraspectrum variance concentrating around the same time when parasympathetic influence starts to show intensification and self-report indicated the occurrences of flow, proves an exciting prospect and strong evidence of the likelihood of flow as trance state contributing to the interplay between heart and brain during a state of high theta activity and high creative performance.

The reader is reminded that the creative proxy plays a significant role whenever any creative research is conducted and that very few conclusive perspectives can be generalised to all facets and manners of creative conduct. In this regards, these findings might be contextually exclusive to music performance, piano playing, genre, style or improvisation, as creativity research in general often emphasise and maintain the opinion of the importance of alpha activity in the creative process [e.g. (22) (23) (24) (25) (26) (27) (10)]. However, due to the fact that so little research has been conducted on individuals during the actualisation of their creativity, most creativity research found revolved around problem solving, insight, alternate uses, idea generation, creative drive, inspiration, and visualisation based tasks. The fact of the matter is that the largest body of creativity research therefore revolve around tasks and methodologies grounded in either divergent or convergent types of creative thinking and the importance of the alpha band may therefore also be contextualised and particular to such conceptualisations of idea generation and creative ideation.

In the same manner we can paint a different picture. In Chapter 2 it was explained that many studies show the particular involvement of the frontal cortex in the evaluation of novelty and originality, which are deemed subcomponents of creativity, and therefore the active role of the frontal areas in the creative process. However, almost contrarily, it is also well reported that flow encompasses a state of hypofrontality, resulting in the down regulation of the frontal areas, allowing the implicit arrangements to execute tasks at optimal efficiency. It seems therefore that the idealist viewpoint of the idea generation or conceptualisation as the core to creativity is expressed more commonly in the literature through creativity tasks such as problem solving or visualisation and its strong associations with the alpha band and the frontal areas of the brain.

Could it therefore be possible, from an action theory perspective, complimented by the literature consulted in this study regarding flow, trance states and implicit functioning in the brain; and the presented findings, that the flow experience sculpts an alternative view of creativity as an expression of skill-based, implicit knowledge and processing in the brain? Can it be said therefore that flow could be governed largely by theta band activity and predominance and that high alpha in the creative process acts as the ‘bridge’ between the explicit and implicit systems (conscious to unconscious processing)? [2, 5] If such separate creative states or conditions could exist, sustained through either high theta or high alpha eminence, this could differentiate the associations of e.g. novelty generation or ideation with high alpha as an archetype of creative thought, versus the fluent, implicitly-driven transference of creative skills such as e.g. improvisation with lower spectral manifestations. Such an impression necessitates further investigation and could shed light on the difference between creative ideation (generation of idea) and creative conduct (expression of idea).

In light of such a distinction it should be mentioned that our study, despite propagating the idea of flow being a theta dominant state of conduct, does not stand in opposition of existing views that stress the importance of higher alpha activity during creative endeavours. In fact our findings showed significant differences (P=.037) in alpha power between the true and comparative baselines, and also significance (P=.037) between both eyes-closed baseline. In pertaining to the latter point, it was mentioned that closing of the eyes naturally causes a sharp increase in alpha power, but our findings showed consistently greater differences in alpha power in the comparative baseline compared to the initial measure. We also observed elevated alpha power throughout improvisation in all but one subject, showing great concomitance with the approximated flow-zones, especially in the right frontal and right temporal areas. Therefore, higher asymmetrical alpha activity was also observed, but at lower power outputs compared to the theta band, with a much more stable expression of elevated alpha occurring throughout the act of improvisation, rather than expressing major peaks like we observed in the theta band. Thus, our findings prove consistent with that found in the literature with specific reference to alpha band activity, however, the superior expression of theta and its offshoots seem the better fit given the current domain and proxy.

5.3.3 Regarding economisation and lobular functioning

Long since the original ideas of hemispheric specialisation, contemporary theories of creative neurobiology focus more on lobar function and connectivity, implicating the frontal lobes and areas of the temporal and parietal lobes as being key to the creative process. [6, 28, 29, 30] The literature often shows opposing findings regarding cortical activation, showcasing a decrease in cortical activation in highly creative individuals whilst performing creative tasks in recent studies, [31] yet earlier findings support notions of increased activation. [8]

Despite the general consensus that the prefrontal areas play a pivotal role in creative thinking, such theories of prefrontal dominance [32, 33] stand inharmoniously to other studies that point to the explicitly necessary role of the temporal-parietal-occipital collective (TPO area). [34, 35] The incongruity between laboratory testing and observable behaviour as displayed in real world creative behaviour adds to such heterogeneity in brain research on creativity. Moreover, extremely little has been published within the particularly focus of improvisation and musical creativity, [36] let alone flow states associated with such practices. No more than five years ago, it was still reported that positive psychological states such as flow “has remained almost entirely unexamined in live music performance.” [37] Nonetheless, some neurophysiological correlates have been put forth for musical creativity and improvisation.[36]

Focussing on the lobular and regional activity as measured in our study, particular attention was directed at the frontal and temporal areas. As was protuberant from the superior right hemispheric power, right temporal (TR) and right frontal (FR) areas also showed greatest power outputs compared to other areas, while the left frontal region (FL) also showed above average power yields. We observed an exceedingly strong relationships between FR and TR (P<.01) with the two areas also showing consistently higher power in the comparative baseline. The right frontal region showed significant (P=.037) correlations with the SMR band when baselines were compared, while the right temporal region showed correlations (P=.037) within the alpha and theta bands before and after performance. The TR region also showed the highest power output in all subjects and across all bands, both at baselines but also during improvisation. Throughput performances the TR region showed elevated power and showed consistent peaking in and around the designated flow areas. The higher power in the right hemisphere as reported earlier is therefore largely due to temporal electrode sites, but more specifically that of T8 and F8 on the right. However we also found greater ipsilateral associations between frontal and temporal areas in both hemispheres immediately following improvisation, however left brain associations were typically at lower amplitudes and showed marked increases in slow-wave power (P=.037). The trending of activity measured between regions also seemed to suggest a convergence of the regional activity in the left brain around the flow-zones, however the T7 site, together with P7 and O1 (all on the left) showed the lowest power outputs of all sites. Prefrontal and medial frontal sites showed moderate or slightly below average power and could be assumed to lean towards a hypofrontality situation. Lower spectral bands (delta through alpha) were very prevalent in all frontal and temporal areas.

Taken together, we see co-lateral frontal regions (F7, F8, AF3, AF4), together with the right temporal region (T8), to be most active during improvisation, especially between the delta to alpha power bands. This is to say that the left frontal and right fronto-temporal areas of the brain was most active, whilst expression greater power within low frequency bands, whereas the left temporal, parietal and occipital areas showed the lowest activity during performances.

Similar findings of increased power within the frontal cortex, alongside the increased desynchronization of the posterior cortex during performance of verbal insight and creativity tasks are cited [38] in support of our findings. In addition, Martindale and Hasenfus [10] have reported increased activity in the right temporal regions in highly creative individuals with a tendency of physiological hyperresponses, while bi-lateral frontal activation was also detected in highly creative individuals during divergent thinking tasks. [39] Furthermore, SPECT scans on figural creativity showed positive relationships between high creative scores and temporal and frontal associated areas on the right (right postcentral and parahippocampal gyri; right inferior parietal lobule), [40] while lesions studies tend to point to the frontal and temporal poles when attempting to localize creativity. [11]

We therefore see various research within different creative facets pointing toward the same activation patterns, however, as mentioned, “neuroscience inquiries of creativity show a muddled picture likely related to subject, modality, and metric issues” and contextually we need greater deliberation on musical improvisation specifically.

Dikaya and Skirtach [36] calculated statistical correlates between music improvisation, professionalism and musical mode, typically finding improvisation related tasks to have greatest effect on left temporal (delta), right prefrontal (beta1) and left occipital (beta1) brain regions. Musical mode, pertaining to differences in major or minor scale improvisation (greater emotional element) showed greatest effect in the theta band across the frontal leads. Furthermore, the authors found significantly higher delta power in the left frontal and posterior temporal regions particular to improvisation in comparison with other musical activities ($p<.05$). Such temporal regions form part of the acoustical associative areas, also connected to rhythm perception and processing of complex musical characteristics. Moreover musical improvisation was further characterized by augmented short coherence between right prefrontal, central and left parietal regions within the delta and theta bands, while right prefrontal, frontal and left occipital regions showed elevated beta power ($p<.05$). This led the authors to claim that this “short-distance low-frequency coherence connections and the high-frequency creative axis are most relevant for the creative process in music."

In light of such correlations, our study showed general agreement, but in some regards we had mixed or inconclusive results. For instance, superior delta power was indeed found in the left frontal regions, but we had mixed results regarding delta activity in the left temporal region, with some individuals showing much lower or around average values. Likewise, we saw raised levels in power within the delta, theta and beta bands in the right frontal area, but prefrontal areas, and occipital areas on the left typically showed lower levels in power across all power bands. Such differences can be imparted to several differences in methodologies between the two studies. In the study mentioned above, EEG measures were conducted on mentally improvised pieces that involved only the perceptual and internal composition of an improvised piece of music. Therefore no instruments were played and EEG measure were done before musicians were allowed to perform there pieces on actual instruments. No measurements were taken while performing, and improvisation was done within specified modes and frameworks. Along such lines, the differences in activity measured might be the product of motor and sensory activity representations within the brains of our actively participating subjects, or perhaps the relative freedom for subjects to progress musically in a direction of their choosing as opposed to conforming to a mode or specific key, could play a role. In fact, premotor and primary motor cortices are indeed allocated within the temporal areas and might be the difference, however paradoxically we typically found decreased levels in power in the left temporal areas which point away from the influence of motor activity.

Alternatively, Flatherty [28] cites from numerous lesion, mania and surgical studies the importance of the temporal and frontal regions in the non-domain specific areas of creative idea generation and creative drive. The author highlights that most temporal lobe conditions that trigger greater creative drive arise through disruption of temporal lobe function. Frontotemporal dementia is a very well-known example where a subset of about 10% of such individuals (selected neurodegeneration in the temporal lobes) develop compulsive musical and artistic interests even if no artistic tendencies existed beforehand. Such notions fit better within the framework of our study where the down regulation of the temporal areas in the left brain might reflect such increased creativity as would be mediated through musical improvisation. The author (Flatherty) goes further to explain that the temporal regions can thus, more accurately be considered as a “region of creative suppression,” clarifying that large temporal lobe efferent fibres inhibit the frontal lobes, [41] and that connections between frontal and temporal regions might play a greater role in creativity than the interconnections shared between right and left hemispheres. [28]

This relates to the chief contributions of frontal lobes to the creative process, most markedly regarding executive functioning, [42] goal-directed behaviour, evaluation of appropriateness and originality, and the integration of already highly processed information.[q] Creative block (as with e.g. writer's block) has been linked to frontal lobe dysfunction with supporting evidence typically found in anxiety and depression studies. [28, 43] However, the involvement of the frontal and prefrontal areas within the context of improvisation is almost enigmatic, often showing a down regulation in activity levels and might further explain some of the differences in our results.

In a critical review, Sawyer [44] explain that "improvisation involves brain regions that are involved in the generation and comprehension of sequences, making decisions among competing alternatives, and the creation of a plan for the motor execution of that sequence. These are domain-general brain regions, suggesting a role for domain-general mental processes in creativity."

The outlook stated here is important to keep in mind as improvisation often provides controverting correlates in brain activity. One aspect that might play a substantial role here, would be the experience of flow and the hypofrontality often described as occurring during such states. fMRI studies on jazz improvisation [45] showed decreased activity in almost all of the lateral prefrontal cortices, in particular that of the dorsolateral (DLPFC) and lateral orbital prefrontal cortex (LOFC). The decrease in activity in the lateral prefrontal regions suggests the inhibition of regions involved in the conscious monitoring and correction of goal-directed behaviours, while changes in activity within the medial prefrontal regions (MPFC) previously associated with autobiographical narrative was also observed. [44] Our findings showed consistency.

The prefrontal sites (AF3 & AF4) and more medial frontal sites (F3 & F4) showed typical means of average or below average power across subjects, compared to other regions, pointing towards a lower level of activity in these regions. On deeper inspection, we found the right temporal (T8) and the more lateral frontal regions (F7 & F8) to exhibit the highest power outputs. We also traced the largest shifts in amplitude within the right temporal region to occur in strong association with the highlighted flow zones in all of the subjects.

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[q] For greater resolution on the involvement of the frontal areas in the creative process, refer to Chapter 2.

From the dynamic power graphs put forth in Chapter 4, it was evident that there were quite prominent shifts in amplitude within each dataset, and that these major amplitude shifts can be attributed to massive power upsurges at those moments in time. These peaks more often than not occurred in close proximity with the predesignated flow-zones, implying the possibility of a causal relationship between the flow experience and rising amplitude levels and higher energy output. Peaks were most profound in the lower frequency bands, but were typically present across spectra. During these flow-zones, alpha activity showed trending elevations, while elevated theta levels were more saliently observed in the frontal and temporal regions in all subjects. Differences in power between the temporal and laterofrontal regions seem to converge on both sides of the brain in and around the apportioned flow-zones, which is to say that the possibility exists of an ‘entrainment’ of activity in these regions during flow, especially within the left hemisphere. Such ‘entrainment’ could be in the form of coherent associations between these regions. In summary therefore, our findings point to the inclination of the lateral frontal and temporal regions towards a lower band presence, together with a down regulation of the prefrontal and medial frontal areas. Additionally, our findings of lower power outputs in the left parietal and occipital areas necessitates greater resolution if it were to prove true.

Our findings and the relative activation patterns can also be likened to the studies on mania. SPECT imaging studies in manic patients have shown increased activity in the right anterior temporal area, while EEG studies show decreases in lower left temporal activity, [28] a very similar pattern that we found. In this regards, likeness can be drawn to the occurrences of hypergraphia (a compulsive drive to write) in manic patients, reflecting decreases in temporal lobe activity, as well as temporal lobe lesions on the right being one of the most prevalent causes of mania. [28] Flatherty [28] explains that hypergraphia in manic patients provides a platform to investigate creative drive, elucidating on the role of the dopaminergic system in the brain and its effects on motivation, idea generation, goal-directedness and reward-seeking activity. Mania can be described as a state of mental illness marked by episodes of great excitement, excessive enthusiasm, euphoria, over-activity and obsession, and it is in this regard that mania and hypergraphia, and its activation patterns in the brain can likely be mirrored in the positive emotions and motivated behaviour experienced during flow. In this regard, it would not be too difficult to imagine that the limbic involvement and positive affect, together with such goal-directed behaviour associated with flow and peak performance might echo the same activity in the brain, which might explain why we observed similar activity in our musicians.

5.4 LIMITATIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

- Due largely in part to the small sample size, statistical power of the study was limited. The greatest restrictions to obtaining a larger populations was related to time and viability of candidates.
    - Time constraints were largely due to the replacement of damaged equipment, with major delays during importation resulting in a truncation of time available for testing. In addition, national protests resulted in the sporadic closing down of campuses in and around critical phases of this project.
    - The restrictions related to candidate viability revolved mainly around the recruitment of professional individuals only which dramatically shrunk the amount of internally available candidates at the university. Additionally, a calculated decision was made to replace the software used for data analysis, resulting in the loss of data recorded up to that point due to compatibility issues.
    - Basic statistical approaches were followed due to the small sample size, however cross-correlation and coherence specific statistical methods paired with a larger sample would add great value to the existing research protocol.
- From the data, exportation restrictions of the software platforms utilized, meant the manual distribution and processing of data which was not ideal. Therefore, an upgrade to more powerful software packages would contribute to lesser time needed for processing and analysis, greater accuracy and a greater number of available analytical tools. Along the same lines, the Emotiv EEG headset, although useful, remains a largely tyro tool for research. However, the enormous proliferation of such technologies and the extreme rate of improved temporal and signal resolutions mean that such technologies are continuously

improving at a rapid rate and provide very promising alternatives for future research.

- Future research should build from this study, employing more powerful methods of assessing the interplay between heart and brain measures, as mentioned. Additionally, building on the more salient findings in this study, concentrating on isolating, inducing and observing high alpha and high theta states might shed light on different facets or types of creative behaviour, such as creative thinking versus creative doing. Therefore, the study carries value in that it can serve as basis for refinement of such protocols that could contribute to the areas of bio- and neurofeedback and music therapy. More sophisticated statistical methods would help to understand the interrelatedness of the heart-brain collective and the potential for breathing, biofeedback and trance-inducing procedures to facilitate creativity and flow experiences.

5.5 CONCLUSION

The research suggests that flow, as an experience of optimal performance and higher creative conduct, is related to an intensification of theta oscillations in the brain. In light of this, it was shown that elevated lower band activity show prevalence during improvisation in professional musicians, and that flow may be responsible for hyper-responses in the amplitude of these frequency ranges. Furthermore, a decrease in LF/HF, inferring a rise in parasympathetic influence on the heart showed strong overlap with the first occurrences of flow, and the apparent entrainment of brain activity with the strong theta presence. In addition, the research suggests the convergence of activity within the right frontotemporal regions, which was also the most active regions during improvisation, while there was a lower energy transfer in the temporal, parietal and occipital areas on the left. Sustained right hemispheric dominance was found across all subjects, and the possibility of differences in high alpha versus high theta states of creative behaviour are advocated.

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PARTICIPANT INFORMATION LEAFLET AND INFORMED CONSENT

Research study title:

Physiological coherence between heart rate variability and electroencephalography during live music performance - A real-time, exploratory investigation using wireless systems.

Introduction:

You are invited to take part in a research study on brain and heart coherence during musical performance. This information leaflet has been created to aid you in deciding whether you would like to participate in our study and to inform you of the purpose, aim and procedures of this study. Before you agree to take part in this study you should fully understand what the study entails and your role in it. If you have any questions that are not explained in this leaflet, please do not hesitate to ask the investigator (Gehart Kalmeier – see contact information below).

What is the purpose of this study?

This study is an exploratory investigation into the physiological aspects and activities of the heart and the brain during musical performance. The study aims to explore the brain waves, heart functioning and mental involvement associated with creative performance and more specifically the performance of music in a live setting.

Explanation of procedures to be followed:

You will be asked firstly to complete a brief questionnaire regarding your personal details and information. The questionnaire should take no more than 10 minutes to complete. This information will be kept safe and private and will only be accessible to the main investigator (Gehart Kalmeier). You're personal information will be protected under all circumstances and will not be shared with anyone.

Following completion of this form, we will prepare you for testing. You will be asked and instructed on how to put on a heart monitoring strap around your chest, which will take measurements of your heart rate, breathing rate and other related heart functions. There is no discomfort involved, but the strap does have to make contact with your skin in order to make accurate readings. Therefore you will be asked to put the strap on in private after receiving instructions on how it should be positioned.

Once you have put on the heart monitor, a brain-wave measuring device called an electroencephalograph (EEG) will be positioned on your head. This device uses electrodes to measure the electric activity of your brain and in order to facilitate this measurement the electrodes needs to make contact with your scalp and is moistened with salt-water to increase conductivity. You will experience no discomfort whilst wearing the device. When the equipment has been set up correctly the testing procedure will commence.

Prior to your performance, you will be required to sit still, in a comfortable position for 3 minutes with your 'eyes open', followed immediately by 3 minutes period with your 'eyes closed'. When the 3 minutes 'eyes closed' period has passed you will start with your performance. Please remain quite throughout all these steps. Talking will cause inaccuracies in the measurement and you are asked kindly to refrain from talking or making any sudden movements. When you have completed your performance, you will be asked to sit again for 3 minutes with your 'eyes open' followed by another 3 minute period with your 'eyes closed'. This completes the testing session.

3 min EYES **CLOSED** → 3 min EYES **OPEN** → **PERFORM** → 3 min EYES **OPEN** → 3 min EYES **CLOSED**

It is important that you understand the sequence of events required and you are encouraged to ask at any point in time if you are unsure about the procedure. Please remember that throughout this procedure you are requested to refrain from speaking. That being said, please feel free to bring any concern under the attention of the investigator at any point in time.

When you are finished with all the steps we want to ask you a few questions about your experience and performance. This will conclude the testing procedures.

Please note that pictures, video and audio recordings are done during testing in order to reflect the data captured against your performance for later analysis. These recordings might be used in academic presentations and future research under your written permission. All such pictures, video and audio recordings, will be used strictly for the reasons specified above and no other. All recordings, video and audio, will be made available to you for your own personal use and distribution.

What is the duration of the study?

As described above, the testing session will be approximately 45-60 minutes in total, depending on how long your performance is. The questionnaire will take about 10 minutes to complete.

Has the research study received ethical approval?

This research study protocol was submitted to the Faculty of Health Sciences Research Ethics Committee, University of Pretoria and written approval has been granted by that committee (S15/2015). The study has been structured in accordance with the Declaration of Helsinki (last update: 2004), which deals with the recommendations guiding studies in biomedical research involving human participants. A copy of the Declaration may be obtained from the investigator should you wish to review it.

What are your rights as participant in this research study?

Appendix A INFORMED CONSENT

Your participation in this study is entirely voluntary and you have the right to withdraw or stop at any time without stating a reason. You have the right to information relating to the purpose, procedures and any other ethical considerations of the study. The investigator retains the right to withdraw you from the study if it is considered to be in your best interest or if the information supplied by you is inaccurate or false; or in the case where you did not follow the guidelines and regulations of the study.

What are the risks involved in this research study?

There are no risks involved concerning your health, safety, comfort or interests in this study. If you have any concerns or feel fatigued you are asked to please bring this under the attention of the investigator at any point in time.

What are the benefits to you for participating in this research?

In a broader sense, by participating in this research you are contributing to an area of creativity research that has not yet received much attention. Not much experimental research has been done on musicians (such as yourself) during live performing. Hereby, your involvement will help us gain more insight into the brain function and underlying physiological processes happening in the brain during creative performance. On a more personal level, we will give you all the video and audio recordings of your performance which you can use for your own personal causes, such as future auditions etc.

Confidentiality:

All information obtained during the course of this study are strictly confidential. Data that may be reported in scientific journals will not include any information which identifies you as a participant in this research study.

Any information uncovered regarding your test results or state of health as a result of your participation in this study will be held in strict confidence. You will be informed of any finding of importance to your health or continued participation in this study but this information will not be disclosed to any third party without your written permission.

Contact Details of Investigator

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QUESTIONAIRE AND INDEMNITY FORM

Subject Number: Number ____________ Date: DD | MM | YEAR

INDEMNITY

I hereby declare that I have read and understand the content of this document and my role and rights in this study. I had the opportunity to discuss any relevant matters with the investigator and participate in this research at my own risk. I will not hold the University of Pretoria responsible in the unlikely event of an injury or any other negative impact that my participation in this study could confer upon myself. I hereby give consent for my participation in the aforementioned study and give permission that video/audio recordings of my performance may be used for academic presentations and future research.

____

Signed Date

☐ I hereby give **consent** to the terms and conditions of the study, as discussed above.

Participant's name
(please print): ____________________________

Date: DD | MM | YEAR Participant Signature: ____________________________

Witness's name (please print): ____________________________

Date: DD | MM | YEAR Witness Signature: ____________________________

Appendix B INDEMNITY FORM AND QUESTIONNAIRE

PERSONAL AND BIOGRAPHICAL INFORMATION

Mark with 'x' where relevant

Subject Number (leave blank)								
Email address								
Tel/Cell number								
Name of piece being performed:					**Time of day:**			
Instrument played								
Gender:	Male	Female	**Date of Birth:**	YYYY/MM/DD				
Age:		**Height (cm)**		**Weight (kg)**				
Ethnicity:	Black	Coloured	Indian	Asian	White	Other		
How many cigarettes do you smoke per day?	0	1 - 5	5-10	10-20	20+			
Have you had any alcoholic beverages within the last 24 hours	yes	no	**How many drinks?**					
Have you been experiencing any sleep abnormalities of late?	yes	no						
If yes, please specify		**How many hours did you sleep last night?**						
Do you have any chronic illnesses? **If yes, please specify**	Yes	No						
Are you on any medication? **If yes, please specify**	Yes	No						

Appendix C REFERENCE TO FIGURE 32

FIGURE 32

Composite graphs for all subjects showing power spectra over time and each individuals approximated 'flow-zones'.