THE NEUROSCIENCE OF MUSICAL CREATIVITY USING COMPLEXITY TOOLS

by

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for my father and mother

Abstract

This project is heavily experimental and draws on a wide variety of disciplines from musicology and music psychology to cognitive neuroscience and (neuro)philosophy.

The objective is to explore and characterise brain activity during the process of creativity and corroborating this with self-assessments from participants and external assessments from professional "judges". This three-way experimental design bypasses the semantically difficult task of defining and assessing creativity by asking both participants and judges to rate 'How creative did you think that was?'.

Characterising creativity is pertinent to complexity as it is an opportunity to comprehensively investigate a neural and cognitive system from multiple experimental and analytical facets. This thesis explores the anatomical and functional system underlying the creative cognitive state by analysing the concurrent time series recorded from the brain and furthermore, investigates a model in the stages of creativity using a behavioural experiment, in more detail than hitherto done in this domain.

Experimentally, the investigation is done in the domain of music and the time series is the recorded Electroencephalogram (EEG) of a pianist's whilst performing the two creative musical tasks of 'Interpretation' and 'Improvisation' manipulations of musical extracts. An initial pilot study consisted of 5 participants being shown 30 musical extracts spanning the Classical soundworld across different rhythms, keys and tonalities. The study was then refined to only 20 extracts and modified to include 10 Jazz extracts and 8 participants from a roughly equal spread of Classical and Jazz backgrounds and gender. 5 external assessors had a roughly even spread of expertise in Jazz and Classical music.

Source localisation was performed on the experimental EEG data collected using a software called sLORETA that allows a linear inverse mapping of the electrical activity recorded at the scalp surface onto deeper cortical structures as the source of the recorded activity. Broadman Area (BA) 37 which has previously been linked to semantic processing, was robustly related to participants from a Classical background and BA 7 which has previously been linked to altered states of consciousness such as hypnagogia and sleep, was robustly related to participants from a Jazz background whilst Improvising.

Analyses exploring the spread, agreement and biases of ratings across the different judges and self-ratings revealed a judge and participant inter-rater reliability at participant

level. There was also an equal agreement between judges when rating the different genres Jazz or Classical, across the different tasks of 'Improvisation' and 'Interpretation', increasing confidence in inter-genre rating reliability for further analyses on the EEG of the extracts themselves. Furthermore, based on the ratings alone, it was possible to partition participants into either Jazz or Classical, which agreed with phenomenological interview information taken from the participants themselves.

With the added conditions of extracts that were deemed creative by objective judge assessment, source localisation analyses pinpointed BA 32 as a robust indicator of Creativity within the participants' brain. It is an area that is particularly well connected and allows an integration of motoric and emotional communication with a maintenance of executive control.

Network analysis was performed using the PLV index (Phase Locking Value) between the 64 electrodes, as the strength of the links in an adjacency matrix of a complex network. This revealed the brain network is significantly more efficient and more strongly synchronised and clustered when participants' are playing Classical extracts compared to Jazz extracts, in the fronto-central region with a clear right hemispheric lateralization.

A behavioural study explored the role of distraction in the 'Incubation' period for both interpretation and improvisation using a 2-back number exercise occupying working memory, as the distractor. Analysis shows that a distractor has no significant effect on 'Improvisation' but significantly impairs 'Interpretation' based on the self-assessments by the participants.

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I do not know what I may appear to the world; but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me

– Isaac Newton

It has been a once-in-a-life-time adventure, having had the opportunity to 'play' on the shores of 'Complexity Science' and to some extent, discover the extraordinary beauty, in the ocean of truth that is Creativity. It has been momentous to me and has really shaped me as a person.

I am forever indebted to Professor Kim Christensen for his guidance, wisdom, inexhaustible patience and curiosity, and meticulous attention to detail. I am very thankful to him for everything that he has done to allow me to pursue and finish this PhD, and words fail to describe the depth of my grattitude.

I have had the great fortunacy to be accepted into such a vibrant group by Professor Henrik Jensen and would like to thank him for teaching me about good 'complexity science' practice, his insight into the research as a fellow musician and the many stimulating and thought-provoking conversations that have helped to distill the essence of our foray into musical creativity, into a coherent research question.

I would love to thank Professor Joydeep Bhattacharya having spent the greater part of my doctorate collecting data in his lab. I would like to thank him for everything he has done from facilitation of data collection to recruiting participants and his eternal tolerance with my infinite bits of equipment, for his advice into direction of the experimental design for both EEG and behavioural studies and direction of neuroscientifical and network analyses. For the latter, I would also like to thank his long-term collaborator Professor Ernesto Pereda for our collaborative work on Network analyses in chapter 7. I am very happy to have met the wonderfully kind post-doc Job Lindsen at Goldsmiths, who led me through the hands-on practical details of data handling, processing and importantly the source localisation program sLORETA.

Very importantly, I would like to thank Richard Dickins, the Imperial College Conductor and Director of the Associated Boards who painstakingly helped me choose a wide variety of musical compositions that would be unknown to music students from the normal Classical

syllabus, gave me invaluable advice as to perceptions of the participants on which final sections of the compositions to present and of course were it not through a casual conversation with him, we would not have found our simple yet robust method of creativity assessment. He was vitally instrumental in the experimental design, wording of the instructions within the protocol and the comprehension of music cognition so fundamental to the research. I would also like to thank him for introducing me to the thoroughly delightful and amazing classical pianist Andrew Zolinsky who offered invaluable support and whose participation in the pilot study shaped our direction in the final study experimental design and analyses. At this juncture, I would like to thank Avgoustos Psillas, Head of Studio at the Royal College of Music for his sensible and practical advice into the experimental design along with the invaluable loan of the keyboard equipment without which there would be no data! I would also like to thank Julian Jacobson, Head of Piano at the Royal College of Music and pianist extraordinaire who very kindly took time out of his busy schedule to be one of our Classical judge assessors.

Equally, on the Jazz front I would like to thank, the Head of Jazz at Trinity College, Simon Purcell, for his enthusiastic interest in and comprehension of the research field to recommend such suitable Jazz judge assessors as Finn Peters, Liam Noble and George Fogel. In particular, I would like to thank Finn Peters on his insightful discussions on the Marking Forms presented for judges' ratings acquisition

Finally, I would like to thank composer and neuroscientist Professor Peter Vuust for the Jazz extracts in the final study and composer, poet and shining polymath, Mathew Lee Knowles who standardised both Jazz and Classical extracts to be understandable to both cohorts of musicians and for composing all the wonderfully original musical extracts in the behavioural study.

I would like to thank my friends and colleagues in the department and all my friends and family who have supported me throughout the personal period of my PhD and my growth as an artist and scientist during this period. They have tried their best to keep me uplifted and have truly touched me with their genuineness, sincerity, kindness and generosity.

Last but not least, I would like to thank my father and mother, without whom, I would not be here and to whom I dedicate my work.

I feel as if I'm emerging from a cocoon though with a slight tinge, I also feel like there was so much more I would have done. It is an enormous quest and one that I hope to continue to discover through my future work and my own practice as a musician.

DECLARATION

I hereby certify that all material in this dissertation which is not my own work has been properly acknowledged.
Collaborative work is outlined in Chapter 6 and 7 with Professors Joydeep Bhattacharya and Ernesto Pereda. All other work in other chapters, is my own.

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INTRODUCTION AND AIMS

Prelude:

It is worth noting how I came to be here as it may strike some as unusual that a neuroscientist and musician undertook a PhD in the Department of Physics at Imperial College London under the Complexity and Networks Group.

My BSc being in Molecular Biology, at the end of it, I was frustrated at the lack of a bigger picture and balked at spending my days alone in a lab, limited to investigating one molecule in a tiny sub system of a sub system of a sub system. So after graduating and a year out, I decided to pursue an MSc in Integrative Neuroscience at Imperial College London, which resulted in a research project investigating the effects of Neurofeedback using a Brain Computer Interface on increasing musical creativity. Though the technique certainly seemed to 'enhance' participants, I was sceptical as to whether the main result of increasing 'openness' during a performance really constituted as creativity. Moreover, the neurobiology underlying musical creativity seemed far too simplistic, assuming as it did that one simply needed to increase the brain frequency ratio of theta, θ, over alpha, α, globally without any attention to localisation, topography or nuances in the characterisation of a network. I did not have the vocabulary to articulate what I felt, but I just knew things were more 'complex'. One day, perusing the world wide web, I came across a new sort of interdisciplinary science called 'Complexity Sciences', that the English institutions were starting to catch on. I contacted a few universities with my thesis idea on modelling musical creativity as a complex system and serendipity struck when a friend forwarded me a little leaflet declaring a friendly looking summer school inviting students to learn about 'Complexity Sciences' right here at Imperial; I thoroughly enjoyed myself. At the end of the school, I found myself seated at the table with both Professors Kim Christensen and Henrik Jensen and in amongst a philosophical discussion on Zen Buddhism, I found myself recounting my idea, which ended in much enthusiasm and an offer of a PhD position. Simultaneously, I had been recommended to contact Professor Joydeep Bhattacharya at Goldsmiths College due to his expert knowledge on music and the brain, who very kindly agreed to be my third supervisor and I was to do my experimental data collection at his labs. All the dots joined, with a generous dash of guidance and equipment from the Royal College of Music, Studio Head, Avgoustos Psillas and Imperial Conductor and Director of Associated Boards, Richard Dickins, I was on my way…

With this thesis, we would like to recount some of the most promising avenues of what we found from amongst the plethora of analyses used from the complexity toolbox.

What mental processes and cognitive pathways give rise to creation? How is something novel triggered and/or evolved and how does this lead us to the proverbial spark of insight? Many experimental studies addressing creativity have focused on problem-solving using mental exercises derived for the purposes of a psychological study. We wish to extend the body of work in this field by developing an experimental protocol which carefully explores a real world situation in the form of a real-time creative performance of music: improvisation and interpretation.

As music making involves decision making and information processing which go beyond the written score, the performing musician can be seen as the ideal laboratory for investigating human creativity as it unfolds in real time. We address here to what extend the psychological creative process correlates with neurophysiologically measurable signatures. To contrast different types of creative music making we compare Classical and Jazz musicians and their creative performances of extracts from these different sound worlds.

Every rendition of a piece of music is an act of creation. Nevertheless, some playing is perceived as more creative than others. It is very difficult to capture all the aspects and facets of creativity by a single operational definition. To circumvent the need for a definition of creativity, we compare and match the assessment of professional music judges with the musician's self-assessment and use these as a measure of the level of creative playing. This twofold psychological evaluation is correlated with the recorded EEG data stream and from this third element, we hope to identify neural patterns and correlates in spatial and temporal structures in the electromagnetic signals, which typically appear during the most creative stages.

The neural correlates of creative processes associated with artistic creativity has been largely uncharacterized. There are only a few studies that have investigated the brain responses of creative professionals in actions (like composing music or artwork). During mental composition of drawings, professional artists showed higher long-range synchronization in low frequency oscillations, thereby indicating enhanced top-down processing in artists; non-artists, on the other hand, showed more local synchronization, an indicative of bottom-up processing [Bhattacharya and Petsche, 2005]. Emphasized top-down processing is also observed in professional dancers during mental imagery of an improvised dance but not during a learned dance routine [Fink *et al.*, 2009]. Both of these studies are

based on EEG. Recently, a Functional Magnetic Resonance Imaging (fMRI) study [Limb and Braun, 2008] reports that during musical improvisational accompaniment, a widespread brain network gets activated but concurrently the dorsolateral prefrontal cortex, a crucial brain region involved with planning and self-monitoring, gets deactivated.

We will discuss some of the studies above and additional research pertaining to creativity and specifically musical creativity in the upcoming literature review.

Our study has the dimension of physical performance (as opposed to just mental imagery), as we reason that this actualization is vital to the coherent processing of music in reality, during a creative state for a performer. In addition, our study focuses on improvisation that is more free (rather than accompaniment), and compositional in nature and does not have the added cognitive complication of memory in EEG signatures as participants are shown extracts they are unfamiliar with.

Due to its high temporal resolution, EEG allows us to observe and characterize how the different regions of the brain interact real-time, during the creative process. Due to the temporal evolution in improvisation [Sawyer, 1992] and interpretation [Dean and Balles, 2010], and also the particular global structure of the music the performer may create or phrase [Cooper and Meyer, 1960], this may also be reflected in large scale brain activity as recorded by EEG. Therefore, EEG as a technique has an advantage over fMRI and other techniques such as PET studies in melody and sentence generation [Brown, Martinez and Parsons, 2006].

By studying the mechanisms of musical creativity we could hope to shed light on how creativity might work in general in other areas and disciplines.

At this juncture we will present a roadmap for the rest of the thesis on a chapter-by-chapter basis:

Chapter 1. We present previous qualitative case study-based phenomenological research classifying the different processes and stages of creativity as a basis for the subsequent quantitative research performed. We then lay down some neuroanatomical foundations that are a basis for two different theories of mapping cognitive function to physical structure within the brain that are prevalent in neuroscientific communities. This leads into a discussion of the pros and cons of different experimental techniques, EEG and fMRI, available to record brain activity and why we specifically chose EEG for the experimental recording part of our study and how this influenced our choice of neuroanatomical analysis in the form of source localisation via the software sLORETA.

Finally, we review particular papers that span previous general creativity research and specifically music creativity research.

Chapter 2. Here we outline the initial experimental protocol in the pilot study, its subsequent revisions the reasoning behind these, and the musical extracts presented to the five participants.

Chapter 3. This chapter outlines the results of the initial exploratory analyses performed on the pilot study comprising simple cross-correlation temporal dynamic analyses and global phase synchrony analyses. We outline, how the results gave us some understanding into the creative process and enlightened what subsequent direction to take with the final study and its analyses.

Chapter 4. Here we outline the experimental protocol in the final study, detailing any changes from the pilot study protocol and revisions to the musical extracts used, including the addition of Jazz music to the experimental design. This study involved eight participants from an equal spread of Jazz and Classical backgrounds and we subsequently acquired external creativity ratings from five expert judges, which we present the marking forms for.

Chapter 5. This chapter presents the results of the final study and is divided into three parts. Firstly, is a presentation of any discernible patterns in the spread, biases and agreements within and between the expert judges from the two backgrounds of Jazz and Classical, how these differ across participants, genre of music and tasks and finally how they compare with the self-assessments of the participants themselves. We also partitioned the participants into a Jazz and Classical background based on the ratings alone, which agreed with phenomenological interviews collected from them.

The second section presents a detailed comparison of different conditions and temporal divisions in the cognitive tasks and their concurrent EEG recordings using a source localisation software called sLORETA. This software allows an accurate inverse anatomical mapping of the scalp EEG recordings onto deeper cortical structures within the brain allowing a distinction of differences in brain activity between conditions and where these differences are localised. Throughout there is a discussion of the functionality known of these areas from previous research in the field and how they could relate to the musical tasks we are investigating.

The final section investigates whether it is the objective judges assessments of ‘creative’ versus ‘non-creative’ extracts that correlate with significant activity differences in

sLORETA localisations or whether the subjective self-assessments of the subjects are the more accurate 'creativity' indicator.

Chapter 6. In this chapter, drawing on sLORETA results that comment on the different natures of the two creative tasks of 'Improvisation' and 'Interpretation', we outline a behavioural study exploring the 'Incubation' period in the creative process. In particular, we investigate whether a distracting task between being presented with the task to be creative and the performance itself, aids creativity be promoting 'Unconscious' thought. We present results of an Analysis of Variance (ANOVA) of participants' self-ratings in tasks that are distracted or focussed during either 'Improvisation' or 'Interpretation'.

Chapter 7. This is a chapter presenting preliminary results of network analyses done in collaboration with Ernesto Pereda and Joydeep Bhattacharia where we use phase synchrony as a measure of functional connectivity to construct brain networks. We compare this to some of the sLORETA resuls and discuss the complementary approach of the two types of analyses to create a more comprehensive picture of the musical brain.

Chapter 8. We review the thesis with the conclusions of the results of the study, their implications and its value to the body of research done on creativity with recommendations and foresight to further additional investigations.

1. CREATIVITY: LITERATURE AND BACKGROUND

1.1 General

What does creativity entail? In its very nature, it is seen to be unpredictable though it is a close cousin with another concept, "talent", where talent is said to originate in genetically transmitted structures and is thought to be partly innate [Eysenk, 2000]. Is this therefore the case with creativity or can one develop or improve on it. Can one thus predict it? Like talent, creativity is also dependent on domain-specific knowledge [Weisberg, 1999] and the focus of this research will be specifically on musical creativity for the purposes of a controlled experimental paradigm but in the hope that it will shed light on general creativity across different disciplines. Our research will attempt to quantifiably detect creativity in brain activity recordings to some extent by the 3-pronged approach of scaled self-assessments and objective expert ratings and matching these to the EEG recordings.

In Chapter 1.2, we delve into existing phenomenological research of the different stages and types of creativity, to inform the design of the experimental protocol.

1.2 Qualitative models of creativity and phenomenology

It is useful to explore general models of creativity that already exist. These models are qualitative and are based on case studies and come from a cognitive and psychology approach but the ultimate aim in our research would be to add a quantitative aspect to them. The following are proposed stages in problem solving:

1.2.1 Wallas

Wallas' [1926] proposed a classification of the broad stages in creativity:

1. The Preparation period: where the problem under consideration is formulated and preliminary attempts are made to solve it.
2. The Incubation period: where the problem is left aside to work on other tasks.
3. The Illumination/Insight period: where the solution is arrived at as a sudden insight.
4. The Verification period: the problem is tested and the problem solver makes sure the solution really works.

This model was put forward after doing case studies on eminent individuals from a wide variety of careers, from chemists, such as Kekule who discovered the benzene ring, to architects and hence perhaps they broadly describe what might happen in a musical mind in

the throws of a creative outpouring although it may be hard to imagine the process being quite so structured or in a time scale longer than a few moments in the case of a performer, however, it may be more applicable to a composer.

The way that the experimental protocols are structured (see Chapter 2 and 4), they explore both stages of Incubation and Insight, by dividing cognitive tasks into a "thinking" section and a "performing" section. Particularly in the pilot study, by allowing participants to manipulate given musical extracts in multiple ways, the protocol assumes that the Incubation period may possibly explore the thought model put forward by Simon (1966). The model introduces the terms control information and factual information about a problem, where the former is a record of the sub goals tried in a problem and the latter is some property of an object or substantive aspect of a problem. Factual information discovered in the *context* of one sub goal will not be available to other goals but interestingly it fades from memory later than sub goal information. Hence, in problem-space theory it is a special type of forgetting (incubating) and thus the factual information will be available to newly generated sub goals of the problem being solved, increasing the likelihood of solving it. As will be further explained using connectionist theories, this sort of model allows lateral thinking by allowing the use of knowledge from other mental models (see Sec 1.2.5) that are not normally related or linked.

Functional fixedness, as proposed by Gestalt[1] psychologists, hinders this sort of creativity and people are unable to reconstruct the problem to look at it from another angle with new connections; this can thus result in a lack of Insight.

1.2.2 Boden

Other models of creativity include Boden's model of "Improbablistic" and "Impossibilistic" creativity (1991,1994). "Improbablistic" discoveries involve novel combinations of the familiar, that is, associative or analogical thinking. "Impossibilistic" discoveries have not been generated before and are radical, that is, when the fundamental rules of a conceptual or problem space have been violated, the space itself must change hence ideas that could not have been generated before, can emerge. For the purposes of our final experimental protocol, "interpretation" could be likened to the "improbabilistic" model and "improvisation" could be likened to the "impossibilistic" model.

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[1] **Gestalt psychology** is a theory of mind and brain that proposes that the operational principle of the brain is holistic, parallel, and analog, with self-organizing tendencies; or, that the whole is different than the sum of its parts. Max Wertheimer is credited as the founder of the movement. (http://en.wikipedia.org/wiki/Gestalt_psychology)

1.2.3 Geneplore

The Geneplore model [Fine, Ward and Smith, 1992] divides creativity into a generative and exploratory phase [Smith *et al.*, 1992; Ward *et al.*, 1995]. Within the generative phase, the construction of mental representations called "pre-inventive" structures occur; these have certain properties. In the "exploratory" phase, these properties are used to elucidate better sense of the "pre-inventive" structures. If these explorations are successful then a creative product may arise but otherwise the cycle is re-started to produce a new or modified "pre-inventive" structure. This model is very general and can be used to account for everything from conceptual combination to imagination to fixation in insight problems.

1.2.4 Analogical thinking

Analogical thinking can help solve more complex sometimes not readily visible or tangible problems. For example, Rutherford used the analogy of the solar system to elucidate the structure of the atom with the electrons rotating about a central nucleus.

Different types of analogical thinking are:

1. Isomorphism: using one-to-one relational mappings between corresponding objects in two domains where they are dissimilar or non-corresponding objects where they are (misleadingly) similar.
2. Semantic similarity: the mapping here is between similar domains.
3. Pragmatic centrality: when parts of a domain are emphasized or deemed more important and are more likely to be used in a mapping.
4. Many mappings for one analogy: this is similar to having many mental models for everyday tasks.
5. Incrementality: the emphasis here is in the order in which two domains are matched and thus this can affect the eventual analogy.
6. Unnatural analogies: describe certain mappings which involve analogical mappings but lack semantic similarities.
7. Mapping predicates with different arguments: despite being labour intensive one can argue that this is more comprehensive.

All the models described above could be used by a musician during and prior to a creative performance (e.g., during the "thinking" and "performing" section of the cognitive

tasks in our protocols); the importance and workings of the incubation period, and the subsequent insight achieved can be highlighted as before. In particular, musical composition relates more to a problem being solved and thus composers are likely to be involved in the process of "creating" more relevantly. However, in a very specific kind of music performance namely, improvisation, this is exactly what performers are doing but in a very rapid time-scale that is probably dependent on their ability to have "insights". Finally, it is worth noting that composers are often performers and vice versa and a quotient of the subjects used in our study are composer/performers.

1.2.5 Mental models

Not all problem-solving requires creativity and not all creative activities are of a problem solving kind and can, as has been alluded to before, make use of mental models.

The proposed functions of mental models are:

1. Models are predictive and suggest different ways in which physical mechanisms (i.e., processes in the real world) may operate.
2. The use of visual imagery is often present and they can thus simulate said physical mechanisms and phenomena.
3. Models are versatile in that multiple models can be used to deal with different aspects of the same system.
4. It follows that models can be volatile and undergo sudden changes depending on the knowledge feeding into them and the individual's conception of the task.

1.2.6 Existential phenomenology research

Creativity is fundamentally a very subjective experience both for the performer and listener and yet often there is thought to be a certain "je ne sais quoi" that is felt instinctively and unanimously agreed upon by all parties when experienced (Richard Dickens, advisor).

In fact existential phenomenology research (EPR, which is the study of structures of consciousness as experienced from the first-person point of view) in the field of musical performance, seems to support this and the approach of using a mixture of the creativity models outlined above in this project [Edge and Lancaster, 2004]. EPR's attitude does not seek to oppose the subjective to the objective, but to move beyond the split into their fundamental correlation [Varela, 1996]. Therefore, some of the findings of this research are

kept in mind for the experimental design and is used to circumvent the whole problem of defining what creativity is by asking the participants themselves to rate their playing and this is compared and contrasted with "expert judges" rating.

1.2.7 Summary

Performing a piece does not easily lend itself to problem solving. However, it does not mean that similar cognitive processes as alluded to in these models are not used, such as the broad stages of incubation and insight in Wallas' model. It also makes sense that a deeper cognitive process of making alternative connections using different sub goals underlies incubation as suggested by Simon and the Analogical thinking model. The Boden and Geneplore model could almost be used together where explorative and generative stages both could be used for either of "impossibilistic" or "improbabalistic" thinking. "Improbablisitic" thinking is mimicked by the first few stages of the pilot study protocol (see Chapter 2) where participants are asked to manipulate specific aspects of a musical extract and this type of thinking could also be thought of as similar to interpretive creativity. Bearing this in mind, "impossibilistic" thinking could be likened to particularly inspired moments of free improvisation. Equally, the use of mental models especially with properties such as their volatility and visual imagery, seem key to improvisation. Therefore the building of a final experimental protocol would incorporate elements of all of these models and build on them instead of regarding them as mutually exclusive or any of them individually as the full picture. In summary, we will be drawing on a mixture of all of these models for the experimental protocols but the emphasis is not to define creativity by adhering fully to or being constrained by these models but rather to use the 3-pronged approach to allow a quantitative mechanism for creativity to emerge.

1.3 Anatomy

The following diagrams show the anatomy of the brain in two sections: the external neocortex and the internal structures. What is measured at the scalp by EEG (see Sec 1.3.1.1) is what is detected from the neocortex but there might also be some activity that is coming to the surface from the internal deeper cortical structures.

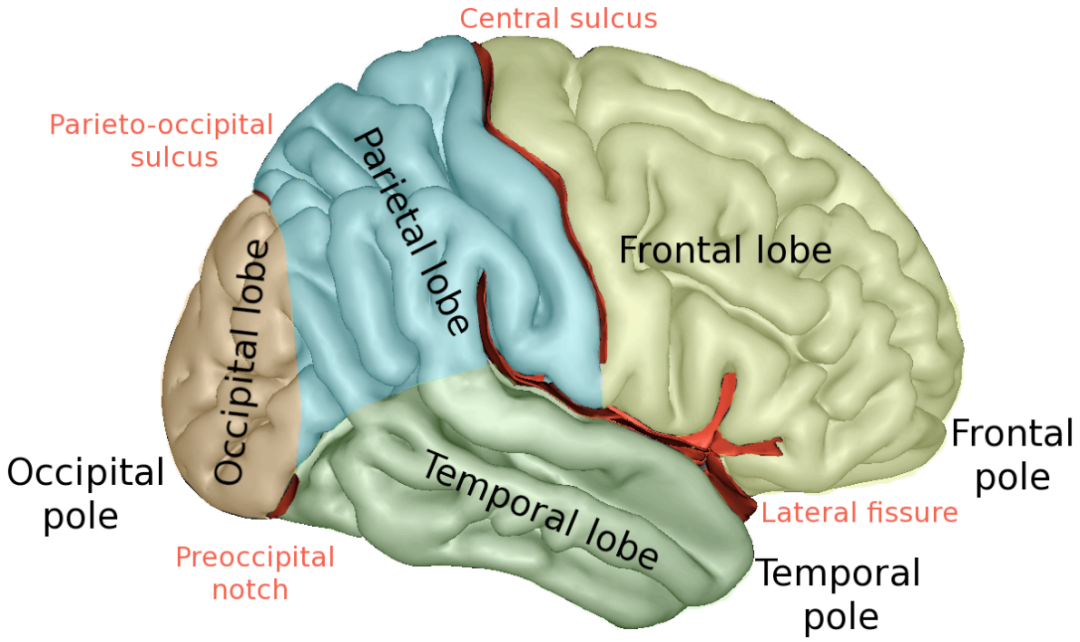


Fig 1.1 Structure of the neocortex which is the most recent evolutionary development. This is where high-level cognitive processes and complex integrative tasks are thought to occur. The frontal lobe has commonly been attributed to be the seat of executive decision and conscious thought; the parietal lobe plays an important role in integrating sensory information, visuospatial processing, and the manipulation of objects; the occipital lobe is functionally attributed to vision ; the temporal lobe to the senses of smell and sound, as well as processing of complex stimuli like faces and scenes. Our study will demonstrate the use of all four lobes in the musical brain. From Wikipedia Commons.

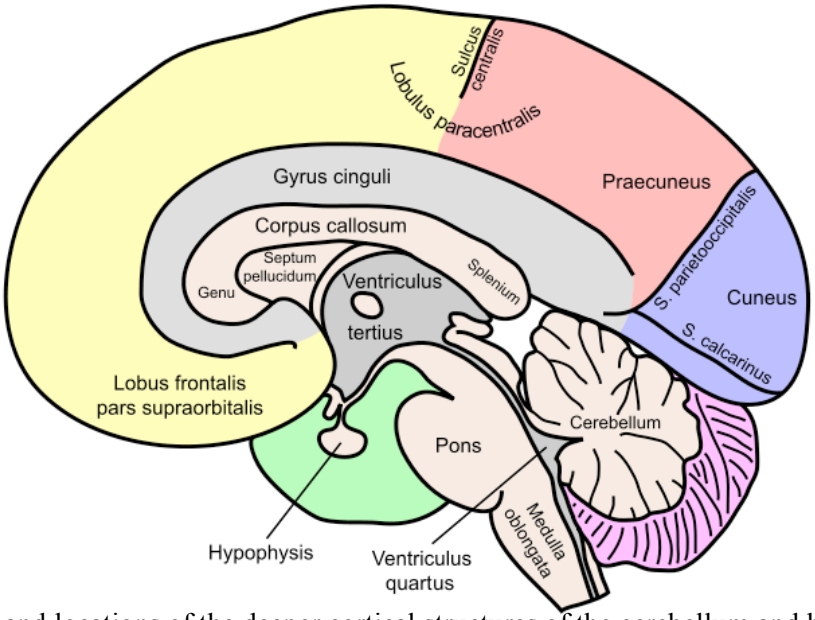


Fig 1.2 Structures and locations of the deeper cortical structures of the cerebellum and brain stem (both for involuntary vital mechanisms such as breathing and heartbeat) and the limbic system (emotion and memory). Of particular note from the diagrams above is the precuneus and its role in 'Improvisation' and the gyrus cinguli and its role in 'creative' tasks as objectively judged by external assessors in our study. From Wikipedia Commons.

1.3.1 Anatomy and activity

1.3.1.1. Mechanisms: two techniques (EEG vs fMRI)

At present time two techniques that are used often in neuroscience to elucidate brain activity, are functional magnetic resonance imaging (fMRI) and electroencephalograms (EEG). The most relevant neural activities underlying complex cognitive processes occur at the level of tens to hundreds of milliseconds [Friston, 1997; Mima *et al.*, 2001; Schack *et al.*, 2003]. This is a problem if using a neuroimaging technique such as fMRI as although it has a high spatial resolution useful for localising brain functions, it has a low temporal resolution in the range of a few seconds. EEG on the other hand has less spatial resolution but offers excellent millisecond range temporal resolution and particularly for this project, 64 electrodes are used in an " International 10-20" standard even spacing across the scalp, which also offers reasonable spatial resolution for signals in the cerebral cortex, see figure 1.3.

Fig 1.3 An example of a 64-electrode cap with active scalp electrodes and facial external electrodes, from the company Biosemi**.** From http://www.biosemi.com.

The decision to use either fMRI or EEG reflects the capacities of these techniques with respect to how they measure the way that the brain functions.
fMRI infers that the brain consists of self-contained areas responsible for any possible function and for this technique, these areas are divided into small discrete 'voxels' (cubic squares). fMRI detects differences in magnetism in deoxygenated and oxygenated blood i.e. BOLD (Blood Oxygen Level-Dependent), see figure 1.4. Blood flow through the brain is closely linked to neural activity but oxygen-rich blood displaces deoxygenated blood two seconds later than activity and rises to a peak over 4-6 seconds before returning to the original level thus having a limited temporal resolution and why fMRI is poor at detecting communication between brain areas in real-time. Furthermore, different regions of the brain have different glucose consumption to blood flow ratios, affecting the BOLD sensitivity

which added to scanner noise and random brain activity, leads to fMRI research paradigms, setting participants cognitive tasks multiple times before an area is subsequently assigned responsibility for that cognitive function, see figure 1.5. For reasons of 'familiarity' this would not be appropriate for our study as will become apparent.

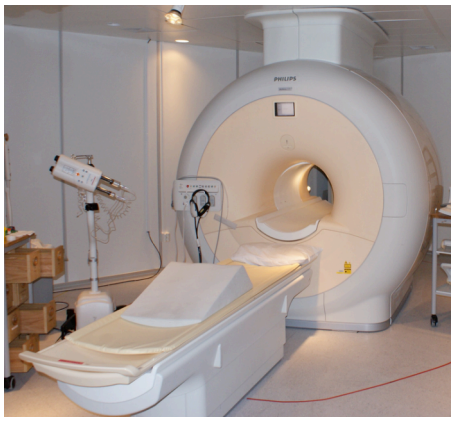
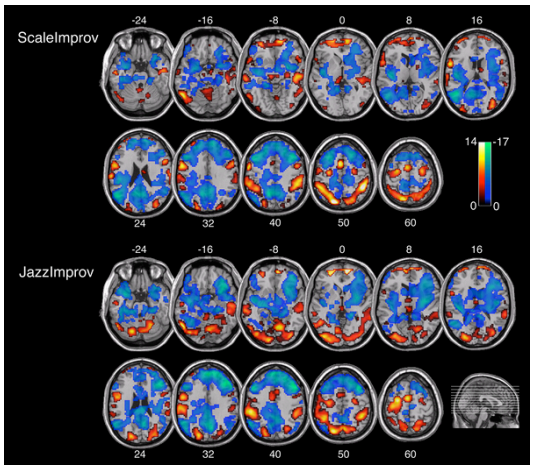


Fig 1.4 fMRI equipment set up where candidates lay down and have to be still whilst they are in the tunnel. From Wikipedia Commons.

(a) 

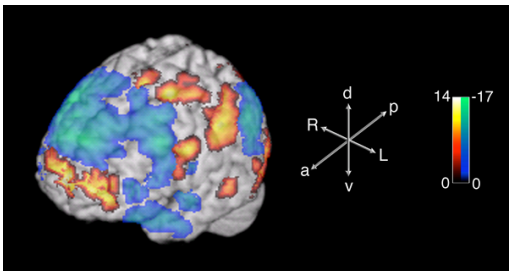
(b) 

Fig 1. 5 (a) An example of fMRI data. In this case these are axial slice renderings of mean activations (red/yellow scale bar) and deactivations (blue/green scale bar) associated with improvisation during Scale and Jazz paradigms [Limb and Braun, 2008]. (b) A 3D topographical surface projection in the same study.

Varela *et al.* [2001], postulate that the whole of the brain is needed for function and that for a unified cognitive moment a "co-ordination of scattered mosaics of functionally specialised brain regions" is required. EEG is a technique that does not assume neuronal activity as it is a direct measurement of the firing of neuronal clusters and also allows a temporal dynamic exploration between neurons. Spatially, it is limited to the number of electrodes used in the research but temporally it has a much higher resolution than any other

imaging technique barring magnetoelectroencephalography (MEG) which records magnetic fields produced by the electrical currents in the brain, and allows a more realistic window into the mechanisms of how the brain works as a whole for music.

An EEG is a measurement of brain waves that are detected on the surface of the scalp as cumulative action potentials from neuronal populations and ones that are generated by cortical neurones in the vicinity of the particular electrode. One scalp electrode can integrate activity from neurons across 10 cm² of cortical surface [Nunez, 1997]. Equally any electrical activity that is detectable at the scalp necessitates approximately synchronous activity of a large number of neurons as a certain number of random fluctuations will effectively cancel each other out [Nunez, 1997]. It is thought a typical cluster size must cover at least 40 to 200 mm^2 of cortical surface [Hämäläinen *et al*.,1993] whereas fMRI detects activity over 2 to 3 mm^2 of cortical surface.

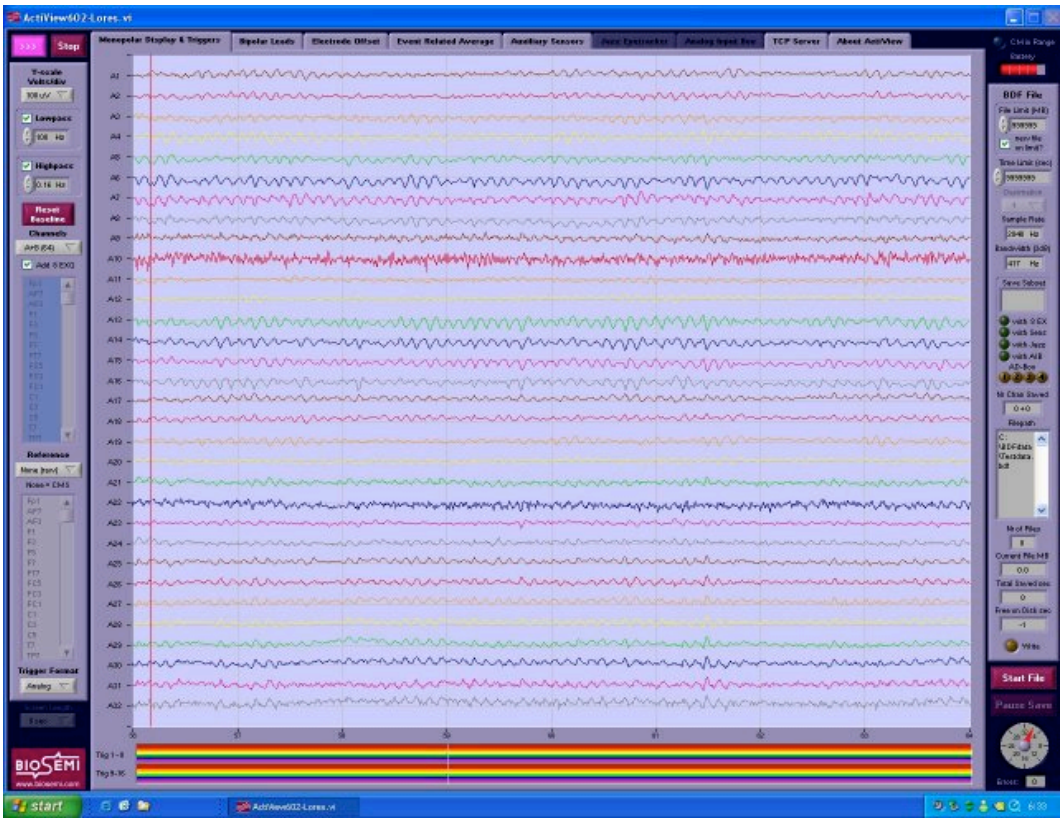


Fig 1.6 Sample EEG measured with separate electrode channels voltage readings. The software used for data acquisition is an interface from Biosemi.

The alpha rhythm (8-11 Hz) activity measured at the scalp is a mixture of spectral components that are frequencies generated by resonances which might be activated by groups of cells in the thalamus known as pacemakers [Nunez, 1995]. Other rhythms may be due to emerging networks from resonant loops between neocortical columns of cells and are

classified as local, regional or global. Historically, the frequencies have been divided into ranges that are meant to be shared by us all and correspond to different arousal states: Delta (deep sleep, 1–4 Hz), theta (drowsy/half-asleep, 4.5–7.5 Hz), alpha (wakefulness, 8–11 Hz), beta (relaxed, alert, 11.5-15; agitated, 15-35). In reality, people have different dominant frequencies within these ranges, which appears to show that the range borders are a little arbitrary. Equally, there is some debate and overlap over the behavioural and cognitive correlates and functions of the alpha, beta and to some extent theta frequencies which is something that influences this project when choosing to analyse the overall voltages measured at the electrodes versus the constituent frequencies. However, gamma (30-100 Hz) is a frequency range that has been more consistently shown to be related to a variety of non-verbal and verbal cognitive tasks [Kahana, 2006] further divided into sub-bands at different locations. Gamma activity has been most widely associated with top-down attentional processing and object perception [Tiitinen *et al*., 1993; Keil *et al*., 1999; Rodriguez *et al*., 1999; Debener *et al*., 2003; Gruber and Muller, 2005] and as will be described in Section 1.5.1, recently, also to certain aspects of Insight in a general creativity task.

It was thus decided to use EEG for this study as its likely that creative moments are spontaneous and dynamic in time (also see 3.5.1 for recent research using EEG into Insight). In addition, neuronal oscillations are well represented by EEG signals [Buzsaki, 2006] and it is quite accepted that large scale brain oscillations in various frequency bands is modulated by a diverse range of tasks in human cognition [Kahana, 2006; Klimesch, 1999; Ward, 2003]. However, one major drawback is of course that EEG is a measurement of electrical brain activity at the neocortex level and does not give much indication of deeper cortical brain structure activity such as that of the limbic system. Equally, the problem of volume conduction of the scalp means that activity detected in neighbouring electrodes could be from the same or overlapping source and is travelling and spreading through the bone of the skull which is conductive, giving rise to spurious synchrony (see Section 1.3.1.2 for description and examples of synchrony).

1.3.1.2. Connectionist theory, dynamics of EEG and cognitive correlates

A seminal review by Varela *et al.* (2001), explains the “connectionist” model in detail. It suggests that large scale integration across neural assemblies, (distances further than 1 cm apart), is what is needed for the co-ordination described above to occur, and that these assemblies are distributed local networks of neurons that are transiently linked by dynamic

connections long enough to accomplish an elementary cognitive act which translates to patterns of activity such as cycles of reciprocal spike exchanges with transmission delays in the order of tens of milliseconds. Thus, it is stressed that the important factor is not the individual activity of the components of the system but the dynamic nature of the links between them. In terms of connections, the review describes two kinds: reciprocal, where connections are in the same cortical area or between areas at the same level of the network, and bottom-up/top-down processing. So what is the actual physical mechanism or evidence to support this sort of a dynamic integration?

In terms of a mechanism, some say that integration is achieved through certain "associative areas" that mediate between sensory and motor areas as the hierarchical organisation of the brain would suggest [Saper *et al.,* 2000], whilst others insist that it is networks of reciprocal interactions that are the key for integration [Damasio, 1990; Mesulam, 1990]. However, the most plausible and most studied explanation is phase synchrony. It is hypothesised that through long-distance phase synchronisation the transient formation of a coherent macro-assembly that selects and binds multi-modal networks is possible. Such assemblies can be between different lobes or across hemispheres which are separated by dozens of milliseconds in transmission time [Thompson *et al.,* 2004].

Two examples of this integration are to be found in vision. The first is the fundamentals of visual binding and processing, that is, how the different attributes of an object are brought together in a unified representation given that its various features such as edges, colour, motion, texture and depth are treated separately in specific visual areas. It is possible that visual objects are coded by cell assemblies that fire synchronously, that is, local integration (over an area of ~1cm²) within neighbouring cortical areas, all specialised in the same modality [Roskies, 1999]. The second example, involves patches of local synchrony between distal brain areas entering into synchrony during a face recognition task [Rodrigues *et al*., 1999].

Phase synchronies occur in a broad range of frequencies. Fast rhythms, meet the requirement for fast neural integration, and thus are thought to play a role in conscious processes on the time scale of fractions of a second [Varela, 1995; Tononi and Edelman, 1998]. These fast rhythms are gamma, which is claimed to underlie visual processing, and beta frequencies, which are believed to underlie several processes such as for short-distance synchronisation between neighbouring temporal and parietal cortices during multi-modal semantic processing. The slower alpha and theta bands are thought to be more commonly

associated with attention and long range fronto-parietal interactions during for example, working memory retention, mental imagery [Sarnthein *et al.*, 1998; Von Stein *et al.*, 2000; Fries *et al.*, 2001] and sensorimotor integration [O'Keefe and Burgess, 1999; Kahana *et al.*, 2001]. In contrast with top-down attentional processing, alpha and theta seem involved in the top-down processing of internal mental context [von Stein and Sarnthein, 2000]. The integration and synchronisation of all the different frequencies also seems to be of some importance for any specific behaviour, such that the slower rhythms could provide the slower temporal framing or a slower beat within which beta and gamma rhythms operate, for successive cognitive moments of synchronous assemblies [Varela *et al.,* 2001].

Synchrony also appears to be integral to a person's holistic experience of and outlook in life as for example, disruption in synchrony is related to the fragmented cognitive experience of patients with schizophrenia [Tononi and Edelman, 2000].

In general, synchrony appears to allow the binding of sensory attributes and the overall integration of all dimensions of a cognitive act including associative memory, affective tone, emotional appraisal and motor planning [Damasio 1990;Varela 1995; Varela *et al.,* 2001]. All of these contribute to a musician's creativity and so synchrony could be a real possible mechanism to be analysed in order to find a signature for creativity.

Disintegration, desynchrony or phase scattering goes hand in hand with synchrony. It is postulated to be important in actively dismantling dynamic links in order to make way for the next cognitive moment in large-scale integration [Varela 1995; Rodriguez *et al.,* 1999; Varela *et al.,* 2001]. For example, in the face recognition study [Rodriguez *et al.,* 1999] in between the tasks of face recognition and the motor response, there was a transient active phase scattering where the probability of phase synchrony was even lower than before stimulation.

In fact, Varela (1999) even suggests that a dynamic of synchrony and desynchrony combined with retention of elements from the previous assembly at the beginning of each new one could be the neural basis of the temporal flow of experience and the experience of moment-to-moment transitoriness. This is a very crucial cognitive aspect of a musical performance.

So what can one expect in terms of patterns in the synchrony? The experimental evidence consistently shows that synchronous networks emerge and disappear in waves that last 100-300 ms where there are no stable attractors as these change depending on activity [Varela 1995; Dennet and Kinsbourne, 1991]. Rather, there seem to be metastable successions

of self-limiting recurrent patterns that are the manifestation of transient co-ordination among populations [Kelso, 1995; Bressler and Kelso, 2001; Vaadia *et al.,* 1995; Friston, 1997; Le Van Quyen *et al*., 1997; So *et al.*, 1998].

In **Chapter 3**, the mathematics of phase synchrony and frequency coherence will be outlined.

1.3.1.3. sLORETA mechanisms

sLORETA is a functional brain imaging method that uses a quantitative neuroanatomical digitised Talaraich atlas of the cortical structures in the brain provided by the Brain Imaging Centre, Montreal Neurological Institute. The cortex can be modeled as a collection of volume elements (voxels) in this digitized Talairach atlas similar to the units found in fMRI. It stands for standardized low resolution brain electromagnetic tomography and according to creators, Pasqual-Marqui (2002), *s*LORETA yields images of standardized current density with zero localization error.

As was mentioned above, fMRI and other functional imaging methods such as PET (Positron Emission Tomography) are limited in their temporal resolution and not sufficient for the speed at which neuronal processes occur. A study by Logothetis *et al.* (2001), showed that the time course of the fMRI haemodynamic response was roughly a low pass filtered (i.e., low time resolution) version of the electric neuronal activity.

On the other hand, EEG/MEG surface scalp measurements do not contain sufficient information on the three-dimensional (3D) distribution of electric neuronal activity for deeper cortical structures as the implication is that the measurements could be due to many different distributions of cortical electrical generators [Helmhotz, 1853].

However, further research suggests that extracranial measurements of EEG and MEG are generated by cortical pyramidal neurons undergoing post-synaptic potentials (PSPs) [Martin 1991, Dale *et al.* 2000, Baillet *et al.* 2001]. The magnitude of experimentally recorded extracranial signals, at any given time instant, is due to the spatial summation of the impressed current density induced by highly synchronized PSPs occurring in large clusters of neurons oriented perpendicular to the cortical surface.

Ideally, it would be optimum to utilise both the temporal resolution afforded by experimentally recorded extracranial signals and localise the brain activity source of these signals by solving the inverse problem (computation of images of electric neuronal activity based on extracranial measurements). Given that brain activity occurs in the form of a finite number of distributed “hot spots”, using the principles of linearity and superposition would

allow the calculation of an instantaneous, distributed, discrete, linear solution capable of exact localization of point sources.

This is what sLORETA claims to do [Pasqual-Marqui, 2002]:

There are N_E instantaneous extracranial measurements and N_V voxels in the brain. The voxels are determined by subdividing the solution space uniformly, which is taken as the cortical grey matter volume or surface. At each voxel there is a point source, which may be a vector with three unknown components (i.e., three dipole moments), or a scalar (unknown dipole amplitude, known orientation). These EEG-based experiments considered here correspond to $N_V >> N_E$.

If the orientation of the three dipoles is not known, the LORETA inverse solution corresponds to the 3D distribution of electric neuronal activity that has maximum similarity (i.e., maximum synchronization), in terms of orientation and strength, between neighboring neuronal populations (represented by adjacent voxels). If the orientation is known but with an unknown dipole amplitude, the cortical surface can be modelled as a collection of surface elements with known orientation. LORETA can accommodate this neuroanatomical constraint, and find the inverse solution that maximizes only the synchronization of strength between neighboring neuronal populations. It does this using the current density estimate given by the Minimum Norm Inverse Solution [Hämäläinen and Ilmoniemi, 1984] but to solve the systematic non-zero error that this has traditionally been associated with, sLORETA infers localization based on images of standardized current density with a method that is unique to it.

As this is not a thesis or study of sLORETA as a software or technique, we will not go into the details of the programming but suffice it to say, we use sLORETA as a tool on the EEG data as a detector of activity difference between different conditions and participants. More technical details can be found in the creator's paper [Pasqual-Marqui,2002].

1.3.1.4 Brodmann areas: historical and present use

sLORETA presents its localisation findings in the medium of Brodmann Areas. Brodmann areas are regions of the cortex defined based on its cytoarchitectonics i.e., the study of varying cell structure and organization into layers to define functional regions in the cortex. They derive their name from German anatomist Korbinian Brodmann (1868-1918) who observed neuronal laminal organisations in humans, monkeys and other species in 1909 using the Nissl Stain. Later a more detailed cortical map was published by Constantin von

Economo and Georg N. Koskinas in 1925 [Economo and Koskinas, 1925].

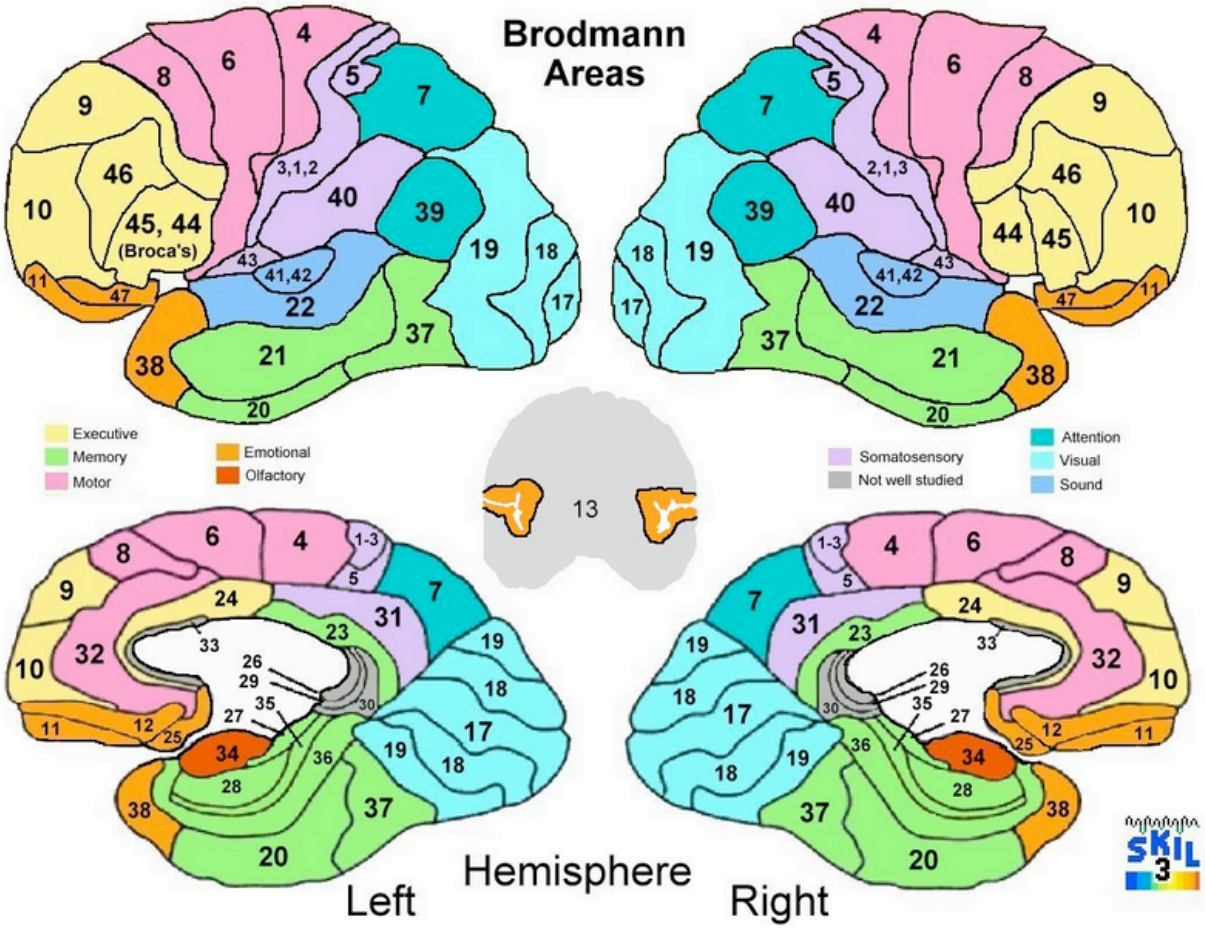


Fig 1.7 A schematic diagram of the division of Brodmann Areas in the left and right hemispheres. Of particular note are Brodmann Areas 6, 7, 9, 13, 18, 32, 37, 40, 45 and 46 which will play various functional roles in the musical tasks in our study.
From http://www.skiltopo.com.

One might query the relevance to present-day neuroscience of a method of classification that is over a hundred years old but is also primarily arrived at via anatomical histological differences rather than a functional basis.

Contemporary research has shown that many of the areas Brodmann defined based solely on their neuronal organization are in fact closely correlated to diverse cortical functions ; the new functional parcellations reinforce the cytoarchitectonical classifications. For example, on some of the more fundamental basic functions, Brodmann areas 1, 2 and 3

are the primary somatosensory cortex, area 4 is the primary motor cortex, area 17 is the primary visual cortex and the primary auditory cortex corresponds to areas 41 and 42. Some more specialised higher order functions such as Broca's speech and language area have also been consistently localised to Brodmann areas 44 and 45 by neurophysiological and functional imaging. Brodmann area 6 spans both fundamental and higher order functions in that it is attributed to being both the Premotor cortex and involved in melody generation which is pertinent to some of the findings of our research.

In fact the evolution of research on this area over the last thirty years is a good example of the validity of the use of Brodmann areas. To begin with, in 1919, Vogt and Vogt [Vogt and Vogt, 1919], suggested that the motor cortex was divided into a primary motor cortex (area 4) and a higher-order motor cortex (area 6) adjacent to it. This was added to by Roland and colleagues in 1980 [Roland *et al*, 1980], with a study using a positron emission scanner that showed that the premotor cortex was more involved in sensory guided movement such as following verbal instructions rather than internally generated movements such as in the supplementary motor area or the execution of simple movement in the primary motor cortex. This was followed by Wise and colleagues in 1982 [Weinrich and Wise, 1982] , where their findings showed Brodmann area 6 to be involved in the planning or preparation for movement. In 1985, Rizzolatti and colleagues [Mattelli *et al.,*1985], brought cytoarchitectonics back into the picture after nearly eighty years, by dividing area 6 into four parts, two dorsal and two ventral: PMDc, PMDr, PMVc and PMVr. PMDc is involved in guiding reaching [Hochermann and Wise, 1991], PMDr is involved in associating arbitrary sensory stimuli with specific movements[Weinrich *et al*., 1984], PMVc has a role in the sensory guidance of movement and is responsive to tactile, visual and auditory stimuli [Rizzolatti *et al*., 1981] and finally PMVr is studied with respect to its role in shaping the hand during grasping and in interactions between the hand and the mouth [Rizzolatti, 1988]. Graziano and colleagues [Graziano, 2008] further supported this division and clarified it by pinpointing that the natural movement repertoire itself is heterogenous and hence regions within the premotor cortex can be assigned to movements of greater complexity because of the subregions contained within it with differing properties.

As the above illustrates, the use of Brodmann Areas seems a good candidate for use in source localisation via sLORETA. Of course what has to be remembered is that this is approximate since the actual boundaries inside any individual brain would require its histological examination which would not be possible during our real-time experimental paradigm!

Brodmann areas also facilitate communication of findings within the neuroscientific research community.

1.4 Previous general creativity research

1.4.1 Analogical mapping and frontal lobes

In this section we will outline specific anatomical areas of the brain that have previously been linked to creative ideation and tasks which will serve as a foundation for our results using sLORETA.

Already well-explored functions of the frontal lobes include working memory, personality, mood, executive function and dynamic filtering. In short it is said to be the seat of thought. There is also evidence that frontal lobes might possibly play a role in divergent thinking, which is often taken as an indicator of creativity. This is such that, the area plays a role in the ability to disengage and shift to new strategies as revealed by the Wisconsin Card sorting test [Weinberger *et al.,* 1986] and the uses of bricks stated by creative subjects in the Guilford's Alternative Uses test [Calsson *et al.,* 2000].

Other research shows that a decline in prefrontal cortex function due to aging causes perseveration which is the antithesis of creativity [Dietrich and Srinavasan, 2007].
To relate to one of the models already mentioned, research using an imaging technique called Positron Emission Tomography, found "analogical mapping" localisation to the left prefrontal cortex and left parietal cortex when subjects were asked to identify source-target pairs of geometrical shapes that were analogous or identical [Wharton and Grafman, 1998].

The frontal lobes also have strong connections with the poly-modal and supra-modal regions of the temporal and parietal lobes where concepts and knowledge are stored [Pandya and Kuypers, 1969; Burgess *et al.*, 2003]. These connections can therefore inhibit or activate portions of the posterior neocortex selectively and contribute to the divergent thinking required for creative innovation [Heilman *et al.,*2003] and allows domain-specific knowledge overlap [Gardner, 1983].

Some research stresses that an important state of mind to be in or personality trait to have, to allow creative innovation, is relatively low behavioural and cognitive inhibition. This is supported by Hudspith (1985), who compared the EEG activity in the frontal lobes of highly creative with less so participants performing two tasks: a visualisation task of an object folded and a verbal association task. During both of these, the more creative people showed a

higher frontal theta-wave amplitude (see 1.3.1.1 for components of EEG) which they claim accompanies less frontal lobe activation. Incidentally, frontal lobes are also involved in cognitive inhibition [Bjorkland and Kipp, 1996; West, 1996].

In Chapter 5, we will discuss the Brodmann Areas that have been consistently linked to the various task contrast analyses in our study and how they relate to the broad areas of the frontal and parietal lobes and their functional relation to creativity as outlined above.

1.4.2 Neurotransmitters, states of arousal, creativity and theta

In this section and 1.4.3., we will look at previous creativity research pertaining in particular to different neuronal frequencies as outlined in Section 1.3.1.1. and 1.3.1.2., that have been previously related to states of creativity as sLORETA source localisations are also further broken down into significant frequency ranges.

Remote associations are said to provide the basis for novel ideas such that they are far removed from the original problems and ideas [Mednick, 1962] and lead to an “a-ha” moment that is the spontaneous integration of previously learned responses [Wallace, 1991]. One state of mind that is said to facilitate these remote associations and provide the sufficient time needed away from the problem (incubation) is when a creative individual enters into a hypnagogic state, reverie or is said to be in “the flow” [Green *et al*., 1970; Dietrich, 2004]. Being in “the flow”, is like a well-oiled and seamless process of neural integration and desynchrony and this is how Tononi and Edelman (1998) describe the very process of consciousness through their “dynamic core” hypothesis.

Incidentally, a particular arousal state that corresponds to this state naturally is one of a drowsy half-asleep/half-awake state and the brain frequency that corresponds is theta [Vogel *et al.,* 1966; Lindsley, 1960]. Theta is implicated strongly in the creative process because of this. Also, creativity is a cognitive task that is domain-specific and in turn, this specalised knowledge might depend on a region’s cellular organisation and the neurotransmitters found in this region [Heilman *et al*., 2003]. Theta waves could influence the cellular mechanisms as for example, it is also implicated in facilitating long-term potentiation in memory [Pavlides *et al.,* 1988].

Lower states of arousal lead to defocused attention [Martindale and Greenough, 1973] which allows more remote and unusual associations that physically correspond to more distal areas in the brain being connected probably through the use of theta waves as it plays a role in long-range interactions important in top-down processing [von Stein and Sarntheim, 2000].

Lower states of arousal also correspond to lower levels of noradrenaline [Heilman *et al.,* 2003]. Interestingly, noradrenaline might modulate the size of neuronal networks [Heilman, 2003] as it suppresses the intrinsic fluctuations of membrane potentials relative to the direct afferent potential input [Hasselmo *et al.,* 1997], which in turn would mean the prevention of many association neurons from achieving firing thresholds. Lower levels of noradrenaline, which are modulated by the frontal lobes which have been linked to divergent thinking (see Section 1.4.1) correspond to low levels of activity in the locus coeruleus. Frontal lobes are also the only structures that project to the locus coeruleus [Arnstein and Goldman-Rakic, 1984] and this brain structure is important in top-down processing that is critical for the innovation stage of creativity [Aston-Jones *et al.,*1991].

Though my study does not examine levels of neurotransmitters, any anatomical source localisation findings from the EEG recordings through sLORETA including potential identifiable networks, could have wider implications in this field of creativity.

1.4.3 EEG neural correlate of insightful problem solving

Some interesting recent research explores insight during a general creativity task by (a) comparing the EEG signature when at insight stage a wrong solution is reached instead of a correct one, (b) EEG signatures of restructuring of a problem if a mental impasse is reached and the effect on the insight reached, and (c) the apparent perception of suddenness (or "a-ha!" moment) of the arrival of insight and whether the speed is reflected in the EEG [Sandkuhler and Bhattacharya, 2008].

This research is interesting to this project as the question of what is creativity is bypassed in the experimental design by asking participants to rate their own creativity after performing the set of manipulations on each musical extract (see Chapter 4 for 'Experimental protocol for final study'). This will be compared to expert judges' opinions and it would be a sub goal to find out whether the EEG signatures would indicate a creative cognitive process irrespective of whether it objectively was or not just as long as the participant subjectively thought so or whether there would be some difference. Sankuhler and Bhattacharya's research approaches the problem with a similar angle by focussing on the insightful nature of the solution rather than the nature of the problem and obtaining fine-grained behaviour/thought patterns by getting post-solution ratings of suddenness, restructuring and confidence on a trial-by-trial basis.

Thus part (a) is interesting as a difference was found such that the gamma frequency band (40-50 Hz) activity at parieto-occipital regions was stronger for correct compared to false positive solutions. Additionally, functional fixedness or a mental impasse was also associated with increased gamma frequency in the right parieto-occipital regions and hence the paper goes on to suggest that perhaps the degree of gamma band oscillations must remain at an optimal, in other words sub-maximal, level to maximise performance.

For part (b), the study found the neural correlate of conscious restructuring to be mainly in the alpha frequency band (8-12 Hz) in the right prefrontal brain regions. This supports other research lining the prefrontal cortex and the frontal lobe to creative tasks (see Section 1.4.1) and gives a further indication that this might be an area where there might be a bias in any EEG signatures found in the present project.

For part (c), the study found the neuronal correlate of suddenness as parieto-occipital areas in the gamma frequency band (38-44 Hz). In previous research, gamma in the right parieto-occipital regions has been associated with retrieval processes from long-term declarative memory [Osipova *et al.,* 2006] and in general with memory match and utilization processes [Herrmann *et al,* 2004]. In addition, as mentioned in Section 1.3.1.2., alpha and theta frequency bands are related to working memory retention.

From the above research, it seems that the frequencies of theta, alpha and gamma may well be particular frequencies which are linked to musical creativity in the present study and this will be discussed further in Chapter 7.

1.4.4 PET study of brain maintenance of verbal creative activity

This interesting study by Betchereva *et al.,* (2004), examines two different types of creativity in the domain of language.

The study was able to narrow down quite specific areas that corresponded to either a Successive strategy or an Insight atrategy. The first strategy was a task that involved generating stories from different or the same semantic area and for the second one, the participant was expected to fill in the gaps between the words offered to him saying aloud what was the result of their own logical associations. Using positron emission tomography (PET), the researchers localised that Brodmann Area 39 in the left hemisphere corresponded to Successive strategies in creativity where Brodmann Area 40 in the left hemisphere

corresponded to Insight strategies. These areas are very near each other and in literature are known together as the parieto-temporal areas so it is impressive that author's were able to pinpoint and distinguish different creative functions between them.

With the language and music areas overlapping in our brain structures [Brown *et al.*, 2006], this research would certainly be relevant to our present study as it explores types of creativity in detail. In fact, there is some correspondence to our two different types of creativity *Improvisation* and *Interpretation* where when partipants were thinking with mental imagery about both tasks, Brodmann Area 40 was activated in the left hemisphere in the contrast of *Improvisation* vs *Interpretation*. The general cognitive tasks attributed to this area and how they may relate to musical creativity will be discussed further in Chapter 5.

1.5 Previous music creativity research

There has been a variety of neuroscientific creativity research focussing on various aspects of musical creativity from lyrical verbal rapping to improvisational accompaniment and using a mixture of EEG and fMRI as experimental techniques. Here we will review a few of these papers and describe how they relate to the present study.

1.5.1 DC-EEG study on musical creativity

This study by Beistener *et al*. (1994), is the first to attempt to provide electrophysiological correlates of creativity in music. However, the methodology only covers DC-EEG (direct current/direct coupled amplifier). This is a specific low frequency bandwidth (0-0.5 Hz) that is often used to show the "readiness potential". If negative, DC-potentials indicate increased activity in those brain areas involved in the mental process of a given task. One advantage of this technique is that there is evidence that topographical changes in activity patterns (i.e. activity in specific brain regions or hemispheric laterality) can elucidate task-specific activity but amplitude changes are due to general influences such as the amount of effort and stress associated with the task. Therefore, Beisteiner *et al.,* point out that when analysing task effects, it is important to not confuse the general arousal or anxiety states of the participants with specifically task related activity.

The study involved 3 musical tasks:

1. Analytic task where participants had to listen to a "tonal" or "atonal" sequence and immediately afterwards had to reverse the sequence in their mind.

2. Creative task where subjects listened to the same sequence as in the analytic task but had to complete with a fitting ending in their mind that was equal in length to the duration of the original sequences.
3. Memory task where the participants are asked to do the same as in the creative task but instead the sequence will be a well-known melody and the completion had to be the same as in the original sequence.

One drawback of this study that is immediate is that the stages involve visualisation with no performing or even humming. However, they did ascertain participants concentration levels, which in this project is also mimicked somewhat through a much simpler self-evaluation than using tried and tested psychometric evaluations (see Chapter 2).

For each of their tasks, about 30 artifact-free trials were averaged per participant. Then a grand average across all subjects was derived and for defined time intervals, mean amplitudes (arithmetic mean) of performance-related DC shifts were calculated. Subsequently, a comparative analysis of variance was performed. This project uses a within subject and within task paradigm such that patterns are looked for that are unique to each individual and task. Our study utilises many contrast analyses within subjects, within tasks and also within genres of jazz and classical.

The study finds that it is mainly the parieto-temporal cortex and the left hemisphere which is involved in the analytic processing of music in the DC-EEG bandwidth. This might be of some interest to the manipulative stages of musical extracts in our pilot study's experimental paradigm and in the interpretive and improvisational stages in both pilot and final study (see Chapter 2 and 4).

In addition, the creative task is the only one where there was a significant change from a right-hemispheric tendency while listening, to a left hemispheric one whilst processing. Whereas, our project does not really have an equivalent task, it might be interesting to see whether there are components of this during the freely improvising task (see Chapter 2 and 4) and of course if there is an element of listening whilst playing. The study concludes with saying that musicians do not have a musical hemisphere but instead have a sophisticated interplay between different brain areas that in the actual task may determine a momentary predominance. This yet again seems to support connectionist theories and as will be discussed in Chapter 5, some of our task contrast analyses findings through sLORETA.

1.5.2 Music cognition vs. language as another verbal/audio cognitive function

In the study of Brown *et al.* (2006), amateur musicians were asked to vocally improvise melodic or linguistic phrases in response to unfamiliar audibly presented melodies or phrases. In other words, they were asked to generate or create endings for these phrases whilst brain activations were observed using PET. What is relevant to our study are the areas that are activated during melody generation (although the study found a surprising overlap of activation areas in sentence generation tasks) and the distinct parts in which the study breaks music cognition down into corresponding to different aspects of a musical phrase.

The study found that music tasks activate the right hemispheric areas homotopic to classic left hemispheric language areas although many music tasks elicit bilateral activations that appear to coincide with left hemispheric presumably language specific areas. In addition, musical expertise can increase bilaterality [Ohnishi *et al.,* 2001; Parsons, 2003; Bever and Chiarello, 1974; Gaser and Schalug, 2003; Parsons *et al.*, 2005]. This has an interesting connotation for the connectionist theory as two questions arise such that, firstly, how can homologous hemispheric regions process different facets of a single function and, secondly, how can a given cortical region be specialised for processing different functions, for example, music and language.

Specifically, the areas in the brain that are activated for generating melodic phrases are the left Brodman area-BA 45, BA 44, bilateral temporal planum polare, lateral BA 6 and pre-supplementary motor cortex.

Cognitively, musical structures that were given importance included absolute pitch, melodic contour, intervals, tonality, rhythm, tempo and motivic structure. For our research, we have used 5 of these as separate steps of manipulation for participants in the pilot study experimental paradigm (see Chapter 2) and have discarded these in the final study, for the purpose of refinement and concentrating solely on interpretative and improvisational creativity.

Other pointers taken from the study included their method of screening their participants in terms of ability and behavioural suitability and also the number of music samples used (30 for the pilot study and 20 for the final study). Whereas, Brown *et al*. (2006), used precise singing skills, we use piano proficiency and ability in technical manipulations (see Chapter 2).

1.5.3 Exploration of piano improvisation using fMRI

This study on musical creativity specifically looks at jazz improvisation using the fMRI technique [Limb and Braun, 2008]. The study looks at jazz specifically and due to the limitations of fMRI, candidates are asked to memorise a piece of music (whether low or high in complexity) that they would either play with a pre-recorded jazz quartet or allowed to play "freely" in the improvisation task but using the same chord structure of the original composition and the same auditory accompaniment as the basis for improvisation.
The general result of the study was that improvisation compared to over-learned musical sequences was consistently characterised by a dissociated pattern of activity in the prefrontal cortex, specifically the deactivation of dorsolateral prefrontal and lateral orbital regions with focal activation of the medial prefrontal cortex.

Differences from our study are:

1. Our study also includes classical western musicians as well as jazz musicians and investigates both types of creativity pertinent to these different genres: Interpretation and Improvisation.
2. Our study has an added element of both self-evaluation and objective expert evaluation of performances.
3. Limb and Braun's study (2008) uses accompaniment as a basis for improvisation. The feel is more towards interpretative goal-oriented creativity whereas our project has scope to explore compositional creativity as well. The freely improvise task in our project, has less restrictions on it and simply asks of the participant to allow a listener to be aware of some element of the original piece in their improvisation (see Chapter 2 and 4)
4. There will be a significant memory effect in activation in Limb and Braun's study and we have gone to some pains to avoid this by carefully selecting unfamiliar extracts and composers that participants would not have come across before, by consultation with music college syllabus coordinators.
5. Limb and Braun's study do not have the real-life ecological validity interests as participants are asked to play whilst lying down, which will involve different motor skills at the very least and may cause different perceptions and reactions than normal, as pianists usually perform sitting upright.

6. Our participants are a mixture of both male and female to maintain a real-life homogeneity of population.
7. Importantly, we use EEG, as explained in section 1.3.1.1, it is a technique more relevant to neural activities underlying complex cognitive processes such as music manipulation.

1.5.4 Neural correlates of lyrical improvisation: An fMRI study of freestyle rap

We will go into much more detail in the review of this paper due to the proximity of its content to our study and also because of its treatment of particular areas in the brain related to improvisation that draws a parallel to our use of source localisation.

Braun *et al.* (2012), have most recently carried on to focus on a genre of music called hip-hop in which it is often common to have free verbal improvisation set to rhythmic backing music called "freestyle rap". They investigate the initial generative improvisatory phase of creative behaviour by comparing this spontaneous lyrical improvised rapping to well-rehearsed over learned conventional performance of lyrics over an 8-bar musical background track via fMRI.

In this study they found dissociated activations in the left medial prefrontal cortex (MPFC) extending from the frontopolar cortex to the pre-supplementary motor area (pre-SMA) and deactivations in the right dorsolateral prefrontal cortex (DLPFC) from its orbital to superior regions when comparing improvised to conventional tasks. Of special note is the consistent lateralisation of the activity and the apparent correlations between the pattern of activation and deactivation discerned via functional connectivity analysis, e.g., stronger negative correlations between activity in the MPFC and the ventral DLPFC indicating that the reciprocal changes noted in these prefrontal areas are not independent. The study also found anticorrelation between the activity in the MPFC and the intraparietal sulcus (IPS). Positive correlations were detected between activity in the MPFC and the anterior perisylvian (LIFG) and cortical motor areas including the cingulated motor areas and adjacent cingulated cortex (ACC), the pre-SMA and the dorsolateral premotor area (PMd and general Brodmann area 6).

The researchers took into account parametric modulation methods to determine how the innovative quality of performance might affect the activity patterns. Questions such as "Did the participant generate a narrative?" or "Did the participant vary rhythmic patterns?" amongst a total set of 13 questions were blind rated. Significant associations were found

between these measures and activity in the posterior and middle temporal gyrus (MTG) and superior temporal sulcus (STS), the left MPFC, specifically lateral Brodmann Area 9, a region near the superior frontal sulcus and the posterior cingulated cortex (PCC). The functional connectivity analyses were also guided by the parametric modulation results outlined above.

Much of the findings seem to agree with the initial study on piano improvisation mentioned above [Limb and Braun, 2008] in the dissociated activity pattern in the prefrontal cortex.

They also attempt to explore the creative process over time by initially comparing the contrast between the improvised and conventional conditions between the a) 1st bar to the 8th bar then, the b) 8th bar to the 1st bar. The first positive contrast shows left hemispheric regions (amygdala (AMG), IFG, MPFC and caudate) more strongly activate during the first than the final measure of each segment. The second positive contrast indicates that activations were stronger in right hemispheric regions (inferior and middle frontal gyri, posterior parietal cortex and other posterior paramedian areas).

This most recent study comes closest to the question we are asking in our current project when it comes to the examination of spontaneous creative "flow" though in our study we focus purely on music and do not have the restraint of an accompanying backing track so our improvisation task is truly "free". The activity patterns described above bear some resemblance to our findings and these will be discussed in more detail in Chapter 5.

However, even as the authors themselves point out, the dominance of the left hemispheric areas coincide with the language areas (inferior frontal and posterior middle and superior temporal gyri) in the brain and this is somewhat unsurprising given the nature of the type of creativity being explored, though the activations during improvised are over and above levels observed during conventional performance.

It would most certainly be interesting to see any areas of commonality or difference when the task is a purely instrumentally musical one as the frontal midline cortices selectively activated during improvisation regulate motivational incentive, intentionality and drive [Stuss, 2007; Kouneiher *et al.*, 2009] and in this instance MPFC could be seen to be operating at the interface of intention and action, synthesising information, encoding goals and guiding self-generated, stimulus-independant behaviours [Soon *et al.,* 2008; Ramnani and Owen, 2004; Tsujimoto *et al.,* 2010; Passingham *et al.,* 2010; Haggard, 2008]. The authors also propose that the anti-correlation found between the dissociated patterns in the MPFC and DLPFC reflects a state in which internally motivated, stimulus-independent behaviours are allowed to

unfold in the absence of conscious volitional control. As a fundamental theory behind improvisation, this would certainly be of interest to our study.

In addition, the authors postulate the lateral prefrontal regions maintain executive control, consciously monitoring and implementing adjustments in an ongoing performance in order to ensure actions conform to explicit goals [Miller and Cohen, 2001; Tanji and Hoshi, 2008]. While our improvisational task does not impose any such explicit or even implicit goals, our study does examine a second form of musical creativity, namely interpretation where there is an element of adhering to a structure outlined by the composer of the piece of music. The authors propose that creativity may be a biphasic process involving an initial generation and a subsequent revision and reevaluation that might predict the activation of supervisory attentional and executive systems that require attention to conscious goal-directed revision. We might almost propose that "Interpretation" is a type of creativity that is in fact very closely described by this and that our study explores it in depth.

The authors propose that an alternate, direct route through cingulate pathways (as these areas were significantly activated during improvisation), may allow the medial frontal regions to generate novel, exploratory behaviours [Daw *et al.,* 2006] bypassing conventional executive controls and providing cognitive flexibility, which is necessary for improvisation. There is some agreement between their findings and our own study in terms of activation of the cingulate and MPFC areas namely during creative improvisational and interpretational tasks when compared with the implicit baseline of just playing and to non-creative performances, which will be discussed further in Chapter 5.

Other differences in our study include the two-fold evaluation of creativity both from the point of view of the subjective participant and the objective expert judge, using a simpler measure of creativity as the question asked for rating in both instances is simply 'How creative did you think that was?'. Additionally, in our study we also incorporate a study of the temporal evolution of creativity but also match these up to ratings of both the self-assessments and the expert judgements. This furthers Braun's study as in the author's own admission, "The mechanisms underlying these interactions between musical improvisation and temporal structure clearly warrant further investigation".

Interestingly, the second positive contrast in their temporal study of creativity, comparing the 8th bar with the 1st bar, highlights a right hemispheric regional activation which also correspond to similar regions in our study when only expert judge ratings were used to segment creative improvisations and interpretations and compared to the baseline of just

playing, in the last four seconds of playing. The 'creative' minus 'non-creative' task comparisons will be further discussed in Chapter 5 and also portrayed in context of analyses of self-assessed creative pieces in their temporal evolution.

Though more refined to the domain area of music, our study widens its scope to general music by exploring two different genres of jazz and classical rather than remaining idiosyncratic about hiphop. Our project also places a distinction on "thinking" about a task and its mental imagery and "performing" a task, hence allowing not only a cleaner correlational evaluation of motor cortex activity but also providing an insight into how important, sensory feedback and the actual motion of playing can be to the process of improvisation and "flow".

A further possible agreement between this study and our own is the suggestion that spontaneous lyrical improvisation is associated with the emergence of a network that integrates motivation, language, emotion, motor function and the representation of subjective experience more effectively during a creative behaviour. Though not including language, our study shows activation in areas that have been related to positive emotional valence, reduction of self-monitoring, increase in empathy and self-reflection and greater control over complex movements. The areas involved though are slightly different and the comparative tasks more detailed and again these will be presented and discussed in Chapter 5.

In addition, there may be a tendency of a lowering in attentional control both in their study (due to the right deactivation of the DLPFC when comparing improvised to conventional rapping) and in ours (right deactivation of BA 7 when comparing improvisation with interpretation).

1.5.5 Cortical regions involved in the generation of musical structures during improvisation in pianists

Here we will briefly mention another study that also used fMRI to examine creativity and this time specifically piano improvisation [Bengtsson *et al.*, 2007] In this study, they instructed pianists to Improvise, Reproduce and FreeImp. In Improvise, they had to improvise on 8 bars of a visually represented piece of music which they then had to commit to memory to replay in the condition of Reproduce. In the condition of FreeImp, they were asked to simply improvise without committing to memory. This is a basic study where the all-male participants were presented with unfamiliar musical extracts that were only in one of two keys (Fminor or Fmajor), pianists were asked to lay supine in the fMRI machine and asked to play on a small keyboard with only their

right hand. Despite the non-ecological validity of the conditions of playing, the extracts themselves and the bias of cognitive findings that an all-male participation would entail, their findings seem to support that of the above research such that activated brain regions during improvisation included the right dorsolateral prefrontal cortex, the presupplementary motor area, and in addition, the rostral portion of the dorsal premotor cortex, and the left posterior part of the superior temporal gyrus.

In this study, one can question the point of the Improvise/Reproduce tasks as even the authors query whether the difference in brain activity of Improvise-Reproduce could be down to a non-accurate replication during Reproduce and hence different motor outputs. It seems a cumbersome method to elicit the role of memory and even goes so far as to introduce the element of memory unnecessarily when simply, unfamiliar extracts could have been used as the visual stimuli. Furthermore, the task of FreeImp directly showed a higher activation in the DLPFC which could be related to the greater freedom in cognitive selection than for the Improvise/Reproduce tasks. The role of the DLPFC for free selection in cognitive tasks has been previously shown as well for word generation [Frith *et al.,* 1991]

1.5.6 Sight over sound in music performance

This study by Tsay 2012, finds that in order for an accurate prediction of the winner of a music competition, listeners only need the silent video of the performance vs sound-only recordings and were more accurate than when presented with both sound and video recordings. However, the study is very specific about the context of performance assessment i.e., a competition and the particular type of judgement needed. In a previous study, expert inter-rater agreement was 67% [Schonberg, 1986] whereas with this particular framework of judgement, the highest accuracy rates for experts were approximately 47% based on video-only assessments and 46-52% for novices.

For our study, we chose to use the sound recordings of the improvisations and interpretations played by the participants for the expert judges to rate, who were chosen for their own musical prowess and/or their facility of assessment as a professor of a music college or the Associated Boards for Piano. This choice was made over having a visual recording of the performance in addition, as it was felt that the sound of the performance was the foremost important element of a post-performance evaluation and we wanted to avoid as little interference from the videos to the EEG recordings and create the most comfortable, non-crowded and relaxed atmosphere for participants in their playing studio. This choice was also

done on the basis that not only was the core content, the sound, but in order for inter-rater reliability and agreement with self-assessments, the only element that would accurately represent the internal mental state of the participants for the external judges during creation of a piece of music, was the sound itself. For our particular 3-pronged approach in the experimental design, it would be important to have a close enough association or partnership with internal mental processes as represented by recorded EEG, such that relationships in the patterns of the EEG could be ascertained with agreements in creativity from either or both of objective judge assessments and subjective self-assessments.

We reasoned that certainly for famously appreciated compositions (and improvisation is real-time composing), played posthumously, the composer did not need to be present or visualised for an assessment of the quality and neither do bands need to be present in our living room, or do we have to watch videos of them, for us to appreciate the sound from their CDs!

Through Tsay's findings one may well use video recordings for assessments of music as it seems that perhaps what the assessors were evaluating for a great performance were based on movement and gesture that belied creativity, motivation and passion. However, as our results for judges assessments will show, sound alone is definitely an accurate assessment tool for music performance and in fact our results imply an inter-rater agreement.

1.6 Summary

In this chapter, we have outlined traditional qualitative models for creativity, emphasising the stages and theories we rationalised were relevant to the different types of musical creativity we are investigating.

We subsequently introduced fundamental neurobiology in terms of traditional modular lobes, divisions into Brodmann Areas and frequencies of the brain, in order to discuss their roles in previous general and musical creativity and their putative functional roles in our study. We briefly discussed different neuroimaging methods and the reasons for choosing EEG as our preferred mode of data collection including two prevalent neuroscientific theories of connectionist versus modular. In light of the neurobiology, we described the basic mechanisms of the source localisation software sLORETA that we will be using in our analyses to pinpoint cortical structures involved in the musical brain.

Finally, we reviewed a broad range of papers and research investigating general and musical creativity, highlighting those studies with a particular relevance to our study.

2. EXPERIMENTAL PARADIGM

In this section, we will go through the actual experimental paradigm used for both the pilot study and the subsequent final study and also discuss why any significant changes were made to the design of the final study.

2.1 Electroencephalogram (EEG)

2.1.1 EEG Equipment and Setup

Firstly, below we will summarise the standard EEG equipment, procedure and setup used for both protocols:

- Biosemi hardware and Actiview/Labview software for data viewing during acquisition.
- 64 active electrodes used in the 10-20 "international spacing" standard (see Fig. 1.3). Active electrodes minimise mains electricity noise pickup of cables by suppression of interference with impedance transformation directly on the electrode, though they are not protective against movement artefacts. Participants were fitted with the correct sized scalp hat and their skin abraded for the placing of the electrodes which were then individually fitted and skin resistance checked until optimal.
- 6 external electrodes used: 4 ocular (2 for blinks and 2 for horizontal eye movement or 'saccades' tracking); 2 mastoidal (for use as reference electrodes post recording).
- 512 Hz sample rate for pilot study and 1024 Hz for final study.
- Adjustable references that can be set post recording.
- Participants were taken into the experimental room, which in this case was not a Faraday cage which is optimal for EEG recordings, because of the amount of electrical equipment used in the experiment itself, i.e., a full-sized weighted electronic keyboard with a pedal mounted on a stand, placed in front of a computer monitor where the extracts and instructions were displayed. There were additional cables to record the midi and audio of the performances.

2.1.2 Signal processing

In this section we will go through the detailed and comprehensive processing of the raw EEG data from both experiments that was necessary to 'clean' it and make it analysis-ready (see Fig. 2.1). This involved EEG data recorded for each condition for 5 participants from the pilot study and 8 participants from the final study leading to a total of 1,340 separate EEG recordings to process and clean. Apart from the automation of certain algorithms (e.g.

Independent Component Analysis (ICA), see pg 56) and application of filters, any final data/artefact rejection was done by eye individually and were the most time-consuming stages.

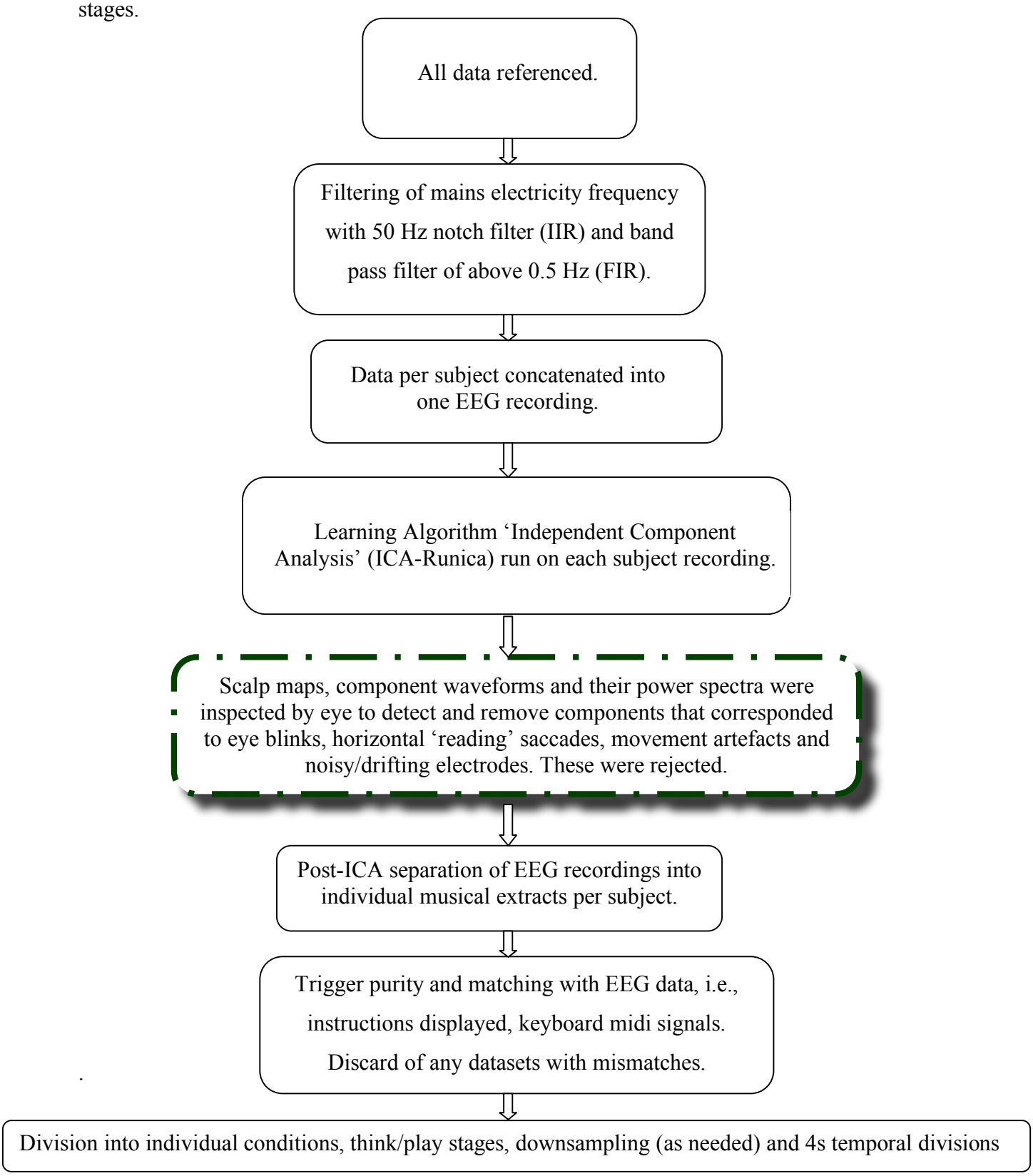


Fig 2.1 A flow diagram of the steps required in the signal processing of each EEG recording. The Stage highlighted in green will be elaborated in further detail below.

Systems with active electrodes (e.g. Biosemi Active Two), record data "reference-free" A "zero" reference must be chosen *post hoc* during the data import and failure to do so leaves 40 dB of unnecessary noise in the data. The reference can be relatively more neutral places (i.e. with less electrical activity than the scalp electrodes of choise) such as the mastoids, earlobes or nose. In our experiments, the external electrodes were placed on the mastoids. However, referencing to the mastoids seems to introduce some distinct characteristics into the waveforms of the rest of the channels (see figure 2.2) and this can be removed via Independent Component Analysis (ICA), see pg 56.

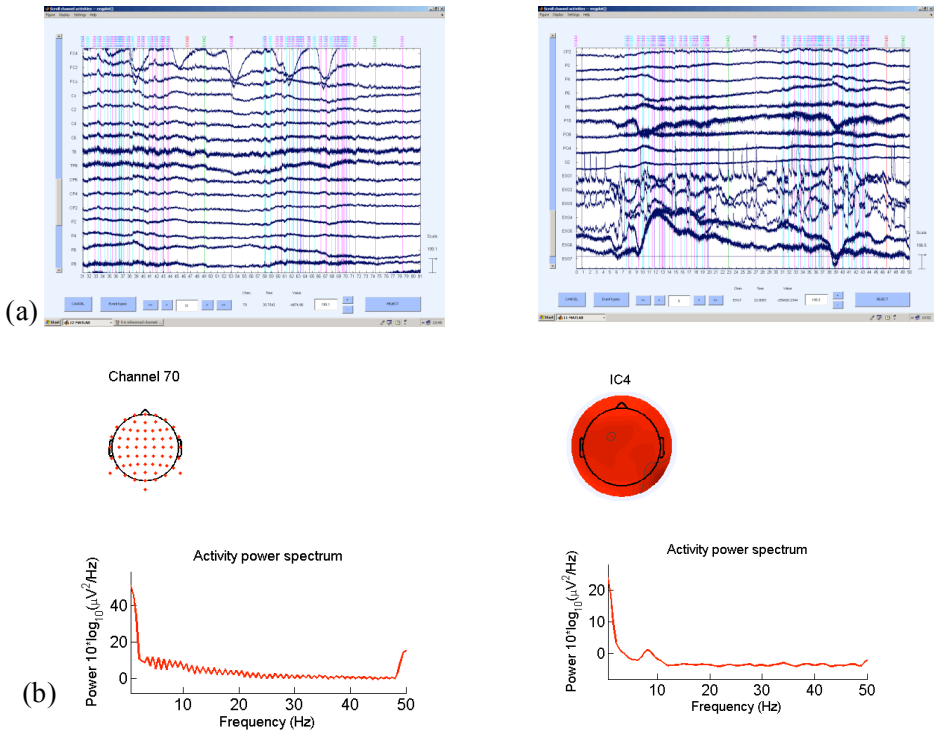


Fig 2.2. (a) Two screen shots of EEG data with the first being of an 'unreferenced' recording and the second showing the introduction of the characteristics of the mastoidal waveform into the rest of the electrode recordings. (b) Two power spectra with their corresponding scalp maps. The first shows the power spectra of the mastoidal electrode and the second shows the ICA component's power spectra and the whole area of the scalp that it is found in, which corresponds to the mastoidal waveform. This can be selected and removed as a 'reference' artefact.

For drift problems that are due to hardware and not cognitive sources (see figure 2.5), as mentioned in the flow diagram, a high pass band FIR filter is applied at 0.5 Hz. The disadvantage with this is that it can reduce the amplitude of the resultant signals to a large extent and along with the other commonly used Buttersworth filter, can introduce artefacts even up to 50 seconds into the recorded data depending on the filter order, see figure 2.3. This

amongst other artefacts corresponding to significant components and waveforms can be detected and rejected with ICA [Jung *et al.,* 2000].

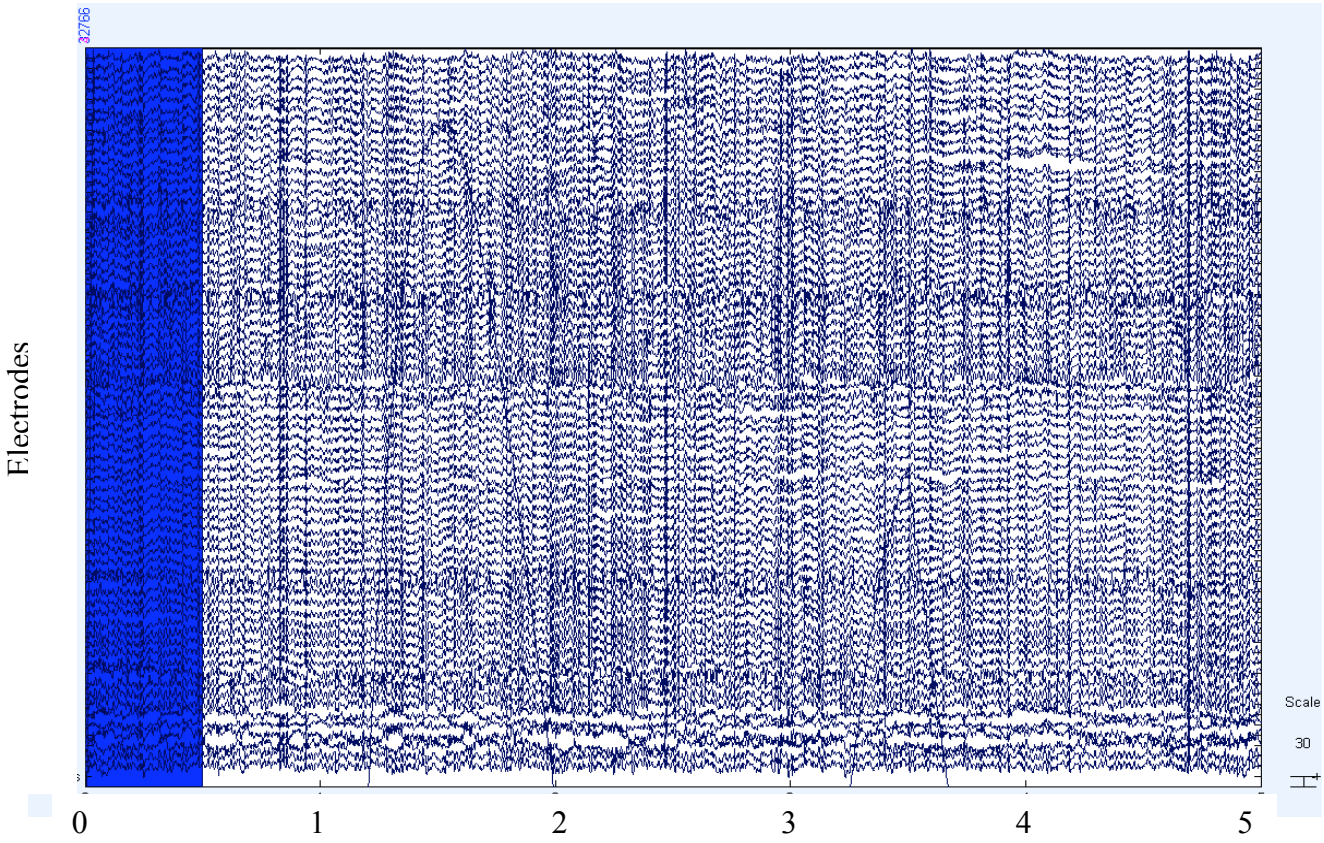


Fig 2.3 Example of a filter artefact in the form of a large oscillation with harmonics with time in secs.

Independent Component Analysis (ICA) helps visually pinpoint the major components contributing to each electrode signal's waveform and each component can be localised to a position anatomically on a scalp map. If there are 64 electrodes plus 6 external electrodes and 2 status channels, the ICA will return 72 components, see figure 2.4.

It is based on the Principal Component Analysis and the EEG 'cleaning' is analogous to solving a problem similar to the 'Cocktail Party' problem: what a guest finally hears is a blend of sounds coming from several sources in the room i.e. the host, the other guests, several music speakers dotted around. The algorithm allows us to pinpoint these individual separate sound sources using only the merged 'blend' of the final sound which is similar to the 'cocktail' of EEG signals we record at the scalp where signals will be a mixture of cortical activity and 'noise' from artefacts such as movements, electric mains, malfunctioning electrodes, filters and references.

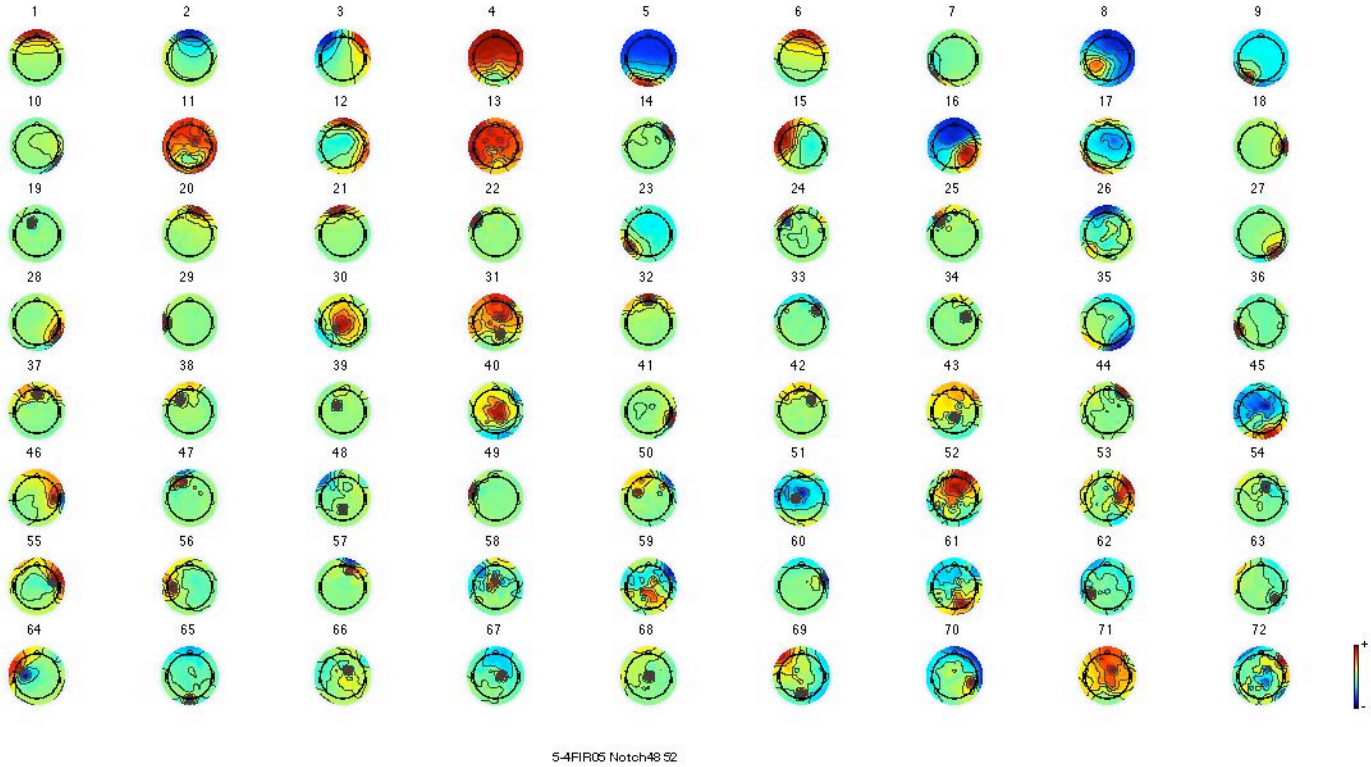


Fig 2.4 An example of the 2D topographical scalp maps returned after the ICA algorithm is run. Each scalp map seen from above (top to bottom corresponding forehead to the back of the head), shows the location of that particular component contributing to the 64 waveforms. For example, components 1, 2 and 6 are due to eye blinks and 3 being due to saccades. They are localised in the prefrontal and frontal lobe electrode positions which can be expected as they are the electrodes closest to the eyes. The external electrodes recordings help calculate these components in a stronger fashion so that they can be removed by subtraction from the rest of the cognitive EEG recorded.

Consequently, some of these components can be different from actual cognitive activity that we are interested in. Electrical interference of 50 Hz, or electrical artefact bursts caused by clenching of the jaw/shoulder muscles or blinking of the eye, permeate throughout the EEG recordings of this cognitive activity and result in generally ‘noisy’ recordings. Fortunately, the movement-related ‘noisy’ electrical activity can be sourced from the 6 external electrodes as they are positioned near the eyes and jaws. The algorithm thus uses these external electrodes as a reference to separate and discard, unwanted ‘noisy’ components from the cognitive components present in all of the 64 electrode recordings. ICA can therefore most commonly detect very strong pulses such as eye blinks and horizontal eye saccades that are a necessary by-product of an experiment that relies on reading music, see figure 2.5.

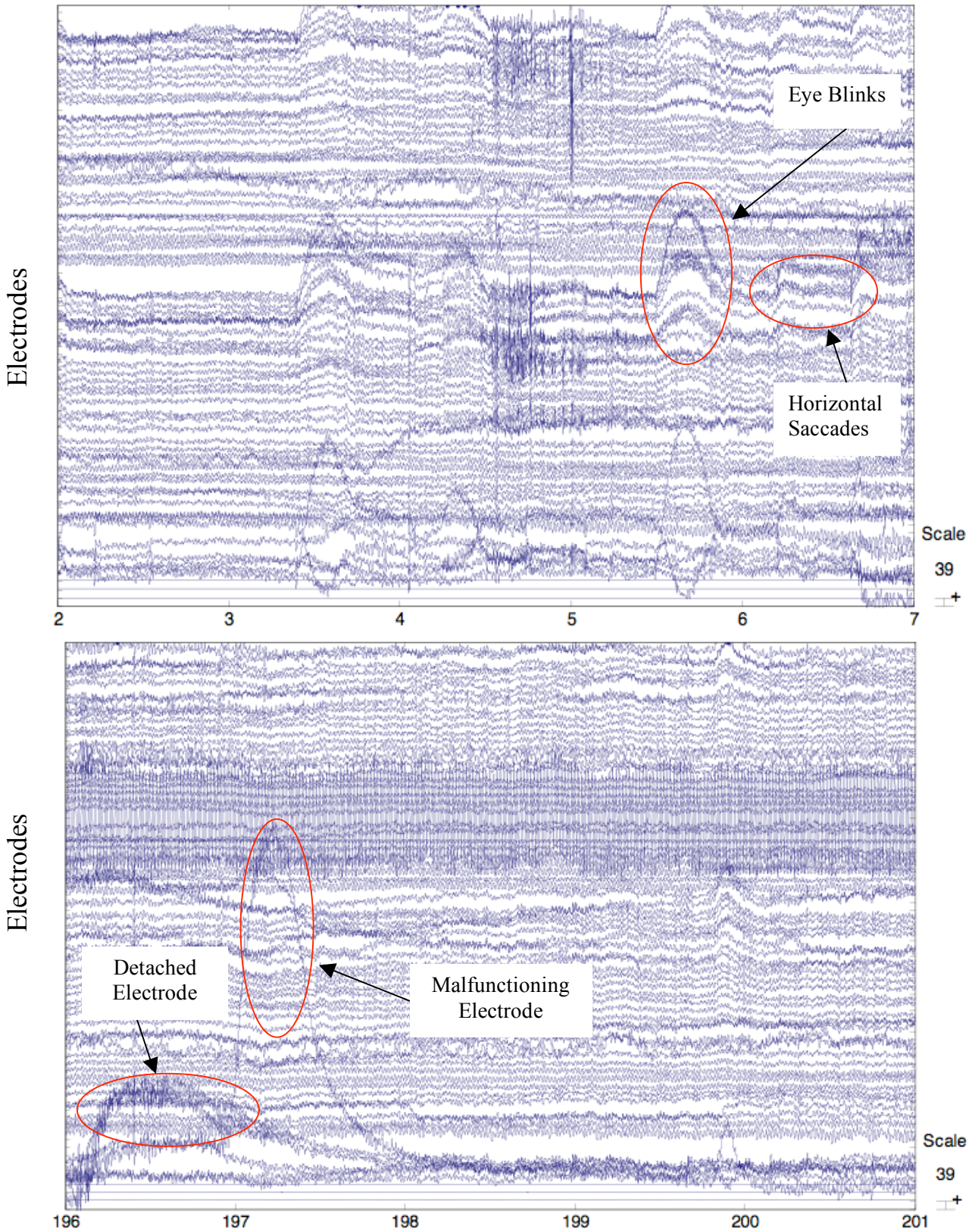


Fig 2.5 Screenshots of EEG recordings from GUI EEGLab. The top is an example of a normal data set with 64 electrodes on both hemispheres and time in secs with some movement artefacts especially eye blinks and saccades detected in the frontal lobe and ocular electrodes. The bottom is an example of a messy recording with a malfunctioning and detached electrode. For both, the appearance looks noisy because of mains electricity and equipment noise.

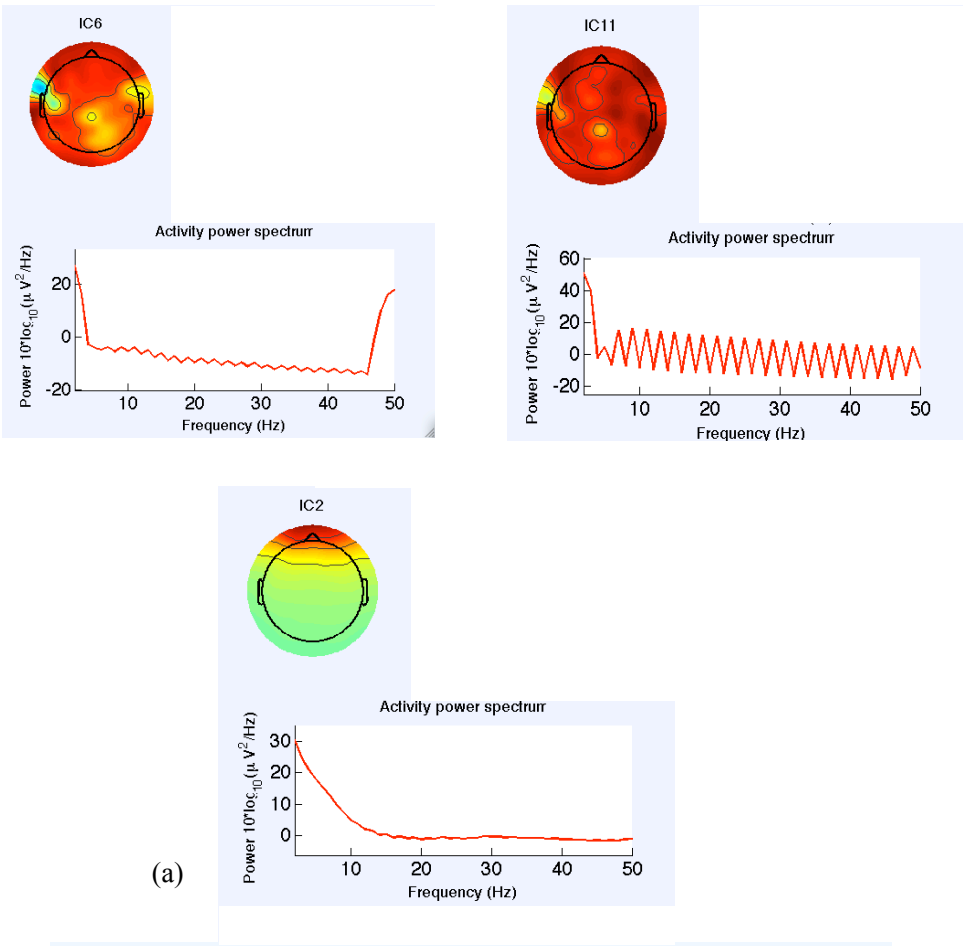
ICA is also able to detect filter and reference artefacts as mentioned and shown before (figures 2.2 and 2.3) and due to the reliance on electrical equipment, any residual 50Hz activity that appears as interference in electrode activity even after the notch filter is applied (see figure 2.6). When the ICA waveform for this 50Hz component is examined, it looks 'noisy' with an increased frequency and amplitude and its corresponding power spectra does not have a clean peak at 50 Hz.

ICA is also able to detect generally malfunctioning noisy electrodes, or that are 'drifting' due to a loose connection (see figure 2.5), that are still present and 'noisy' even after being corrected for by the 0.5Hz band pass filter. The ICA algorithm commonly returns the top 10 components in order first and non-surprisingly, they consist of eye movements, filter and reference artefacts, electrical interference and noisy/malfunctioning/drifting electrodes whilst movement artefacts are finer and more spread out amongst the other remaining components.

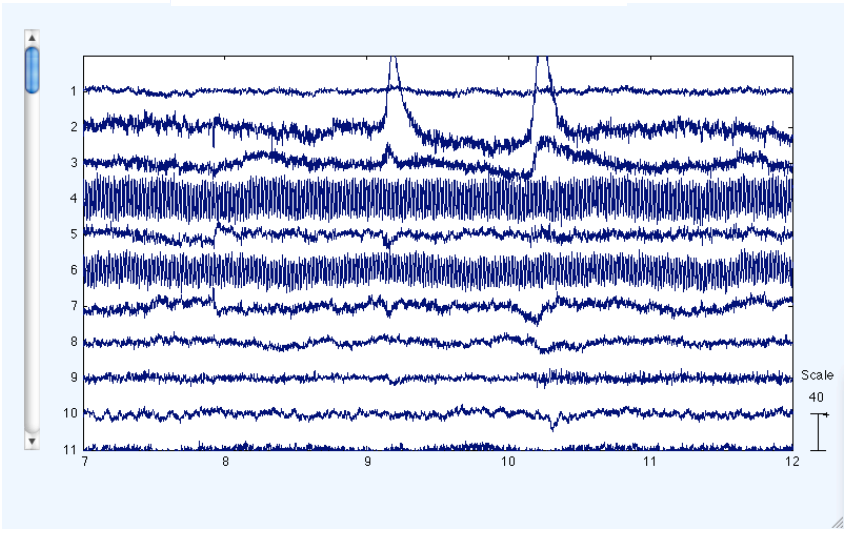
After the automation of filters, referencing and the running of the ICA algorithm, all the artefacts have to be removed individually by eye, by carefully considering the resultant components through their waveforms and corresponding power spectra, see figure 2.6 for example.

The underlying mechanisms of ICA, how it relates to the more commonly known Principal Component Analysis (PCA) along with a more detailed explanation of how ICA components make up a recorded waveform and why it can be used for artefact rejection as described in this thesis can be found in a paper by Jung, Makeig and colleagues, Makeig being one of the creators of the freeware EEGLab that allows us to perform ICA and reject components [Jung, 2000].

Eventually, we obtain a whole set of clean EEG recordings, see Fig 2.7 for a typical example.



(a)



(b)

Fig 2.6 (a) An example of some of the power spectra linked to the individual ICA components. The top left spectrum shows ICA component 6, corresponding to electrical 50 Hz mains current before a notch filter is applied and the top right power spectrum shows residual electrical interference after the notch filter. The bottom ICA component 2, power spectrum corresponds to eye blinks. (b) The corresponding waveforms of the ICA components to the power spectra above. Of note is waveform 6 corresponding to electrical 50 Hz mains, also looking noisy and waveform 2 showing very marked eye blinks at 9s and 10s.

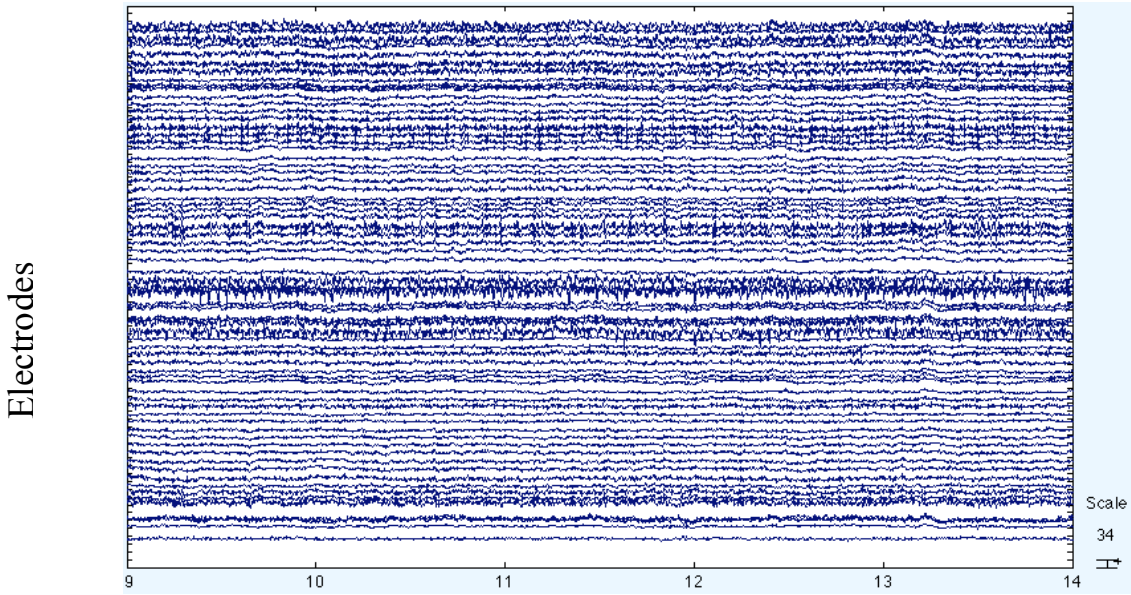


Fig 2.7 An example of ICA removed EEG data with no eye blinks/horizontal eye movements.

2.1.3 Clean EEG data segmenting

After the final stages of cleaning and signal processing, the EEG recordings are then subsequently segmented and manipulated as needed for the analyses. For example, the time duration of any piano playing was visually overlaid real-time onto the EEG recordings so as to facilitate distinguishing and segmenting into regions of participants 'thinking' versus 'playing', see Figure 2.8.

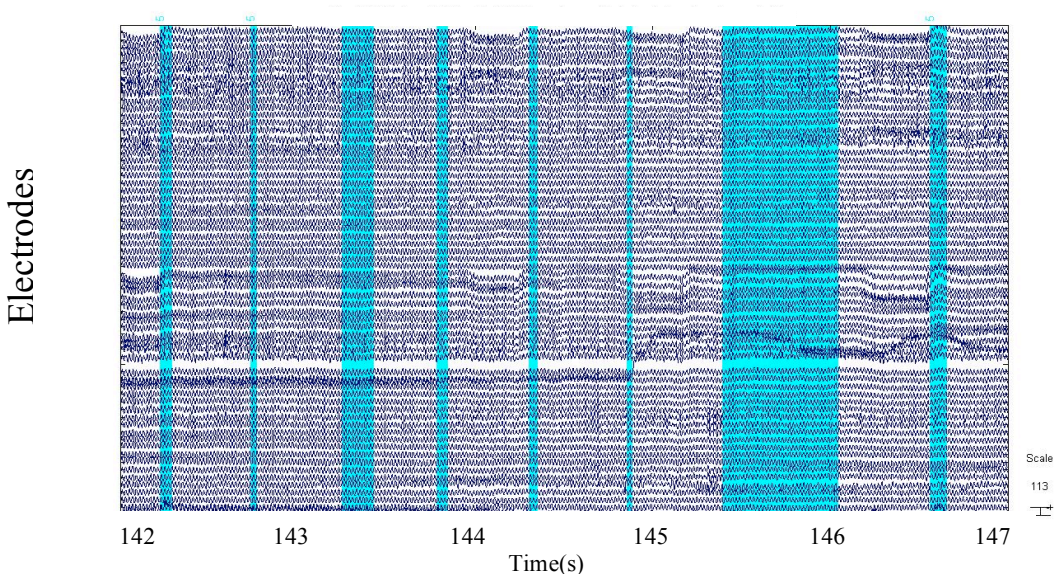


Fig 2.8 EEG displayed using EEGLab software. This recording is during a participant playing the piano which is indicated by the accurately timed blue coloured bands across the EEG recordings.

Apart from elements adapted from other studies as mentioned in Chapter 3, the experimental paradigm was designed using classic neuroscience, psychology and cognitive neuroscience techniques. Musicology advice was given by Richard Dickens (Conductor of Imperial College Orchestra and Director of Associated Boards).

2.2 Screening of participants for pilot study

In this section, we summarise how the musicians participating in our study were chosen taking into account homogeneity of sample, type of instrument played and what the resultant sample comprised of.

- Musicians with classical background with at least Grade 8 level (entry minimum to music university) and music as a degree to have homogeneity of population. They were also asked whether they were comfortable with sight-reading, technical manipulations and free improvisation.
- Due to the need to have minimal movement because of noise artefacts in the EEG, pianists are used in the pilot study and not singers, wind or string instrumentalists.
- Subjects are screened for any mental or physical disorders or variation from 'neurotypicals', including synaesthesia and dyslexia. They were also asked if they were on any medication.
- The handedness of participants is noted as is their general state of alertness and mood (i.e., S for sleepy, R for relaxed, G for good/alert and A for anxious/tense).
- 5 participants (4 male, 1 female) were chosen, with 4 of them at early stage careers at an age range of 20-30 and one highly skilled professional and teacher at age 45.

2.3 Musical extracts-how they were chosen for pilot study

We now describe the detailed musicology and neuroscientific criteria used to select the classical extracts eventually used in the study along with any interim musicology considerations taken into account that were not implemented.

- A range of 30 short extracts (approx 5 sec) in only a visual form, i.e., the musical score.
    - Each stimulus is approximately 4 bars long known as a gobbet in western classical music.

- They comprise a range of short extracts in a mixture of keys, tonalities (major and minor) and tempos. A variety of rhythms, motivic patterns, number of notes and melodic contours will be presented.
- All scores are standardised with a program called Sibelius that reproduces them in the same font to avoid extra subliminal messages will be given (even the typeface can betray such things as country and era of origin). Even if the extracts chosen will be in the middle of the score, the time signature and general instruction of the piece (e.g. *andante*) will be cut and paste and maintained/changed to Italian. Additionally all scores will include phrasing and slurs.

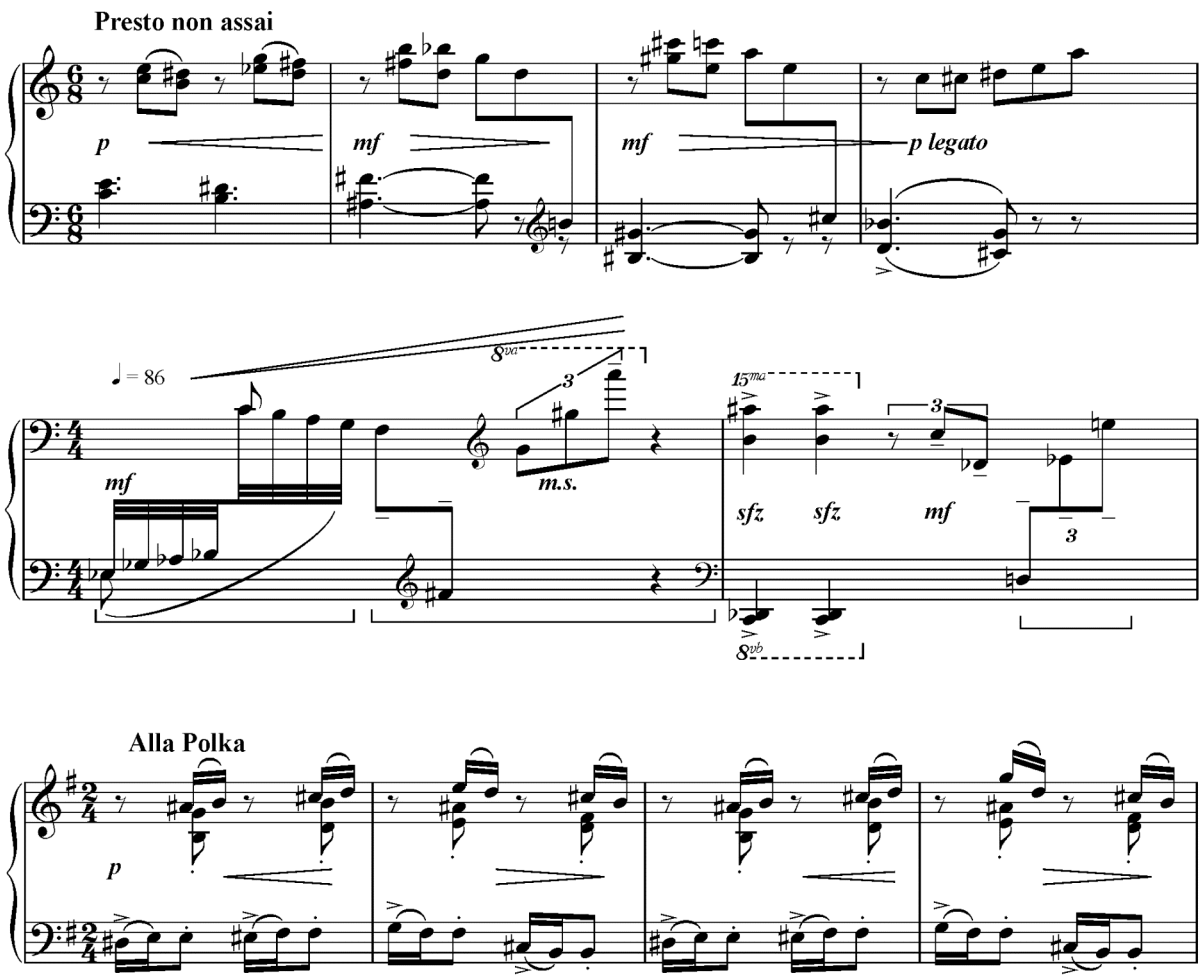


Fig 2.9 A range of musical extracts that were used as stimuli in the pilot study. Note the variety of time signatures, rhythms, tempi, tonalities, keys, dynamics and melodic contours.

These factors were considered, but were decided against for the design of the musical extracts for the pilot study, for the following reasons:

- *The extracts will consist of a single melodic excerpt as opposed to a harmonic one as this is a simpler parameter to control for. Therefore in pianists this will be the music written for the right hand as this is usually the more melodic rather than rhythm keeping of the two. This was decided against as it was desired that gobbets that are presented simulate real situations and stimulate "real" responses and creative impulses in participants***.**
- *Possibly present the same extract but in different keys. This was discarded as pianists will find it strange to be given a piece that to them is quite obviously written to be in a specific key (on advice from Richard Dickens). This might have repercussions in perception cognition.*
- *Possibly present the extract in the same key but change the rhythmic patterns and tempos. This was discarded for the same reason as above.*
- *Being aware of the rate of harmonic change when choosing the extracts. This was discarded as was thought to be unnecessarily complicated for the sake of presenting a non-biased selection of extracts.*

- Neuroscientific factors we considered when choosing extracts:
    - Preferably unfamiliar piece (in consultation with syllabus assessors). This is to try and avoid too much role of recognition and long term memory in any brain activity pattern observed. Also if the subject has worked upon a piece before they are more unlikely to have a flash of inspiration or insight. Rather than show the participant all the extracts before the study to ask familiarity (there will be a practice effect otherwise), this is done throughout the study, and they are asked to flag anything they find familiar.
    - All pieces are from a wide range of time from 15th century to modern day. However, they are still recognisably from the same sound world.

2.4 Experimental Protocol

2.4.1 Pilot study-Version 1

In this section, we describe the protocol used for our pilot study along with brief explanations as to why certain choices were made. What follows is a step-by-step guide that one should be able to follow to carry out the experiment:

1) Subjects were presented extracts in the same settings with the same instructions on a computer screen. A computer program was written to automate all extract and instruction presentations and superimpose the timings of these and any midi information from the keyboard onto the EEG recordings simultaneously as markers. This was so that it would be a very accurate time division of the different tasks, during analysis of the EEG.
2) Subjects were first presented the gobbet of musical extract to look at.
3) With this first protocol we reasoned that as we are examining brain activity at different stages of creativity it would be valuable to break up the stages. Consequently, four instructions (see a,b,c,d below) for each individual subject would be presented for a short while and then the presentation of just the musical extracts will be resumed:
    a. Play the extracts exactly as presented.
    b. Interpret the extracts suggesting being mindful of dynamics (emotional conveyance), tempo and "phrasing and articulation" (slurring). This stage is to investigate an "interpretive" creativity.
    c. Change the musical extracts with respect to only one dimension at a time as instructed (these will be in random order) i.e. with respect to:
        - Technical aspects
            i. tonality,
            ii. rhythm.
        - Leaning more towards improvisation (these are investigating the different structural components of music cognition itself, and to look at the adventurousness of each change).
            i. motivic patterns,
            ii. number of notes,
            iii. melodic contours

   d. Freely improvise for 4 bars as at least in western classical music, 4 bar phrasing is instinctive. This stage is to investigate a "compositional" creativity.

4) For each instruction, the subject is presented with just the score for 2 seconds and then given a further 3 seconds to think about the instruction that is presented on the screen simultaneously with the musical score and 8-9 seconds to perform (in the computer program this will range from 8-9 seconds so as to reduce an "anticipation" EEG signature, and therefore a random number generator will be used for the variation in time). For the instruction of "freely improvise", the subject will be given 15 seconds (the "preparation" stage of creativity) and given at most 20 seconds to perform.
5) Participants were put through a practice run with two extracts that were not included in the actual experimental run.
6) The time taken to present the full protocol per extract is approximately 130 seconds. Therefore taking into account some breaks between each extracts, with 30 extracts, the whole protocol will take approximately 70 minutes. In addition to this, the setting up of the EEG equipment before and after will be approximately 30 minutes in total. 10 minutes for a practice run through to make sure the subject understands what is expected from them. Therefore total run through would be approximately 110 minutes.
7) There are two types of control here:
   a. A within subject control- when the subject is asked to play the extracts exactly as presented.
   b. A between subject control- different musicians asked to do the same protocol with the same musical extracts in common.

2.4.2 Pilot study-Version 2

Version 1, above was run a couple of times and after feedback from Richard Dickens and a couple of test participants, the protocol was revised to make it clearer, and more elegant.

In particular there were changes in instructions such that:

1. The manipulation stages were preceded with the words "in an improvisatory way"
2. The "Rhythm" instruction now includes the motivic pattern instruction by the addition " you may wish to consider dotted rhythms" so as to avoid an extra instructional stage as musicologically, *rhythm* encompasses *motivic patterns*.

3. The "Tonality" instruction is now clearer with the addition of "i.e. major or minor" and a verbal instruction of "don't worry if you conceive it to be neither as in the case of some modern pieces. You can introduce tonality for example".
4. The "Melodic Contour" instruction is clearer with the addition of " i.e. changing the visual shape of the extract e.g. ascending to descending or vice versa".
5. The "Number of notes" instruction is now clearer with the addition of "more or less notes within the basic phrase structure".
6. A "Time signature" instruction was also included in addition to the "Rhythm" instruction and was worded " Please change the time signature or implied time signature making sure to keep the same phrase structure and number of notes".
7. The "Freely Improvise" instruction was changed to "freely improvise on some element of this extract".

The revised instructions for section 3 of Version 2, were thus:

a. Play the extracts exactly as presented.
b. Interpret the extracts suggesting being mindful of dynamics (emotional conveyance), tempo and "phrasing and articulation" (slurring).
c. Change the musical extracts with respect to only one dimension at a time as instructed (these will be in random order) i.e. with respect to:
    - Technical aspects
        iv. tonality i.e. major or minor-don't worry if you conceive it to be neither as in the case of some modern pieces. You can introduce tonality for example,
        v. rhythm (you may wish to consider dotted rhythms).
        vi. time signature or implied time signature making sure to keep the same phrase structure and number of notes
    - Leaning more towards improvisation (these are investigating the different structural components of music cognition itself, and to look at the adventurousness of each change).
        i. number of notes i.e. more or less notes within the basic phrase structure,
        ii. melodic contours i.e. changing the visual shape of the extract e.g. ascending or descending or vice versa
d. Freely improvise on some element of this extract.

Importantly, section 4 in the experimental protocol was changed such that when the instruction is presented there is **no fixed time for thinking.** The participants, were allowed freedom to start playing whenever they liked and **continue playing at their own pace** instead of having to finish playing in a period of time. This increased the full running time of the protocol to a maximum of 4 hours.

Finally, version 1 was also pruned to be less-time consuming as this has a detrimental affect on the quality of the cognitive activity measured. The number of extracts were cut down from 30 to 20 because some were too hard for participants to sight read. All were asked to rate the difficulty of the extracts post-experiment. Below is a summary of the extracts used including any practice extracts:

Time Signature	
4/4	5
2/4	4
3/4	2
5/4	
6/8	3
3/8	2
12/8	1
4/8	1
2/2	1
6/4 or 3/2	1
9/8	1
5/8	

Number of Flats/Keys	
None (sharps or flats)/ C Major	3
One / F Major or D Minor	2
Two/ B Major or G Minor	2
Three/ E flat Major or C Minor	1
Four/ A flat Major or F Minor	
Five/ D flat Major or C Minor	1

Number of Sharps/Keys	
One/ G Major or E Minor	3
Two/ D Major or B Minor	4
Three/ A Major or F# Minor	1
Four/ E Major/C# Minor	3
Five/ B Major/G# Minor	1

Table 2.1 A table displaying the tally of the extracts (20 experiment and 1 practice) that contained different time signatures and keys.

2.5 Summary

In this chapter we outlined the stages required to process and clean the signals of the EEG data recorded. The initial steps were simple referencing and filtering (low band-pass at 0.5Hz and notch fitering at 50Hz) followed by the more arduous task of artefact removal by eye. This was aided by running an ICA algorithm that allowed separation into the different components contributing to all 64 waveforms collected at the electrode locations. The components for artefacts such as eye blinks and saccades, and jaw clenches are particularly prominent due to the use of external electrodes positioned at the eyes and the mastoids. These aid the algorithm, returning stronger components. Any residual mains electricity interference can also be detected after running the ICA, on examination by eye of the very distinctive power spectra corresponding to the component. In addition, malfunctioning or drifting electrodes can also be detected readily by examining the waveforms of the components themselves. More subtle muscle contractions and artefacts are more spread out amongst the components and are more difficult to characterise and subsequently remove.

We subsequently outlined how we chose participants and musical extracts for the pilot study and the accompanying several considerations.

Finally, we outlined the different instructions as a step by step protocol of the experiment along with any modifications to version 1, to present version 2 with 10 fewer musical extracts of a total of 20.

3. ANALYSES AND RESULTS OF PILOT STUDY

We tested out a few possible measures on the dataset collected in the pilot study and in this chapter we will outline these analyses and the subsequent development of the 'Experimental Protocol Final Study' and its chosen analyses.

3.1 Correlation

One of the most common analyses performed on EEG data, is that of the simple cross-correlation function. In the instance of EEG, cleaned voltage data recorded from each of the 64 electrodes can be thought of as 64 random processes.

A random variable X by definition is a function of the possible outcomes x_i of an experiment and when this is expanded to include time it is called a random process.
The first-order density of a random process is defined as

$$f_x\,(x_1;t_1). \tag{3.1}$$

In this instance, the EEG signals we are measuring at the scalp can be likened to random processes. If we were to assume that they were stationary (i.e., the probability distribution does not change with time) and were to perform simple correlation functions on the raw scalar voltages then the following are some properties to keep in mind.
An expectation value of a function is defined as

$$E[X(t_1)] = \int_{-\infty}^{\infty} x_1 f_x(x_1;t_1)dx_1. \tag{3.2}$$

If, the random process is stationary, that is,

$$f_x\,(x_1;t_1) = f_x\,(x_1;t_1 + \Delta), \text{ for all } t_1 \text{ and } \Delta \tag{3.3}$$

then, the expectation value is time-independent

$$E[X(t_1)] = E[X] = \text{constant}.$$

A second order density function is defined as

$$f_x(x_1,x_2;t_1,t_2). \tag{3.4}$$

An auto-correlation function of a random process X(t) in general, is the expectation value $E[X(t_1)\,X(t_2)\,]$ of the process at times t_1 and t_2 and can be denoted as $R_{xx}\,(t_1, t_2)$:

$$R_{xx}\,(t_1, t_2) = E[X(t_1)X(t_2)], \tag{3.5}$$

where

$$E\,[X(t_1)X(t_2)] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x_1 x_2 f_x(x_1,x_2;t_1,t_2)dx_1dx_2. \tag{3.6}$$

If, the random process is stationary to second order, that is,

$$f_x\ (x_1 x_2; t_1, t_2) = f_x\ (x_1, x_2; t_1 + \Delta, t_2 + \Delta) \text{ for all } t_1,\ t_2,\ \Delta \tag{3.7}$$

then

$$R_{xx}\ (t_1,\ t_2) = E[X(t_1)X(t_2)] = E[X(t_1+\Delta)X(t_2+\Delta)] = R_{xx}\ (t_1+\Delta,\ t_2+\Delta). \tag{3.8}$$

The auto-correlation function is one of time differences and not absolute time; in other words it is stationary. This can be seen by setting $\Delta = -\ t_1$. Therefore if $\tau = t_2 - t_1$ then

$$R_{xx}(t_1,\ t_1+\tau) = E[X\ (t_1)X(t_1+\tau)] = R_{xx}(0,\tau), \tag{3.9}$$

is a function of τ only.

Now, if we turn our attention to two independent random processes which would correspond to the raw voltage values recorded at two different channels on the scalp:

The joint possibility probability density function is denoted by

$$f(x,y)\ . \tag{3.10}$$

A cross-correlation function of two random processes X (t_1) and Y(t_2) is defined as

$$R_{xy}\ (t_1,\ t_2) = E[X\ (t_1)Y(t_2)] \equiv \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} xy\, f(x, t_1; y, t_2)\, dxdy\ . \tag{3.11}$$

The cross-covariance function for two processes X(t_1) and Y(t_2) is defined by

$$C_{xy}(t,\ t+\tau) = E[(X(t) - E[X(t)])(Y(t+\tau) - E[Y(t+\tau)])]$$

$$= E[X(t)Y(t+\tau) - X(t)E[Y(t+\tau)] - E[X(t)]Y(t+\tau) + E[X(t)]E[Y(t+\tau)]]$$

$$= E[X(t)Y(t+\tau)] - E[X(t)]E[Y(t+\tau)]$$

$$\equiv R_{xy}\ (t,\ t+\tau) - E[X(t)]E[Y(t+\tau)]. \tag{3.12}$$

For this project, correlation functions on the raw scalar voltages were done first so as to have as minimal pre-analysis manipulation done to the data as possible and to elucidate any patterns at the top-level. As the correlation functions will be integrals, they should be matching signals over a prolonged period of time thus generally including phase, frequency and amplitude information when trying to ascertain correlation.

In practical calculation, for EEG data from two electrodes x and y, the following cross-correlation equation was used (which is the same as (3.12) but normalised wrt to standard deviation) :

$$r_{xy} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2}\sqrt{n\sum y_i^2 - \left(\sum y_i\right)^2}} \in [-1,1]. \qquad (3.13)$$

If X and Y are independent then

$$f(x,t_1;t_2) = f(x,t_1)f(y,t_2). \qquad (3.14)$$

Therefore this implies that

$$\begin{aligned} R_{xy}(t_1,t_2) &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} xy\, f(x,t_1;y,t_2)\,dx\,dy \\ &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} xy\, f(x,t_1)f(y,t_2)\,dx\,dy \\ &= \int_{-\infty}^{\infty} x\, f(x,t_1)dx \int_{-\infty}^{\infty} y\, f(y,t_2)dy \\ &= E[X(t_1)]E[Y(t_2)] \end{aligned} \qquad (3.15)$$

Therefore substituting (3.11) and (1.12) will give

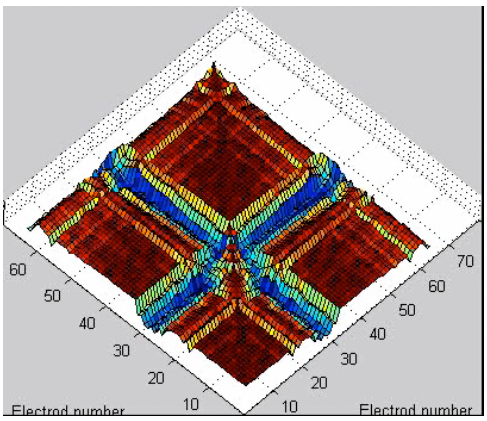
$$R_{xy}(t, t+\tau) = E[X(t)]E[Y(t+\tau)] \qquad (3.16)$$

Implying $C_{xy}(t, t+\tau) = R_{xy}(t, t+\tau) - E[X(t)]E[Y(t+\tau)] = 0,$ (3.17)

when two random processes are statistically independent and uncorrelated. However, it is important to note that uncorrelated processes are not necessarily independent.

3.1.1 Correlations in pilot study dataset.

A matrix of size 64 by 64 was created to represent cross-correlations between each combination of pairs of electrodes along a sliding time window of 50ms and a time difference τ of 25ms. This was then visualised in a colour grid and a polar plot that was collated into a movie for each subject and conditional task ('Play', 'Interpret' or 'Improvise'*).* Red indicates a positive correlation (the more intense the red, the closer it approaches 1), blue indicates a negative or anti-correlation (the deeper the blue, the closer it approaches -1) and pale yellow/green indicates uncorrelated but not necessarily independent pairs (i.e. the correlation value is close to 0):

(a) 

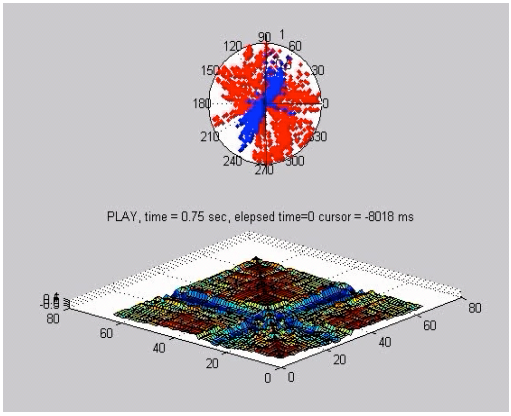
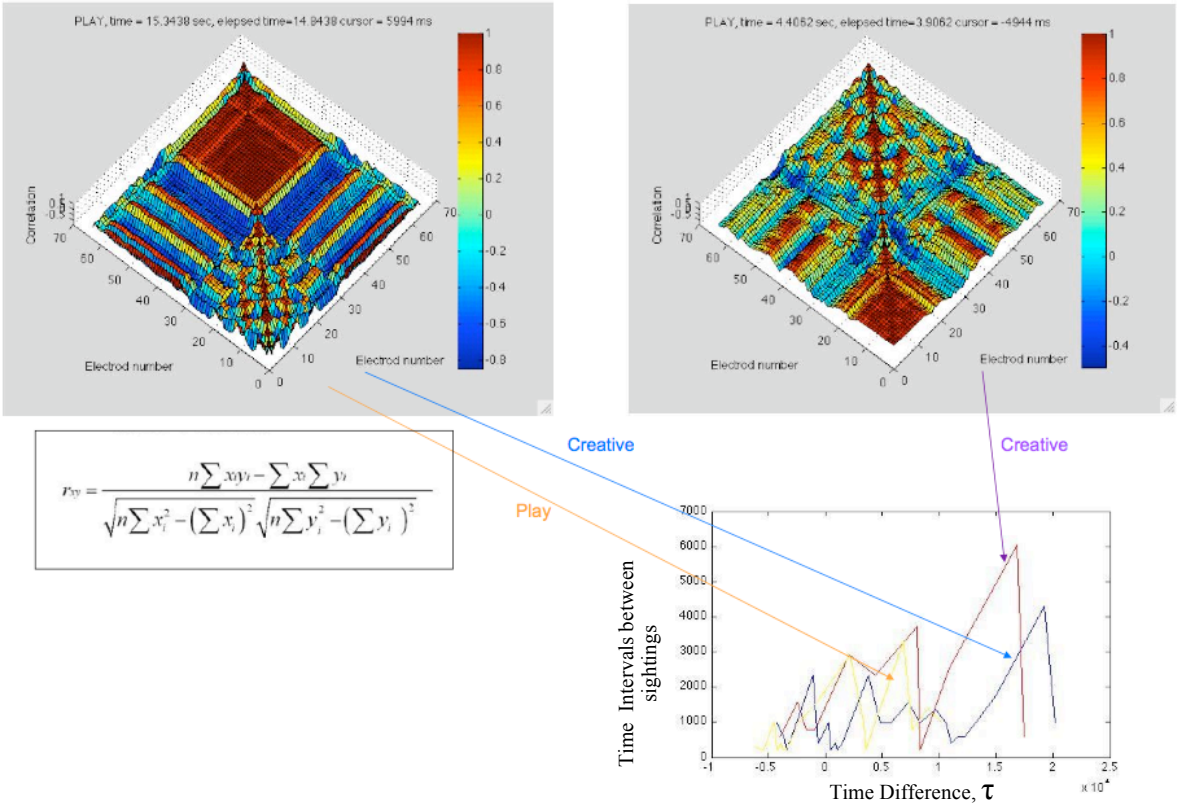
(b) 

Figure 3.1 64x64 matrix of cross-correlations of raw voltage data between 64 electrode channels a) an example of a colour grid representation of 64x64 cross-correlation in one instance in time (over 50ms) (b) A still from a movie done with a sliding time window of 25ms with a concurrent polar plot to have a different visualisation that allows an easier detection of total hemispheric or full brain correlation (approaching 1) or anti-correlation (approaching -1).

The aim was to detect any signature patterns in the cross-correlations over time, taking into account temporal dynamics. On qualitative observation, there seemed to be sudden and frequent occurrences of total correlation (approaching 1) and total anti-correlation (approaching -1). By eye it was observed that there were two striking patterns observed frequently where there would be a concurrent full hemispheric integration of total correlation and the opposite hemisphere being disintegrated with waves of correlation and anti-correlations, see figure 3.2. Through an initial observation by eye of the EEG of a single subject, it was possible to detect that these patterns were present more frequently during tasks of 'Improvisation' and 'Interpretation' than in the task of 'Play'.

Though this was promising particularly due to the implication that interhemispheric integration and disintegration were correlated as implied by Braun *et al.*'s study (2012), it was untenable to continue this for the full dataset without automation. An attempt at automated pattern detection was done via formulating a 'distance algorithm' where the distance was measured between each full set of correlations to the ideal set of values of correlations corresponding to the above patterns. Unfortunately this was unsuccessful, as the range of values was wide both for the full interhemispheric correlations and the ridge patterns of correlation vs anti-correlation. They also seemed relative to each other such that it was possible to detect the above pattern visually but with no absolute values it was difficult to get a reliable automated detection. This would have required a great deal of algorithmic refinement to detect a very specific pattern (i.e., no pattern recognition algorithms were

already present for use) and in the end it was decided that the aim of the PhD was not pattern recognition or detection, but rather to be able to characterise a wide picture of musical creativity. However, the occurrences of total correlation were explored further using overall phase synchrony and a possible scale invariance (which will be discussed in the next section).



$$r_{xy} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2}\sqrt{n\sum y_i^2 - \left(\sum y_i\right)^2}}$$

Figure 3.2 Two correlation grids showing two distinctive patterns such that the grid to the left shows a right hemispheric integration with correlation values approaching 1 (denoted by the upper quadrant of the correlation grid) that was more prevalent during 'Improvisation'. The grid to the right shows a left hemispheric integration (denoted by the lower quadrant of the grid) and is a pattern that was more prevalent during 'Interpretation'. The frequency and time intervals between sightings during the task of 'Play' is also marked in the graph below the two grids.

3.2 Phase Synchrony and Perseverance

The connectionist theory points towards long-distance phase synchronisation being the mechanism for the transient formation of a coherent macro-assembly that selects and binds multi-modal networks, such as assemblies between different lobes or across hemispheres which are separated by dozens of milliseconds in transmission time [Thompson *et al.*, 2004].

Phase synchronies occur in a broad range of frequencies that allows not simply the binding of sensory attributes but the overall integration of some dimensions of a cognitive act including associative memory, affective tone and emotional appraisal, and motor planning

important for musical creativity and performance [Damasio 1990, Varela 1995, Varela, Rodrigues and Martinerie 2001].

Long-scale integration establishes dynamic links but active dismantling is also important in order to make way for the next cognitive moment, i.e., desynchronisation or phase scattering. This seems to be supported by the pattern of the Correlation grids observed above and concurrently the connectionist theory points towards whole networks of neurons working together not just locally. It also points towards networks of thoughts and towards networks underlying models of behaviour. How these networks form from moment to moment, i.e., the study of phase synchronisation and its complexity spatially and temporally could be the key to different structural frameworks of mental paradigms.

Even with reduction of all artefacts and other signal processing, real raw EEG data is unlikely to be periodic and noiseless and not a contender of phase estimation by linear interpolation. This is because what is measured at the scalp is a mixture of outputs from many oscillators from within the brain, partly due to volume conduction.

Therefore, for the phase estimation of narrow band EEG, a Hilbert Transform is recommended after first applying the analytic signal concept [Gabor, 1946]. The whole process involves changing the scalar signal to a complex one and the Hilbert Transform amplifies local (in time) signal information so that instantaneous amplitude and phase can be calculated. The complex signal is:

$$x(\mathrm{t}) + jx^{H}(\mathrm{t}) = \mathrm{A(t)e}^{\mathrm{j}\varphi\,(\mathrm{t})}\,, \tag{3.18}$$

where x is the scalar signal, x^{H} is the Hilbert transform, A(t) is the instantaneous amplitude and φ is the instantaneous phase.

The phase, φ, can be extracted from the following equation:

$$\varphi(t) = \arctan\left(\frac{x^{H}(t)}{x(t)}\right). \tag{3.19}$$

Phase synchrony is a common tool used in the EEG community but for the purposes of our analysis, we have modified how it is used slightly. To calculate the phase synchrony between two time-series, I and k at time t (i.e., two electrode recordings), the phase difference between them is calculated. This is otherwise known as pair-wise phase synchrony.

$$\Delta\varphi_{ik}(t) = \varphi_{i}(t) - \varphi_{k}(t) \quad (i,\ k = 1, 2, \ldots, 64) \tag{3.20}$$

We calculated the average pair-wise synchrony, R(t), over all N= (64x64)/2 pairs as defined as:

$$R(t) = \frac{1}{N} \sum_{\substack{i,k=1 \\ i<k}}^{64} e^{j\Delta\varphi_{ik}(t)} \quad . \qquad (3.21)$$

This plot was then thresholded to examine the periods of time in the top quartile (25%). This was entitled 'perseverance', and it was logged how many 'perseverance' periods occurred above this top quartile threshold along the time series for the different conditions of 'Interpret' and 'Improvise':

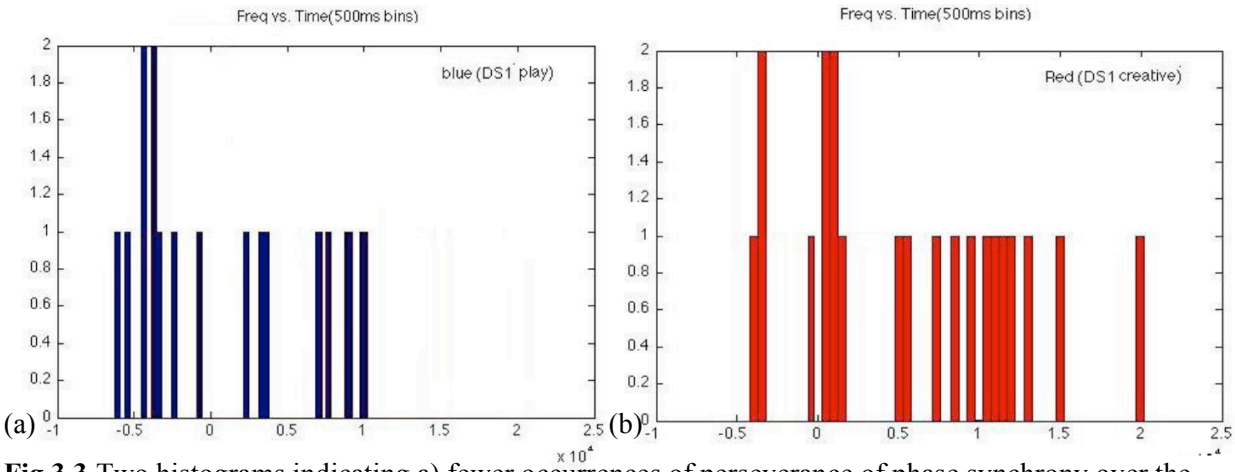


Fig 3.3 Two histograms indicating a) fewer occurrences of perseverance of phase synchrony over the threshold during the condition of 'Play' than for b) the condition of 'Improvisation'. These also support higher incidence of the right hemispheric integration pattern observed in the Correlation grids in figure 3.2.

The duration of the time period 'persevered' over the threshold in phase synchrony was also measured for the two conditions and these periods spanned two orders of magnitude in timescales which indicate a degree of scale invariance through a possible observed power law, though due to the sample resolution being only 512 Hz, there weren't enough data points in smaller time periods to be able to scale three orders of magnitude and get enough detail in the tail to calculate a defined exponent. This possible tendency towards a scale invariance in total pair-wise phase synchrony could be a putative characterisation to the instances of observed overall total correlation observed in the correlation grids above.

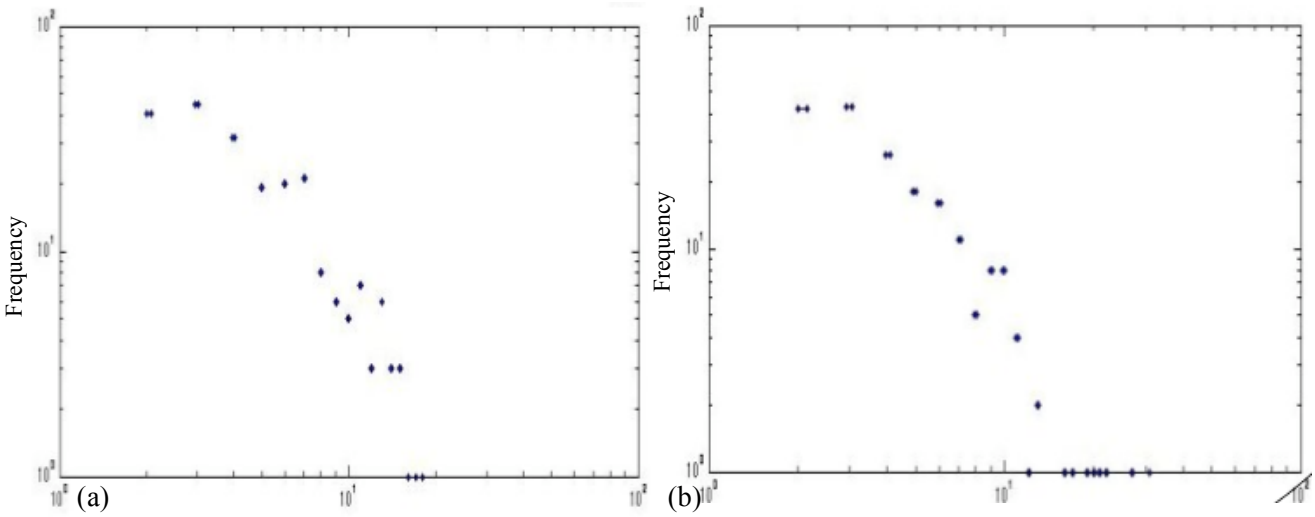


Fig 3.4 Two log scaled plots with the y-axis signifying 'frequency' and the x axis the time duration 'persevered' above the threshold. (a) This is the plot for the condition of 'Play' and (b) is the plot for the condition of 'Improvisation' which shows a slight tendency toward a fatter tail.

3.3 Summary

In this chapter we outlined cross-correlation and phase synchrony methods used in an attempt to investigate a global state of the brain during the creative states of 'Improvisation' and 'Interpretation' as compared to the resting baseline state of 'Play'.

The cross-correlation grids indicated intra-hemispheric integration that corresponded to the different types of creativity such that 'Improvisation' indicated a right hemispheric integration and 'Interpretation' indicated a left hemispheric integration as these patterns appeared more frequently during these musical cognitive tasks than the resting state of 'Play'. Though the hopeful beginnings of a characterisation, without a systematic screen through all the extracts in an automated fashion, the patterns only remain as a possible indication as to global integration during a musical creative task. In addition, due to the nature of the recordings and the cross-correlation function itself, any scalp volume conduction between local electrodes would appear as a spurious correlation and could contribute to an entire hemisphere appearing correlated.

Taking the global integration indication further with phase synchrony and time spent globally synchronised, there were higher incidences of global synchronisation above a threshold of 75%, during 'Improvisation' tasks rather than the resting state of 'Play'. Investigating the actual duration of time 'persevered' above the threshold, revealed a possible power law with a tendency towards a fatter tail for the musical task of 'Improvisation' rather than 'Play', putatively suggesting a scale invariance. This was only calculated over two orders

of magnitude in time scale and warrants more investigation by modifying the experimental data collection to have a time resolution of 1024 Hz.

The results of the pilot study though suggestive of greater brain activity integration during creative tasks, were not conclusive and helped narrow our research question for the final study as described in Chapter 4.

4. EVOLUTION TO PROTOCOL - FINAL STUDY

The pilot study was too complicated for the essential question of creativity that we were trying to ask, and the analyses as described above were mainly done on the *Improvisation* and *Interpretation* sections, so in an attempt to simplify further and inadvertently make it more elegant, in the final study we focussed on just these two manipulations rather than *rhythm, melodic contour* etc. as well.

The results of the pilot study data analyses, though implicative were not significant or conclusive enough. So it was in the final study that we really brought the 3-pronged approach into practice by introducing the self-rating and the judges rating. This improved the experiment by simultaneously avoiding the definition of creativity but pinpointing its existence through an investigation of agreement within judges assessments and between self and judge ratings. This was hopefully reflected in the EEG recordings such that 'creative' signatures were brought into sharper relief.

In this section, we will describe the refinement of the pilot study and its protocol into the final study which was extended to include the exploration of Jazz music and jazz musicians as participants.

The idea was to give each type of musician their own ecologically valid musical excerpts and ask them to perform the same sets of creative manipulations on them: interpret and improvise. The classical pianists are not normally asked to perform improvisations (although there are certain western composers that have this in their pieces) so this might be out of their comfort zone but it is important to be able to compare them equally in the same task to the jazz musicians. From experience of five classical pianists and the pilot study, they do not seem fazed by this request.

In the same vein, it would be necessary to include the task of interpretation for the jazz pianists to be comparable to the equivalent task for classical musicians. A creative task might not be normally so rigidly defined for jazz pianists although they would be used to sticking to some defined parameters improvising on jazz standards.

Each type of musician is also given extracts from the others genre and asked to perform both types of creative tasks: interpret and improvise. In this way the total musical extract set is divided half into classical and half into jazz.

The extracts were presented in a manner that would be readable, accessible and comfortable for both jazz and classical musicians where each extract will display chord symbols along the

top of the extract and will also include a melody line in both hands which is based on the same chords. All extracts were again standardised by Sibelius to maintain a consistency for visual perception. The idea was to present the same visual stimuli but the classicists will probably prefer to play the more laid out complex melody whilst the jazzists focus on the chords. The actual melody lines will be a mixture of jazz composition and "simpler" classical composition (mixture of 2/4, 3/4, 4/4, 6/8) extracts and both with varying keys and time signatures etc. as before. To maintain the unfamiliarity of music, the jazz extracts were freshly composed just for the study by Neuroscientist/Bassist Peter Vuust (Professor at the Royal Academy of Music, Aarhus, Denmark, Associate professor in Cognitive Neuroscience at the Centre of Functionally Integrative Neuroscience (CFIN), Aarhus University Hospital) who laid down a basic chord progression outline and a more prescribed/complex right hand melody which was then modified by Composer/Pianist Matthew Lee Knowles to include dynamics (such as getting louder, slower etc) understandable for classical pianists and the classical metre notation for the two most commonly found rhythms in jazz: *Swing* and *Even Eighths.* Matthew also added chords to the classical extracts included in the study so as to make these more adapted for jazz pianists and finally he standardised all extracts with Sibelius.

4.1 Screening of participants for final study

Eight participants were screened for level of musical education, mental disorders with 4 males and 4 females and classical to jazz expertise. They underwent EEG recording at 1024 Hz with 64 electrodes in the 10:20 Biosemi system whilst being presented with 20 musical extracts via the experimental protocol below.

4.2 Musical extracts chosen for final study

- A range of 20 short extracts (4 bars) in only a visual form, i.e., the musical score.
- They comprise a mixture of keys, tonalities (major and minor) and tempos in a variety of rhythms (2/4, 3/4, 4/4, 6/8), motivic patterns, number of notes and melodic contours.
- Ten unfamiliar classical pieces (in consultation with syllabus assessors) and ten freshly composed jazz pieces.

(a)

(b)

Figure 4.1 Classical extracts with Jazz chords. (a) With expression for interpretation. (b) Without expression for play (see instruction 1) and improvisation.

.

(a)

(b)

Figure 4.2 Jazz extracts with chords and accompanying melody. (a) With expression. (b) Without expression.

4.3 Experimental protocol for final study

The aim was to look at brain activity during different types/stages of musical creativity and this is reflected in the experimental protocol.

What follows is a step-by-step guide that one should be able to follow to carry out the experiment:

1) Participants were presented extracts in the same settings with the same instructions on a computer screen. A computer program was written to automate all extract and instruction presentations and superimpose the timings of these and any midi

information from the keyboard onto the EEG recordings simultaneously as markers. This was so that it would be a very accurate time division of the different tasks, during analysis of the EEG.

2) Participants were first presented the gobbet of musical extract to look at.
3) There are essentially 3 different instructions; when an extract is presented, the order of instruction was 'a', 'b' or 'c' (randomized), then 'a' as a return to base line:
    a. Play without expression (just the bare notes exactly as presented so this instruction is a base resting state-verbally described to participants as "expressionless or even boring").
    b. Interpret with expression and dynamics (tempo, dynamics, i.e., emotional conveyance and volume, ornamentation, articulation and phrasing, "note inegale" such as double dotted notes, i.e., "swing" and "even eights" in jazz parlance, as written by composer and interpreted by player).
    c. Improvise freely (freely improvise on the extract, or part thereof). This is to investigate a "compositional" creativity.
4) For each instruction, the participant is presented with just the score for 4 seconds and then given fixed times to just think (11 seconds for instruction 'a' and 16 seconds for Interpret and Improvise) about the instruction that is presented simultaneously with the musical score and then left to physically play the extract in the time they would naturally take to finish without being rushed.
5) After the completion of instruction 'b' or 'c' the subject is asked to rate their own creativity subjectively via pressing 1 of 5 keys in the lowest octave on the keyboard itself that correspond to a rating (outlined in the point below). Subsequently, the performances are listened to by musical judges and along with the participants use the ratings scale of 1-5 (1 being very poor, 3 being ambivalent, 5 being excellent). The form of acquisition of judges ratings will be outlined in the section 4.5.
6) Participants were put through a practice run with two extracts that were not included in the actual experimental run.
7) The time taken to present the full protocol per extract is approximately 70 seconds not including the time it takes to play any of the instructions. Therefore taking into account, playing (ranging between 40-90 seconds), some breaks between each

8) extracts, with 20 extracts, the whole protocol will take approximately 40-60 minutes. In addition to this, the setting up of the EEG equipment before and after will be approximately 30 minutes in total. 5 minutes for a practice run through to make sure the subject understands what is expected from them. Therefore total run through would be approximately 75-95 minutes, which at its lowest range is half the time of the original pilot study protocol. This was seen as a significant improvement on the quality of cognitive activity measured as participants would be more focussed on the tasks at hand and less tired.
9) There are three types of control here:
    e. A within subject control- when the subject is asked to play the extracts without expression, 'a', as a baseline.
    f. A between subject control- different musicians asked to do the same protocol and the same musical extracts in common.
    g. The Self and Judges Creativity assessments

There was also a further behavioural experiment conducted to illuminate further the incubation period in creativity where the role of conscious and unconscious, focused and defocused attention on musical creativity were examined. Specifically, subjects are given a musical "task" and then subsequently asked to do something different and distracting before coming back to the musical task. This will be described in more detail in Chapter 6.

4.5 Acquisition of judges assessments

Judges were sent out a marking form with the visual score of each extract to refer to and an audio CD with all eight participants' performances to listen to in the same randomised order (interpret and improvise tasks), as was presented to the participants themselves. They were also given the same rating scale as the participants and asked to be fairly instantaneous with their "gut feeling" as there was only a 7 second gap between each audio performance on the CD. Below is the first page with accompanying supplementary notes to the assessors along with an example of what they were asked to do:

Dear Assessor,
Thank you for agreeing to take part in this research. Your participation is invaluable to the success of this innovative research. When we have concluded the project we would be delighted to invite you to a presentation of how your contribution fits into the wider context of our project.

The task is to assess the performances that you will hear on the accompanying audio.

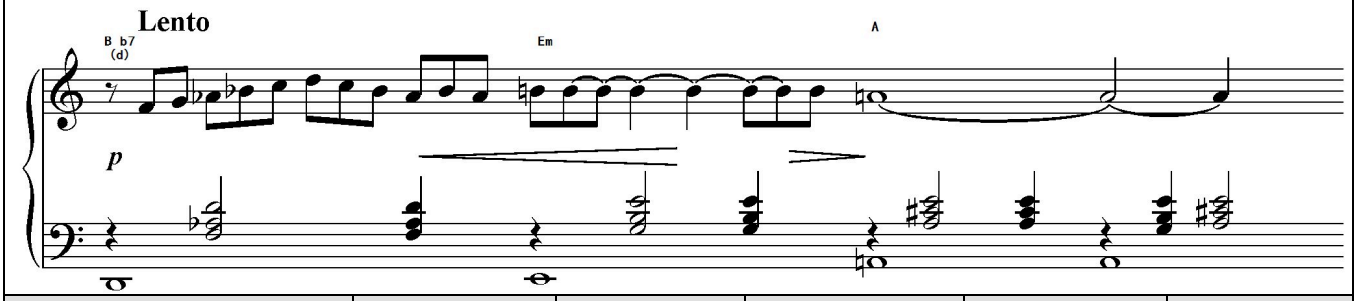
The score for each extract (either classical or jazz) will be presented visually to you but you will hear each extract being played as per two instructions given to the subject:

1. '*Please interpret this extract using the composer's markings included'*
   (shortened in the tables below as "Interpreting")
2. '*Freely improvise on this extract (or a part thereof)'*
   (shortened in the tables below as "Improvising")

For "freely improvise", the participants were told that there had to be something audially recognisable that linked their improvisation to the original extract. The order of these instructions are randomised in the experiment and you will hear a voice clearly indicating the sections as either "Interpreting" or "Improvising".

A voice will then ask you to rate the creativity of the subject either interpreting or improvising - you will be given a moment to do this,alternatively you may wish to pause if longer needed. Please rate creativity on a scale of 1(very uncreative) to 5 (very creative) by ticking the appropriate box as indicated by the following example table:

Extract 1:



Creativity ratings *Was the subject creative when*	**1** v. uncreative	**2** uncreative	**3** ambivalent/neutral	**4** creative	**5** v.creative
Improvising	√				
Interpreting				√	

Please attempt to complete one participant assessment per sitting (approx 20 min) in order to maintain consistency of assessment. Please be aware that external stimulants/factors i.e. coffee/alcohol, time of day could have a significant effect on your perception/partiality.

Note that the emphasis of this assessment is on creativity rather than accuracy and that the participants are from a diverse background ranging from classical and contemporary to jazz. All have sight-reading ability but will tend to interpret and improvise on the score according to their education.

Thank you very much for your time,

Shama Rahman

4.6 Summary

In this chapter we outlined the protocol used for the final study. It is the results of this study that will be presented and discussed from this point forward in the thesis.

The final study was modified to include 10 Jazz extracts and the Classical extracts were also reduced down to 10 from the pilot study, presenting eight participants with a total of 20 extracts which were as varied and unfamiliar as those of the pilot study to avoid bias or the role of memory.

The experimental protocol for the final study was simplified into only three instructions of the resting state 'Play', and the creative tasks of 'Improvise' and 'Interpret', with the 'Play' instruction being presented twice in between the creative task to return participants back to a baseline so as not to bias consecutive creative tasks. Both creative tasks were presented in a randomised order to avoid a practice effect.

An additional feature of the protocol was the acquisition of ratings both from the participants as soon as they had performed each creative task and from external judges using a marking form and an audio CD that presented the extracts and instructions in the same order as within the experiment to replicate conditions avoid bias. They were asked to assess using the same rating scale of 1 to 5 with the same question of 'How creative did you think that was?'.

5. FINAL STUDY: ASSESSMENTS ANALYSES AND sLORETA

In this chapter we will outline, the results of our 3-pronged final study by first presenting the analyses on the performance assessments made by the participants and external judges. This will be followed by the results of the sLORETA analyses, highlighting the main areas of the brain involved in the different conditions of 'Play', 'Interpret' and 'Improvise' and their associated 'Think' tasks. In the final section, we will present sLORETA analyses informed by the assessments (participant and judge), in particular looking at the differences in brain activity between Creative and Non-Creative extracts and whether the brain activity of Jazz pianists differ in their interpretations and improvisations from Classical pianists.

5.1 Assessments

One of the most important aspects of this study is the element of assessment-based ratings of the interpretational and improvisational musical outputs of the experiment. Previous studies have investigated various aspects of piano improvisation and accompaniment [Bengtsson *et al.*, 2007; Limb and Braun, 2008] and even spontaneous creative generation through verbal lyrical rapping [Braun *et al.*, 2012].

But none have compared and contrasted both Classical and Jazz piano music or investigated the neural correlates of musical creativity based on both subjective self-assessments and objective judges' ratings across a range of classical and jazz musicians comprised equally of both sexes.

Most recently there has been a study investigating fMRI brain activity of an all-female sample set from a music therapy course during a rhythm task [Villareal *et al.*, 2013]. Highly creative individuals were compared to lower creative individuals as assessed through SCAMPER, a tool used in the marketing industry. This study was restricted to tasks concerned only with rhythmic modifications as the authors reasoned that differences in brain activation between the higher and lower creative participants would be easier to decipher when examined with simpler tasks and assumed any regional similarities with previous studies would then be considered independent of melodic processing but would indicate a definitive association with creativity. While this is an astute choice for analytical purposes, it does not address the fundamental and comprehensive understanding of musical creativity, which by definition encompasses many more factors than just rhythm and inherently involves melody. One could even say that the melodic processing and feedback is fundamental to the creative musical process. Our experimental design has endeavoured to be true to real-life

ecologically valid scenarios and as a nod to ease of analysis has been narrowed down to focus on the topics of interest: “Interpretation” and “Improvisation”.

Furthermore, there are no universally accepted creativity tests, and the majority of functional neuroimaging studies have explored creativity using different methods of assessment to each other [Trefinger, 1986]. Villareal’s team used SCAMPER, which is a marketing tool that may or may not be relevant to assessing music.

In our experimental design, we circumvented the reliance on creativity tests through an open-minded inclusion of musicians’ opinions themselves on what constitutes creativity, as we as scientists are investigating their trade after all. On interview with advisor Richard Dickins, it transpired that during a musical performance, the realisation of whether one was in for a truly inspired performance was palpably ‘felt’ instantly by both performer and listener. Thence the idea arose that one should therefore simply ask the question: ‘How creative did you think that was?’, based on an instant gut or emotional judgement that should not be subjected to prolonged agonising or over-analytical thinking. If creativity was ‘felt’ by both performer and listener then why not ask the performing musicians themselves their self-evaluation and then external judges, their assessment based on the same ranking system of 1 to 5 (1 being very poor, 2 being poor, 3 being neutral or ambivalent, 4 being good and 5 being excellent). This would be a creativity assessment very tailored to the specific domain being explored by the experiment and would be more direct than other indirect creativity assessments that often measure types of thinking and exercise performances conducive to or that could be inferred to creativity (such as different uses of a brick), or aspects correlated with it such as ‘openness’, ‘emotionality’, ‘psychoticness’, etc.

The hypothesis was that if there was an agreement between all the judges (a minimum of 3 as per psychology standards) in their assessments, then we could explore the EEG-recorded brain activity associated with the different extracts that were deemed more or less creative by the judges. If there was an agreement with participants’ self assessments then this would complete a 3-way analysis.

We were conscious of the possible effect of the temporal evolution of a performance on the final overall evaluation of the performance submitted by both judges and participants. For example, a participant could rate his performance as ‘4’, based on how the initial section of the improvisation started out, or how well it went in the majority of the middle section or the rating could be based on a lasting impression of the ingenuity of the last few chords and notes. Any signature ‘creative’ EEG pattern would be linked to a specific region within the

performance rather than being present throughout. This was therefore explored by segmenting the EEG recorded during both interpretation and improvisation into 4s chunks during the initial, middle and end sections of performance. Four seconds was chosen as a duration of time that would include most extracts from all conditions as the performances of these varied in duration but the minimum length was 4s across conditions, see figure 5.1.

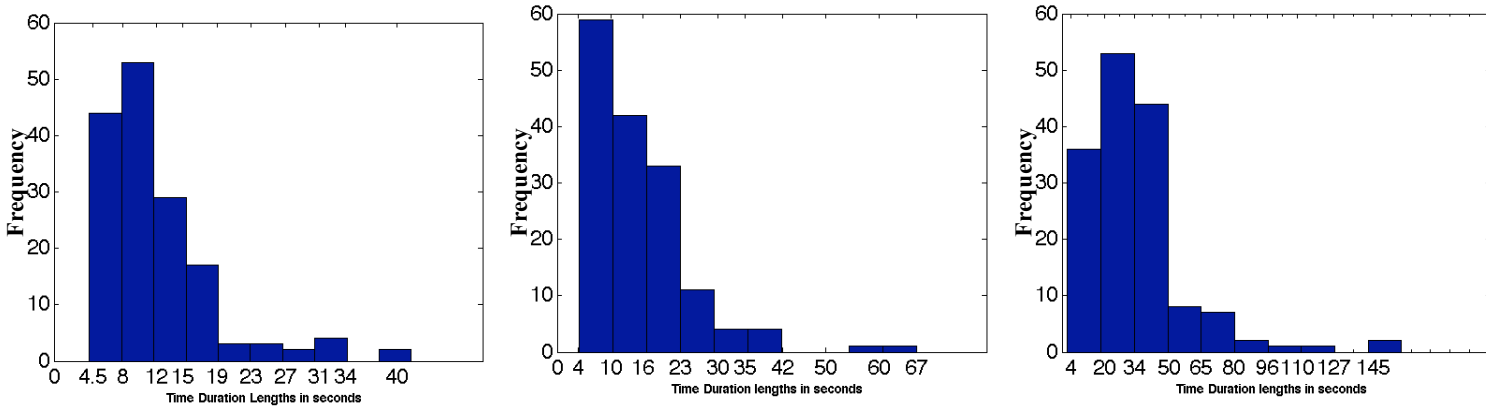


Figure 5.1. Histograms of the frequency of performance durations of the three conditions in the order of 'Play', 'Interpret' and 'Improvise'. Notice that for 'Improvise', there is a large variability of duration.

There were five judges in total: two from a Classical background and three from a Jazz background. The two classical judges comprised of Julian Jacobson who is the Head of Piano from the Royal College of Music and Phil Aslangul who is the Head of Surrey Chamber Choir and is a regular assessor for the Associated Boards. The three Jazz musicians were working professionals chosen on recommendation from Simon Purcell, Head of Jazz at Trinity College Of Music based on their high standing reputation as performers. These were pianists George Fogel, Liam Noble and flautist Finn Peters who has also previously worked on the interface of music and EEG for compositional purposes.

All of their assessments were collected via the Marking Form displayed in the previous section, Chapter 5, along with an accompanying audio CD of the participants' 'Interpreted' and 'Improvised' performances. Both were presented in the same randomised order that the participants were, in order to recreate as far as possible the same conditions.

5.1.1 Judges' assessments: Corrections

It was noticed that although there was overall agreement between judges for individual extracts, there might be a collective bias of the Jazz judges to be systematically harsher in their assessments.

Two Centres of Mass (CM) for the three Jazz judges and the two Classical judges, were calculated separately for the Classical and Jazz extracts, leading to a total of four values: CM(JJ), CM(CJ), CM(JC),CM(CC), where JJ depicts Jazz Judges' assessments for Jazz extracts, CJ depicts Classical Judges for Jazz extracts, JC depicts Jazz judges for Classical extracts and CC depicts Classical judges for Classical extracts, e.g.

$$CM(JJ) = \frac{\sum_{JJ} scores}{N_{JJ}} \tag{6.1}$$

where N_{JJ} is the total number of JJ assessments. These were then plotted as two co-ordinates (CM(JJ), CM(CJ)) and (CM(JC), CM(CC)), depicted by the stars in Figure 24 'a' and 'c' superimposed on the Classical and Jazz Judge scores for the separate batches of Classical and Jazz extracts. The deviance from the identity line (y=x), confirms that the Jazz judges were indeed marking harsher for both Jazz and Classical extracts.

The deviances were then corrected for in the Jazz judges in the separate batches of Jazz and Classical extracts by adding the difference from the CM of the Classical judges to the individual Jazz judges' marks for each extract i.e., 'CM(CJ) - CM(JJ)' for the Jazz extracts and 'CM(CC) - CM(JC)' for the Classical extracts, see Figure 5.2.

After this correction, a consistency is achieved between the different types of judges so that the assessments are calibrated and means are equal to each other. From here on we will use the corrected Jazz judge assessments together with the Classical Judges assessments, for a more accurate representation of the external evaluation of the participants' performances. As such it is these calibrated corrected means that are used to clearly distinguish the two sets of high and low creatively played extracts in Sec 5.3.2., in order to elucidate areas of the brain associated with playing more or less creatively with sLORETA.

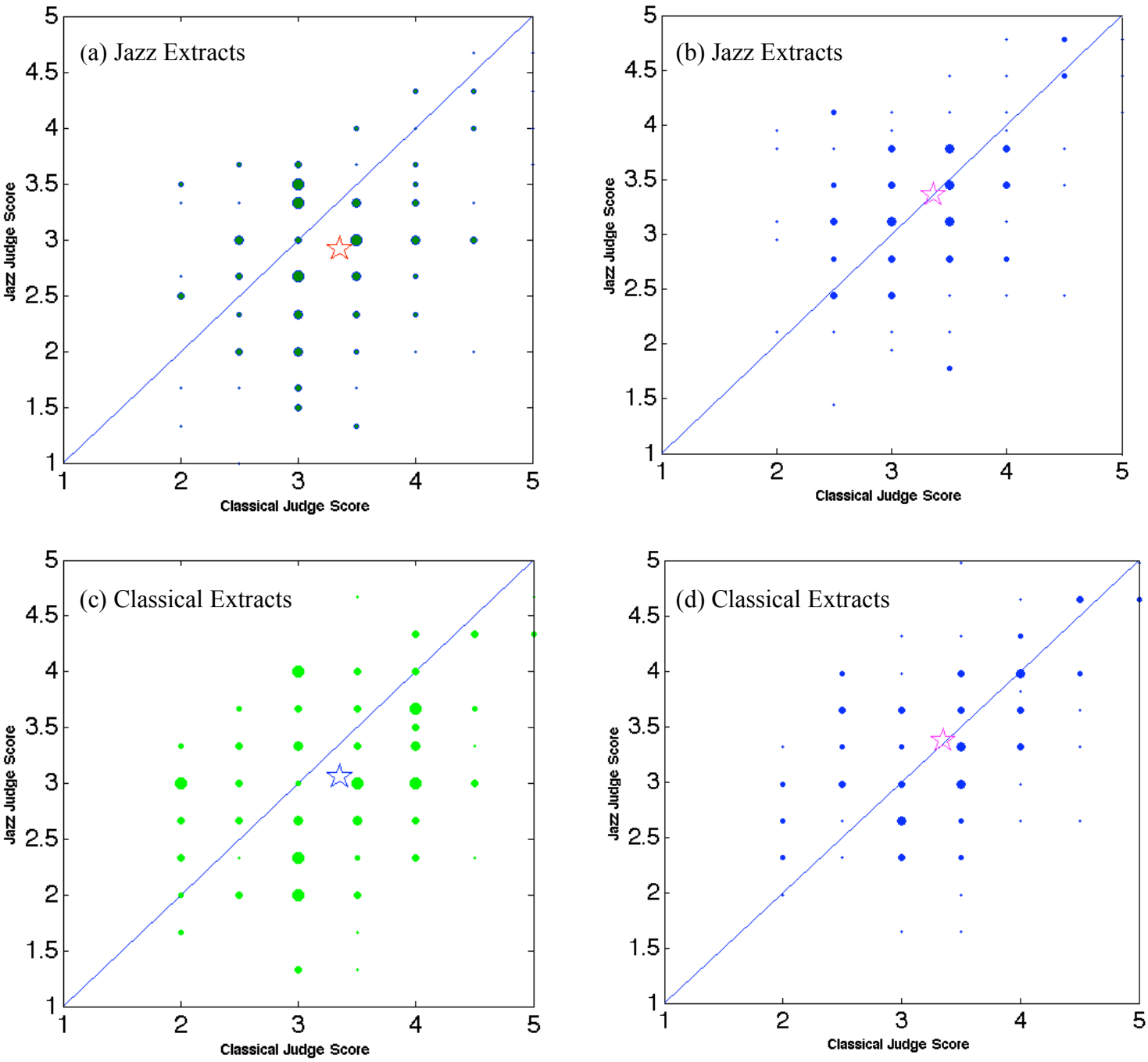


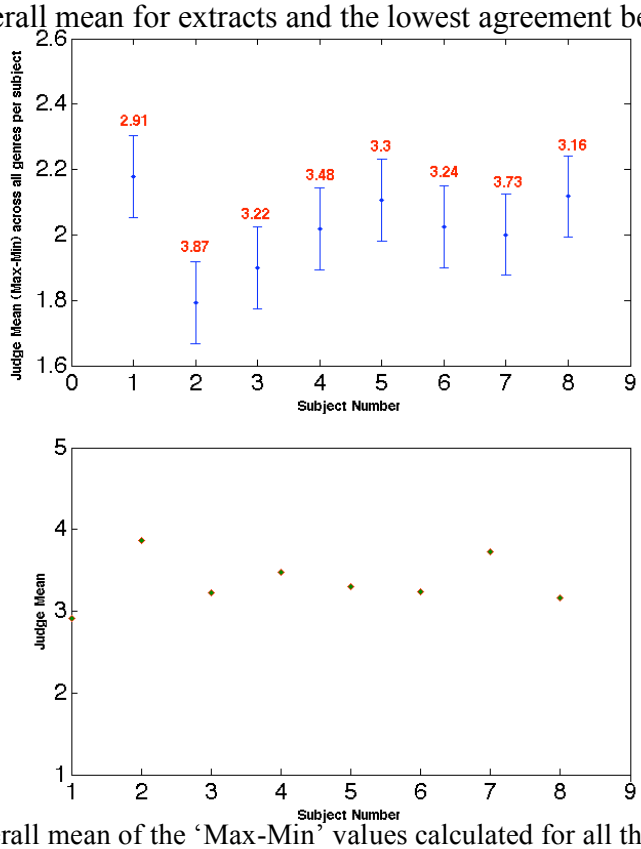
Figure 5.2 (a) The scatter plot depicts mean scores given by Jazz judges versus Classical judges for Jazz extracts with the larger markers for more instances of that combination of judge scores. The centre of mass (shown by the star marker) indicates that Jazz judges give lower scores than Classical judges. (b) After correction, the scatter plot shows the centre of mass now lies on line with x=y with the rest of the combination scores better balanced on either side. (c) The scatter plot depicts mean scores given by Jazz judges versus Classical judges for Classical extracts again with the centre of mass showing that Jazz judges give lower scores than Classical judges. (d) The plot after correction with a balanced set of mean score combinations. (Because there are two Classical Judges, their mean values are in units of ½ while for the three Jazz Judges, their mean values are in units of 1/3).

5.1.2 Judges' assessments: Range and overall mean of marks at participant level

In the following section, we seek to further our understanding of the assessments dataset by investigating its profile; this is not used in further EEG analysis. Firstly, we see more clearly the agreement between judges at a coarse grain level by calculating the overall mean extremes ('Maximum' and 'Minimum') of the judges' scores per participant (see figure 5.3):

$$\frac{\sum Score_{judges}(Max - Min)}{N_{extracts}} \tag{6.2}$$

We can also investigate the possible relation between a higher agreement between judges' assessment for a participant (low value for 'Max-Min'), and the overall mean assessment of the quality of performance for said participant. In particular at this coarse grain level, Participant 2 stands out as having the highest overall judge assessment mean for all extracts and all conditions and the greatest agreement between judges' assessments depicted by the lowest calculated 'Max-Min'. Whereas Participant 1 has the opposite characteristic of having the lowest overall mean for extracts and the lowest agreement between judges.



(a)

(b)

Figure 5.3 (a) The overall mean of the 'Max-Min' values calculated for all the Judges' assessments (classical and jazz) for all extracts per participant with the bars showing one standard error of the mean. Overhead, displayed in red, are the means of total Judges' scores per participant and this is displayed in (b). Of particular note are Participants 2 and 7 for having high judge mean scores and low 'Max-Min' values of judge scores, compared to Participant 1 who has a high 'Max-Min' value and a low judge mean score.

5.1.3 Judges' Assessments: Range and Overall Mean of Marks at Genre Level

If the analysis is taken one level finer in detail into the different types of extracts of Classical and Jazz and the two tasks that participants are asked to perform of 'Improvise' and 'Interpret' (see figure 5.4), then we can see that the Genre/Task combinations are not significantly different from each other in Judges' agreements (calculated 'Max-Min').

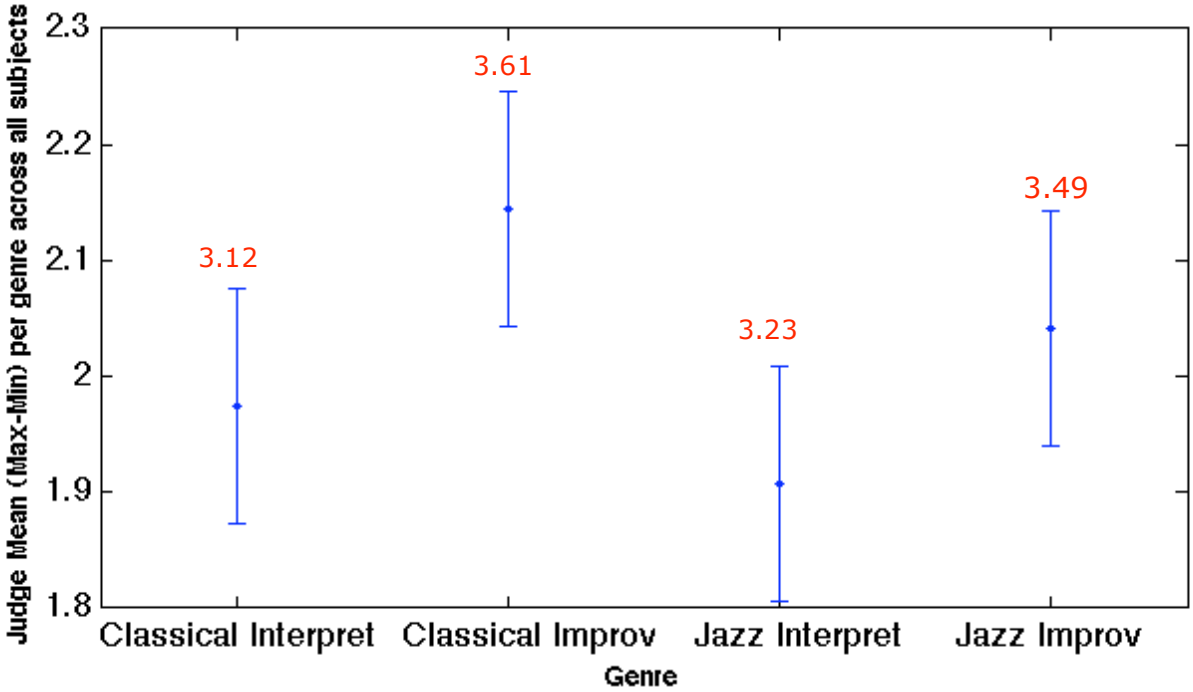


Figure 5.4 The corrected mean of 'Max-Min' values with the overall mean of Judges assessments in red overhead, for the different genres and tasks of the experiment: Classical Interpretation, Classical Improvisation, Jazz Interpretation and Jazz Improvisation. We note that the Judges' do not differ significantly in their agreement of assessment of extracts performed from the different genres or during the different tasks.

Didactically, Classical interpretation is the most common musical task that has stringent rules taught by musical educators and adhered to by classical performers world-wide. One would have imagined that every judge knows what they are looking for and every performer knows what is being assessed when it comes to classical interpretation: an accurate and masterful representation of composers' markings. It is surprising therefore, that the disagreement between Judges for this Genre/Task combination wasn't significantly lower from the other combinations, as would be depicted by a lower calculated 'Max-Min' value. However, on the other hand, the results above then suggest that one may trust the judges' ratings across all genres in an objective fashion.

Improvising on classical extracts, though in the past performed and written by some of the greatest classical composers and pianists (Liszt, Gould, Mozart, Beethoven and Bach), is something that is no longer taught or encouraged widely. Hence though not significant a difference, the highest 'Max-Min' value being for the classical improvisation task could indicate the uncertainty surrounding its assessment.

If we examine the condition of classical improvisation at participant level, again we can see that the participants for whom the judges had the most agreement in assessing (lowest 'Max-Min' values), also had the highest mean judge scores, see figure 5.5(a). In other words, if the participants' performances were truly excellent, then the judges were more unanimous in their assessments. If the 'Max-Min' value of Judge assessment is plotted against the mean value of judge assessment per participant then there is an approximately linear relationship where the higher the 'Max-Min' values, the lower the overall mean values, see figure 5.5(b). It seems if performances did not grab attention with their brilliance leading to an unanimous agreement, there was more variability and uncertainty in assessments for less brilliant and more murky performances in conditions that were not the norm such as classical improvisation.

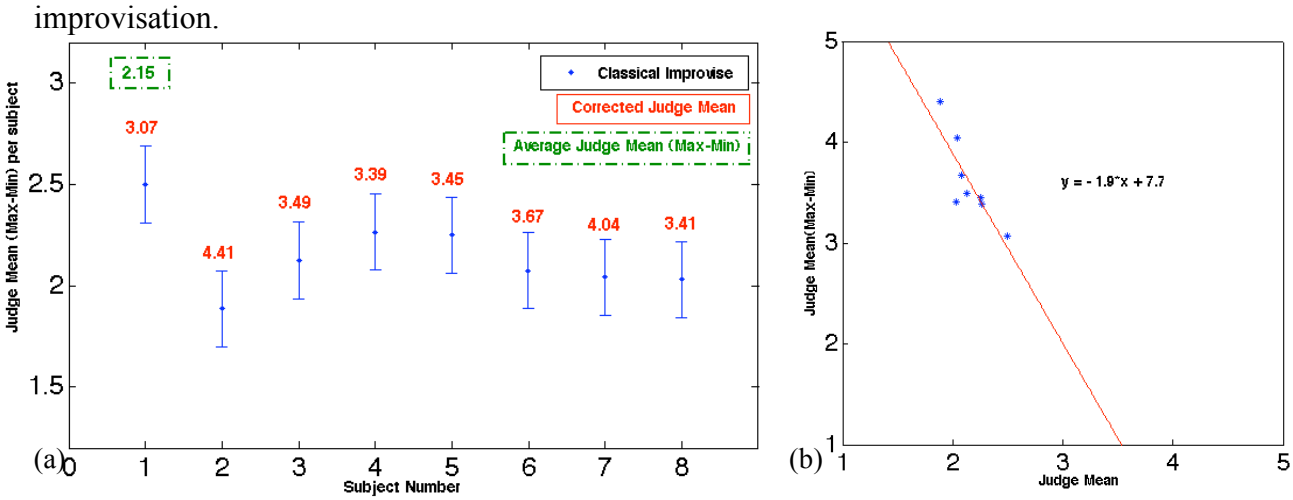


Figure 5.5 (a) The mean 'Max-Min' values of the judges' assessments of the improvisations on classical extracts. Highlighted in red is the mean value of judges' assessments per participant and in green is the overall mean of the 'Max-Min' values for improvised classical extracts. Of particular note again are participants 2 and 7 for high judge mean scores and low 'Max-Min' values of judges' assessments and participant 1 for lowest judge mean score and highest 'Max-Min' values. (b) The relationship between the overall mean and the mean of the 'Max-Min' values of judges' assessments per participant for improvised classical extracts. The higher the judge mean, the lower the mean of the 'Max-Min' value.

This was also the case to a lesser extent with the condition of improvisation with Jazz extracts and interpretation with Classical extracts, see figure 5.6. Perhaps this reflects the comparative familiarity of assessors and performers alike with improvisation on jazz extracts and interpretation on classical extracts indicating a more confident appraisal of uncreative performances. Curiously for Jazz 'Interpretation' extracts, the lower the mean judge score, the lower the 'Max-Min' value, see figure 5.6(c).

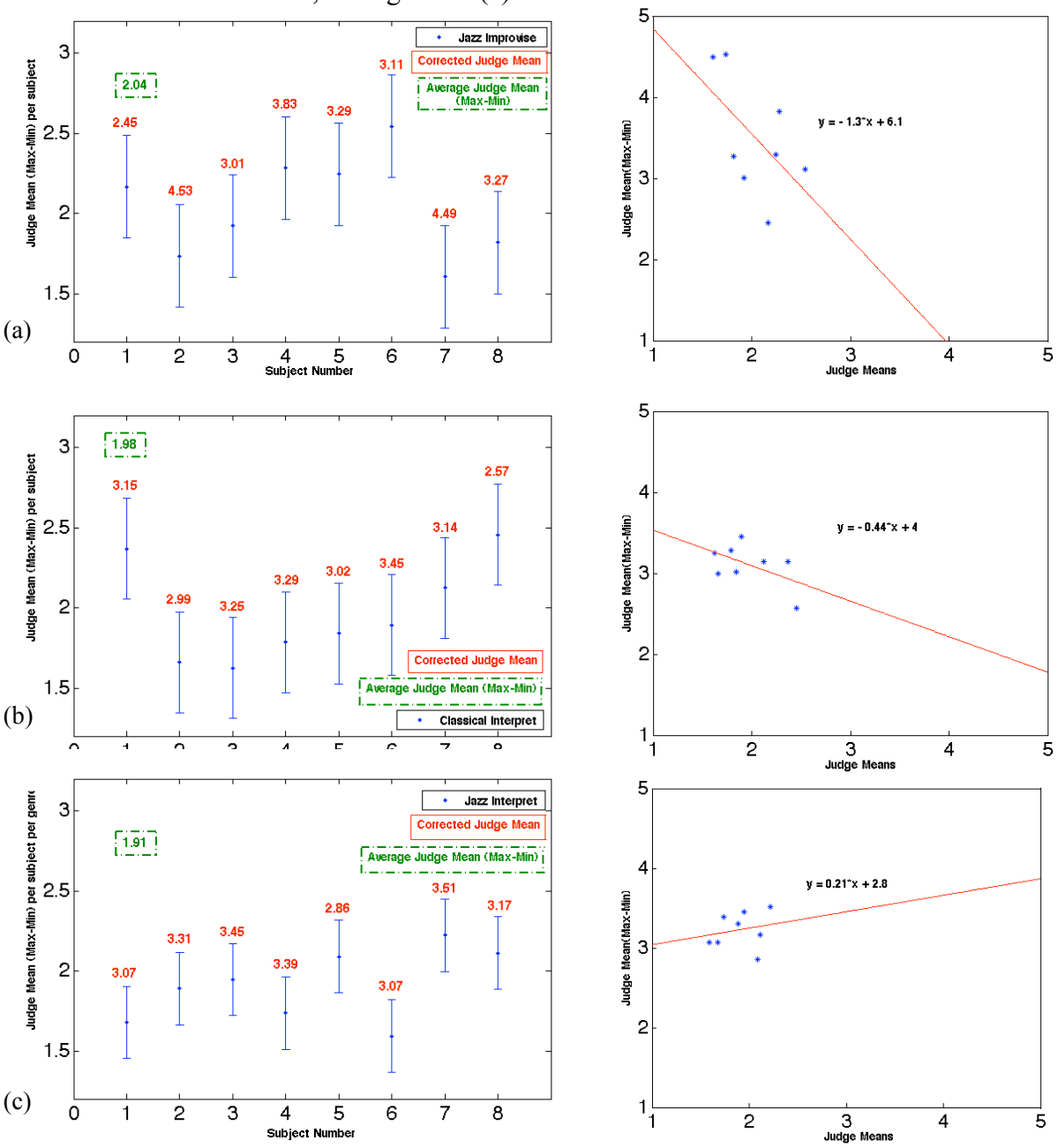


Figure 5.6 The mean 'Max-Min' values of the judges' assessments of eacn participant and the corresponding plot of the relationship between these and the overall mean values in the tasks of Improvisation on (a) Jazz extracts, (b) Interpretation of Classical, and (c) Jazz extracts. In red is the mean value of judges' assessments per participant and in green is the overall mean of the 'Max-Min' per genre/task.

Again this is a condition that is not of the norm, however the jazz extracts presented were considerably easier and less technically taxing than the classical extracts so it could be the case that the more uncreatively an extract was played, the simpler it was to assess it being so, but the more creative, tastes ranged more widely on creative preferences as the baseline standard to compare it to ('Play' condition of the extract) was more basic and easier to get a handle on at first glance with the marking form. This is supported by the relatively smaller variability (depicted by the standard error of mean) and range of 'Max-Min' values for this condition.

In conclusion, from the plots of 'Max-Min' values, it can be seen that Judges tend to more or less agree on assessments of participants' performances with a difference of opinion ranging in the mean 'Max-Min' values of 1.8 - 2.2 depending on the participant, see Figure 5.3.

When looking at a finer grain of different extracts and tasks, the most agreement between judges was for interpretation of Jazz extracts within a range of 'Max-Min' values of 1.5 - 2.2 (mean of 1.91) with progressively wider ranges for Interpretation of Classical extracts within a range of 1.6 - 2.45 (mean of 1.98), Improvisation of Jazz extracts within a range of 1.6 - 2.5 (mean of 2.04) and Improvisation of Classical extracts having the widest range of 1.8 - 2.5 (mean 2.15).

5.1.4 Self vs judge assessments at participant and genre level

If we now move on to how participants' self-assessments compare to the judges scores, when examined at a participant level, both means range between 3 to 4, signifying an overall agreement, see Figure 5.7 (see also Appendix C for standard multivariate statistics).

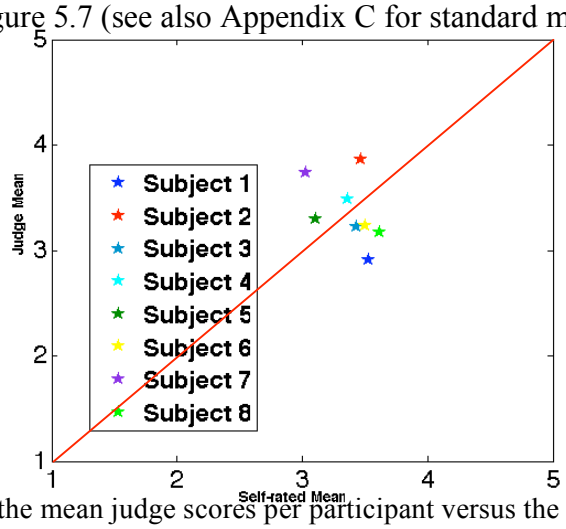


Figure 5.7 A scatter plot of the mean judge scores per participant versus the mean of the participants' own self-assessments across all extracts encompassing both genres of Classical/Jazz and both tasks of Improvisation/Interpretation.

Another way of examining the evaluation of performances by both judges and participants, is by visualising the overall range of scores that both judges and participants give to the performances, see figure 5.8.

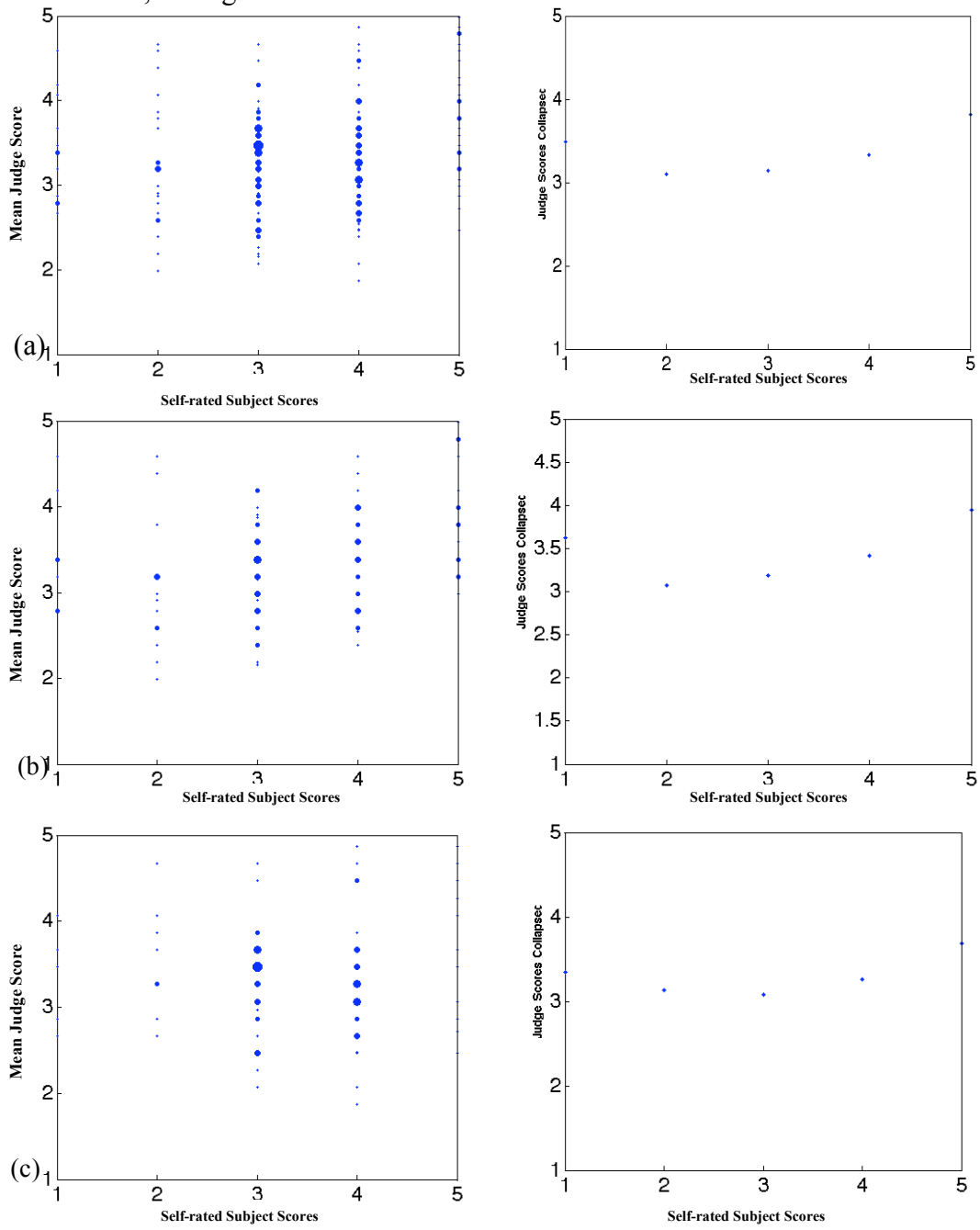


Figure 5.8 Scatter plots of judges' mean scores in combination with participants' self-assessments for the same extracts accompanied by the collapsed functions (mean judge score for each participant rating, 1 to 5) for (a) all extracts across classical and jazz b) classical, and (c) jazz.

It is evident when looking at a coarse grain scale of all extracts, with a collapsed function (taking the mean of the judges' scores for each participant rating, 1 to 5), that judges mean scores have a relatively narrow range of approximately 3 to 3.8. This is true even when

we fine grain down further to Jazz extracts and Classical Extracts with judges being slightly broader for Classical extracts (+ 0.1) and slightly narrower for Jazz extracts (- 0.1).

The plots above highlight the role that subjectivity plays in participants' self-assessments at individual extract level as compared to the relatively objective assessments made by the five judges on each extract. This would need to be borne in mind in Chapter 5.3., when LORETA analyses is presented on the 78 top creative and bottom non-creative extracts as based independently on judges' mean scores and participants' self assessments.

5.1.5 Self vs judge assessments for participant background

Finally, if we examine in more detail, the relationship between judges' assessments and participants' self assessments of their performance qualities, at the level of Jazz extracts versus Classical extracts we can paint a clearer picture of the background of each participant i.e., jazz or classical pianist (see figure 5.9). We calculated the area x*y below the graph for each extract type per participant, using the coordinate (x,y) : '(Judge Mean, Self-Rated Mean)'. The two area values for each participant were then compared for Jazz extracts versus Classical extracts and dependent on which was greater, participants were classified as being either Jazz or Classical musicians (see also Appendix C for standard multivariate statistics).

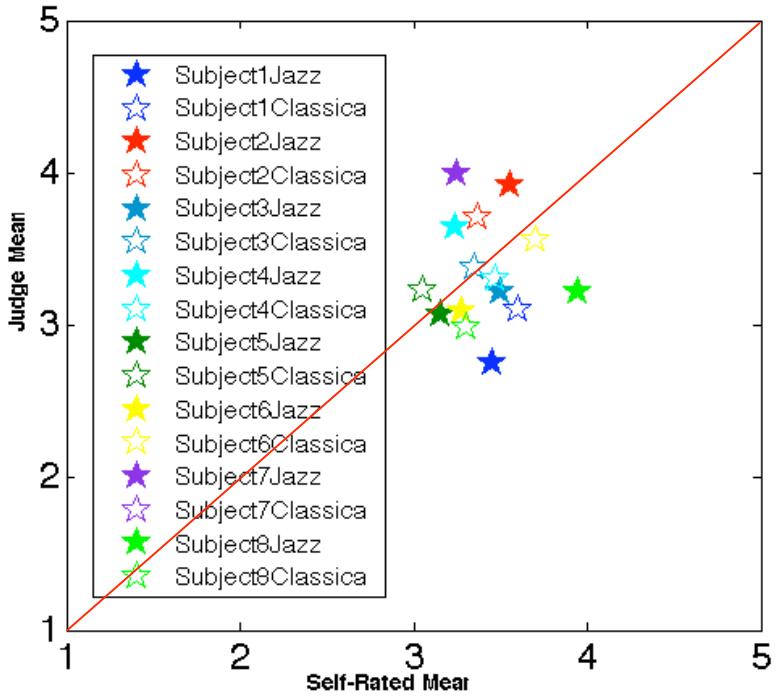


Figure 5.9 Scatter plot of mean judge scores versus mean participants' self-assessment separately across Jazz and Classical extracts.

Participants 2, 4, 7 and 8 were deemed to be of a Jazz background, and participants 1, 3, 5 and 6 were deemed to be of a Classical background. This agreed with a phenomenological combination of qualitative statements taken from the participants at the beginning of each recording session: what and for how long their educational and practical background were (including any differences and progressions into one practice from another) and their future preference of practice with an emphasis on listening material and personal performing style. This also matched an examination of bivariate histograms of judge means versus self-ratings separately across classical and jazz extracts calculated for each participant, see Appendix A.

Using these two classifications of participants, sLORETA analyses were performed on the tasks of Improvisation and Interpretation and presented in Chapter 5.3.

5.2 sLORETA results

The cleaned EEG recordings were analysed with a source localization software, sLORETA that allows us to locate areas in the brain that are positively or negatively modulated, reflecting the direction of the EEG currents, during the different musical cognitive states of 'Improvisation' and 'Interpretation' versus the baseline resting state of just playing the notes ('Play').

It is recommended to use sLORETA's statistic values when comparing tasks (as opposed to absolute modulation values of tasks) as estimates of activity and highly recommended to not use these values as actual statistics in the testing of hypotheses [Pasqual-Marqui, 2002]. These statistics are commonly used in psychological experiments, i.e., the 't-test' (one and two-tailed) and its corresponding p-values. However, the example in the tutorial used to clarify the caution expressed by authors is that there is a possibility for the software to declare a result as significant simply if there was a large area (in voxels) that was slightly more positively modulated than in the partnered task in the comparison, rather than the difference in modulation actually being large enough to be significant, i.e., it does not correct for multiple voxel-by-voxel comparisons. So herein lies the difficulty of accepting the statistical significance values 'within task' comparison but furthermore, not only does the software only allow one task comparison at a time rather than multiple factors at once, our individual task comparisons also involve inputting different amounts of datasets. Therefore, comparing the sLORETA statistics between each individual task comparison would not be meaningful, i.e., the positive/negative modulation in specific areas from the task comparison

of 'Improvise-Interpret' in section 5.2.2, involving 160 datasets for each condition, could not be assessed as more or less significant to those of the task comparison of 'Creative-NonCreative' in section 5.3.1, involving 78 datasets for each condition.

However, the results presented here are for Brodmann areas that repeatedly appear in task comparisons, lending more weight to their validity of involvement in the different musical tasks. Exploring previous research, the areas also lend themselves well in cognitive functional roles to different music processing strategies for the different tasks. Finally, some of the areas also match the areas of activation in the previous fMRI studies mentioned to do with musical creativity in Chapter 1, albeit with a different hemispheric activity pattern; this can be due to both the variation in type of creativity explored and also because fMRI measures oxygenated blood levels whereas sLORETA measures current source densities and thus could present a complementary activity pattern.

sLORETA presents activity divided into frequency bands of δ(1.5-6Hz), θ(6.5-8Hz), α_1(8.5-10Hz), α_2(10.5-12Hz), β_1(12.5-18 Hz), β_2(18.5-21Hz), β_3(21.5-30Hz), and finally an amalgamation of these bands, Ω(1.5-30Hz) ; it currently does not present γ (30-100Hz).

5.2.1 'Think' tasks

There is a 'Think' and 'Perform' component to each of the conditions of 'Improvise', 'Interpret', 'Play 1' and 'Play 2'. Note that we have included a condition of 'Play' between each creative task of 'Improvise' and 'Interpret' to return the participant back to base level. These 'Think' sections are of constant duration, being 11 seconds for the 'Play' conditions and longer at 16 seconds for the 'Improvise' and 'Interpret' conditions. Due to a restriction of the sLORETA software at being able to analyse a dataset of maximum 8192 data points, we downsampled the 'Think' sections by 2 which serendipitously for the 16 second extracts came to exactly 8192 data points and meant we could include the whole section without the need for segmenting. For the analyses, all extracts across Jazz and Classical were averaged, leading to 160 datasets for each condition (8 participants*20 extracts) and the comparison within sLORETA was for paired groups.

5.2.1.1 'Improvise' and 'Interpret' compared to 'Play 1' and 'Play 2'

When comparing the tasks of 'Improvise' and 'Interpret' each to 'Play 1' and 'Play 2' respectively, the occipitotemporal lobe, also known as the inferior to middle temporal gyrus and the fusiform gyrus, Brodmann Area (BA) 37 was positively modulated in the left hemisphere for all four tasks (see Figure 5.10 for a typical example).

BA 37 is an area that appears frequently throughout these analyses, so it is worth spending some time looking at previous research associating function to this region. The BA 37 coordinates from the Talaraich Atlas generally presented in our analyses have a range of: X= -45:-50, Y= -60:-65, and Z= 0:5. It is part of the visual association cortex and specifically activation of the left BA 37 has been associated with the generation of mental imagery [D'Esposito *et al.,* 1997] which seems the most relevant to our condition of thinking about improvising or interpreting a piece of music as opposed to thinking about just playing the bare bones of an extract.

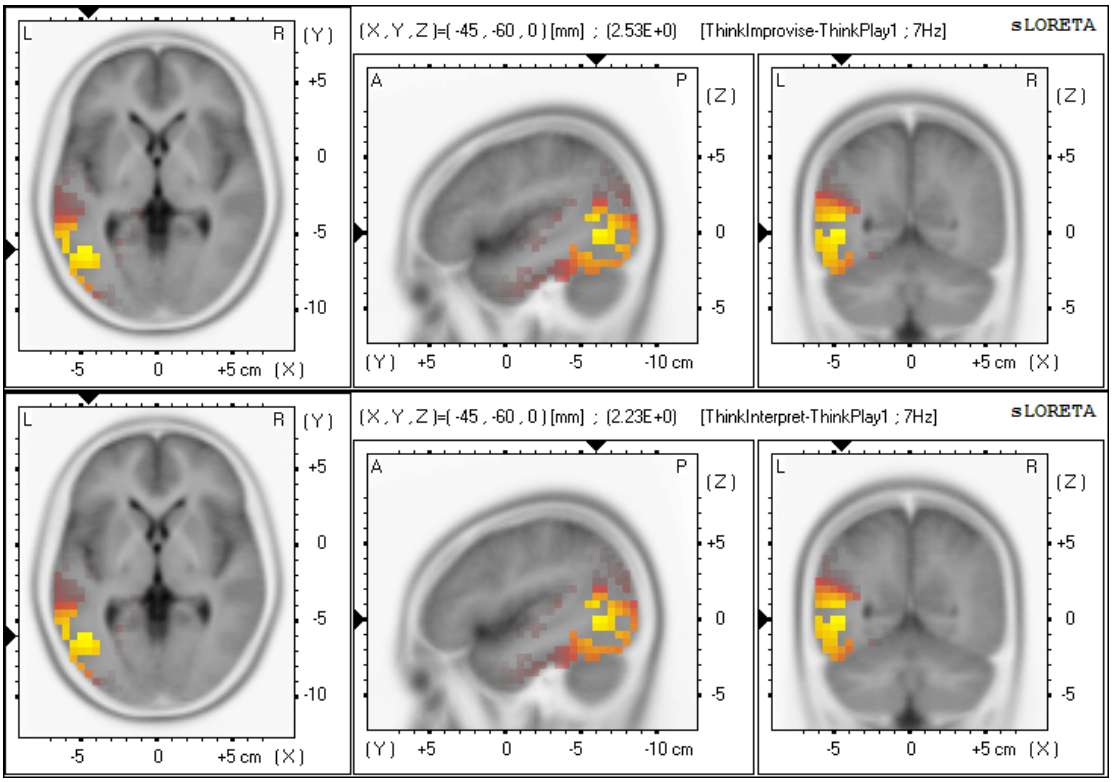


Figure 5.10 Left BA 37 positively modulated in the task of 'thinking' about conditions of 'Improvise'-'Play 1' in the top panel and 'Interpret'- 'Play 1' in the bottom panel across all frequencies (omega). Each panel sequentially displays the top (left to right), side (anterior to posterior) and back (left to right) cross-sections of the brain along with the Talaraich Atlas co-ordinates X, Y, Z of the location of modulation, along the top. For all the sLORETA images displayed, a positive modulation is depicted in an orange-red colour and a negative modulation in a blue colour. The positive modulation is suggested to be related to metaphorical and semantic processing of the written score, 'visualising' more complex musical tasks than 'Play'.

The left BA 37, has also been linked to metaphorical processing of sentences when compared to literal sentences [Rapp *et al.,* 2004], been named as instrumental to linking orthology to phonology [Hashimoto and Sakai, 2004] with lesions causing alexia [Greenblatt, 1976] and associating a picture to a name (confrontational naming) [Abrahams *et al.,* 2003]

which all paints a picture of semantic processing of visual cues which is hardly surprising given its position in the visual association cortex and fusiform gyrus (most famously known to be specialised in face-recognition [McCarthy *et al.*, 1997]).

In our study, participants are required to read a musical score and in the task of thinking about each of the conditions, would be required to 'visualise' and/or almost hear what the music would sound like in their heads before actually playing it. It seems reasonable that this would be more the case during thinking about 'improvising' or 'interpreting' than 'playing' as these are more complex musical tasks.

In addition to the BA 37 positive modulation, the Inferior Frontal Gyrus/Ventrolateral Prefrontal Cortex, BA 45 was also negatively modulated in the right hemisphere only for 'Interpret' minus 'Play 2' (see figure 5.11).

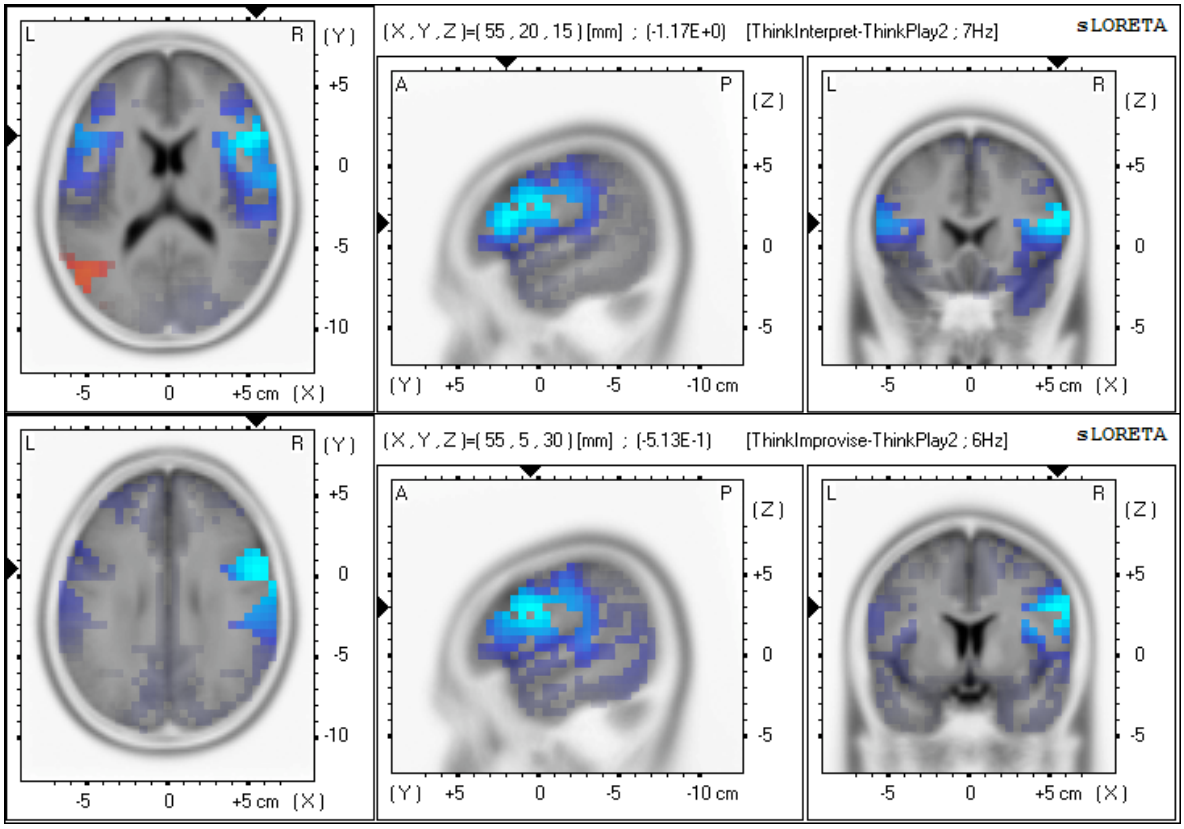


Figure 5.11 BA 45 negative modulation for the task of 'thinking' about the condition of 'Interpret'-'Play 2' and BA 9 negative modulation for the task of 'thinking' about the condition of 'Improvise-Play 2'. Of note is that for the condition of 'Play' the second time, areas related to maintenance of memory over a short period of time and non-verbal memory retrieval are important.

BA 45 is also part of the speech related Broca's area and the right BA 45, has been selectively linked to non-verbal/pictorial memory retrieval [Grady *et al.,* 1994; Haxby *et al.,*

1994] which might imply that the second time round participants were asked to contemplate about just playing the extract as a baseline they remembered the information from the first 'Play 1' and retrieved it from the pictorial representation of the music (music score). This could indicate a practice effect and would not be present for the condition of 'Interpret' which they would have been done only once.

The dorsolateral prefrontal cortex, BA 9, was positively modulated in the right hemisphere for the condition of 'Improvise-Play2'. BA 9 has been associated with maintenance of information across short delays [D'Esposito *et al.,* 1999] and again this is consistent with repetition of thinking for the condition 'Play 2', see Figure 5.11.

5.2.1.2 Differences in the baseline conditions 'Play 1' and 'Play 2'

This prompted an investigation of 'Play 2' minus 'Play 1' which hypothetically should be the same as they are the same condition. However, this yielded a positive modulation in the right hemisphere of the Primary Motor Cortex, BA 4 and Pre-supplementary Motor Cortex, BA 6 and left BA 37 (see Figure 5.12).

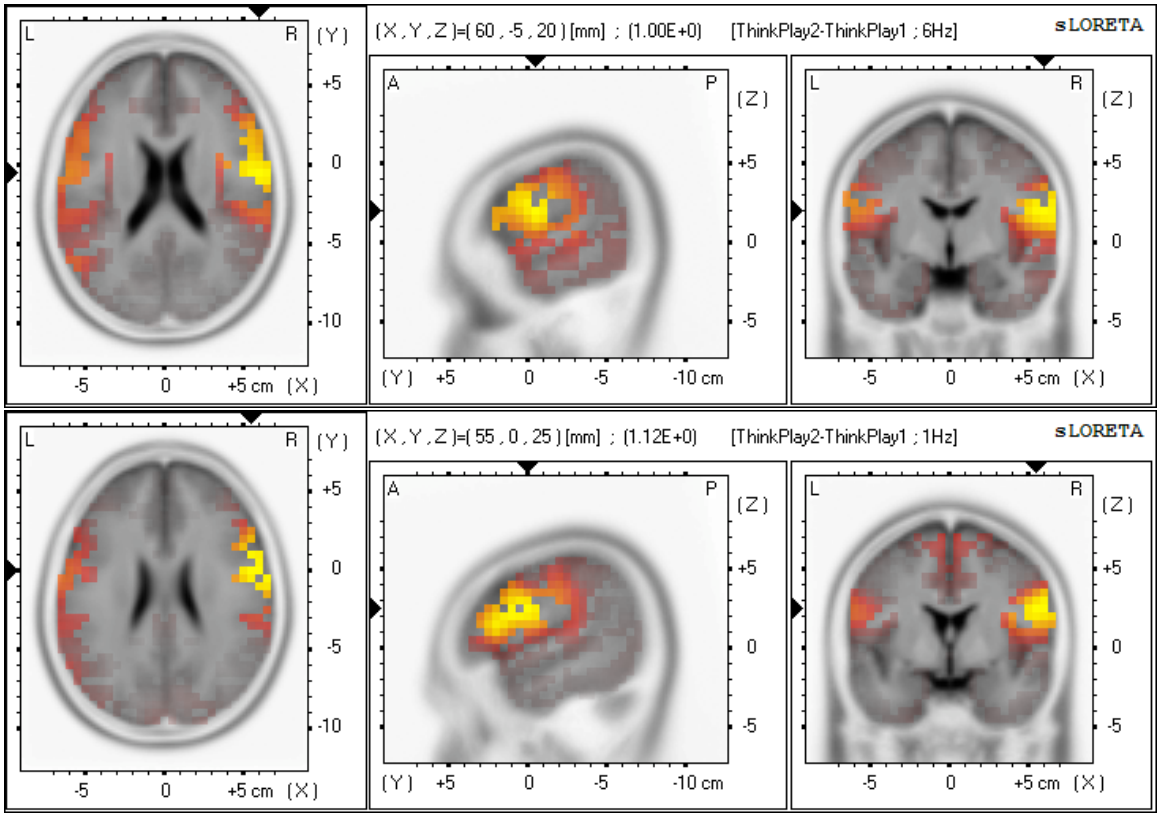


Figure 5.12 BA 4 and BA 6 positive modulation for the task of thinking about the condition of 'Play 2'–'Play 1'. This indicates that participants form a defined mental imagery for complex motoric output when thinking about a task prior to performing it the second time around.

As was discussed before in Chapter 1.3.1.4, the premotor cortex can be assigned to movements of greater complexity because of the subregions contained within it with differing properties [Graziano, 2008]. The second time around, participants know exactly what motoric output is required and so can form a more defined mental imagery for this motoric output [Jeannerod, 1994].

The 'Think' condition for 'Play 1' is the first time the participant has ever seen the musical score, so it follows that for the subsequent 3 conditions that are always sequentially after, participants would have more information for mental imagery and semantic processing when 'thinking' about the task.

5.2.1.3 Differences between 'Improvise' and 'Interpret'

When directly comparing the 'Improvise' minus 'Interpret' tasks during thinking, there is a negative modulation of the left BA 37, right BA 7 and a positive modulation of the left BA 40 (see figure 5.13).

The negative modulation in BA 37, may indicate that less metaphorical/semantic processing or direct translation from reading the written score into mental sound or imagery, is required for thinking about 'Improvisation' rather than for 'Interpretation'. This is further supported by the findings of comparisons of the actual performances of 'Improvisation' versus 'Interpretation', where the left BA 37 is negatively modulated in the middle sections of performances (see Section 5.2.2.). This also implies a different form of mental imagery during thinking about 'Improvisation' when compared to 'Interpretation' in addition to and unlike when both were compared to the baseline state of 'Play 1'. This is further supported by the positive modulation of the left BA 40, which has previously been related to an 'Insight' strategy in creativity in the language domain [Betchereva *et al.,* 2004]. This might further support the work of Brown *et al.*, 2006, who found an overlap of areas for melody and sentence generation.

The involvement of BA 7 which is also known as the precuneus or superior parietal lobe (SPL), is a constant not only in the thinking task when comparing 'Improvisation' to 'Interpretation' but also to the performing of them (see section 5.2.2.).

It is an area where there has not been an integrative consensus as to its function. The precuneus is very well connected with reciprocal corticortical connections in adjacent areas leading to an interconnection that is bilateral, bridging the two hemispheres and it is also selectively connected to other parietal areas such as the caudal parietal operculum, inferior

and superior parietal lobules, and the IPS known to be involved in visuo-spatial information processing [Selemon and Goldman-Rakic, 1988; Cavada and Goldman-Rakic, 1989; Leichnetz, 2001].

Mainly, it is connected to the frontal lobes, namely BA 8, 9, 46, 6 and 32 [Petrides and Pandya, 1984; Goldman-Rakic, 1988; Cavada and Goldman-Rakic, 1989; Leichnetz, 2001]- the latter four of which are areas that are instrumental in the different conditions of our study.

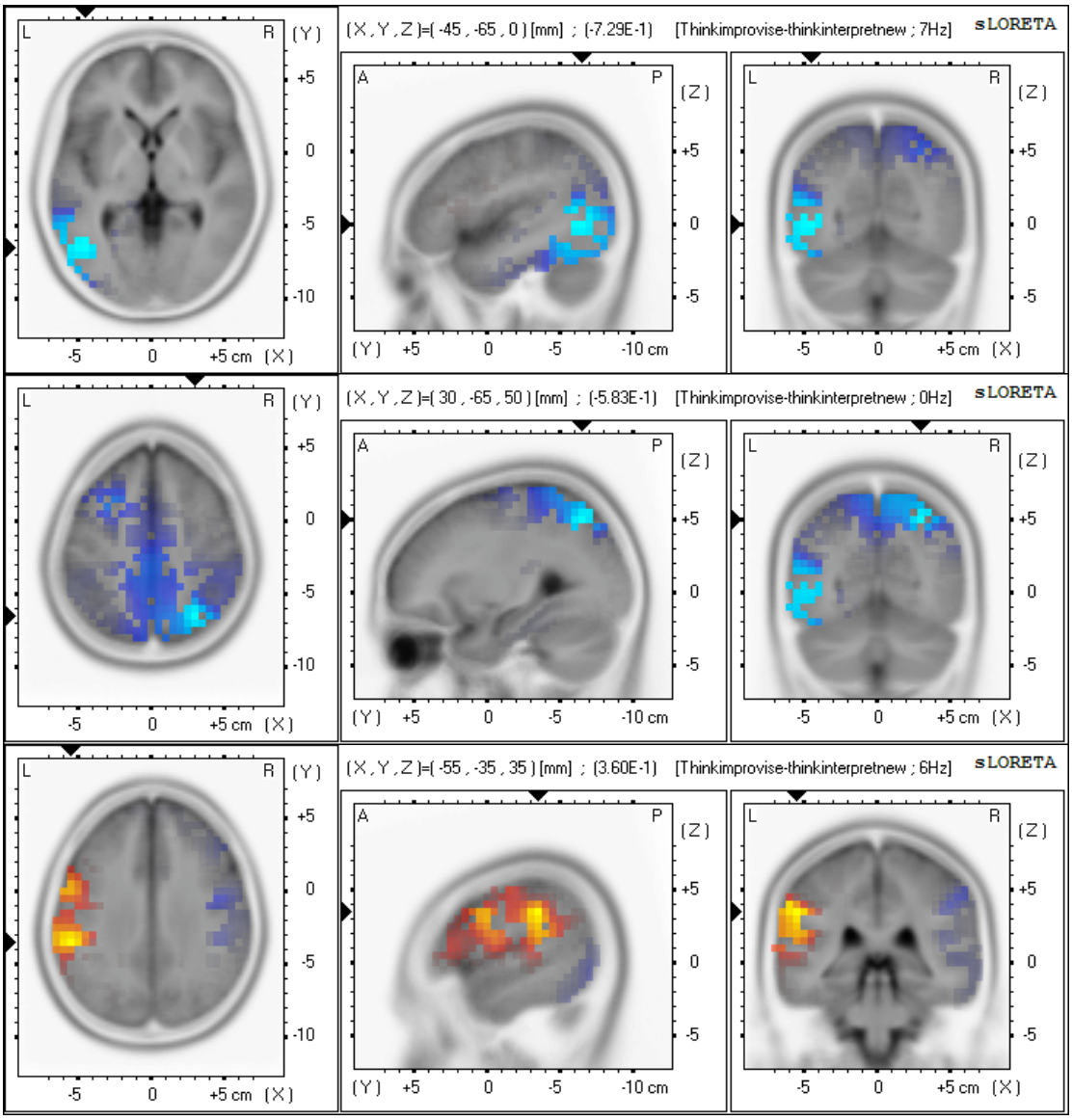


Figure 5.13 Comparing the tasks of 'thinking' during 'Improvisation' minus 'Interpretation' shows a negative modulation in the left BA 37, right BA 7 and a positive modulation in the left BA 40. This implies less semantic processing is required for 'Improvisation' and points to a different mental imagery required, in the form of an 'Insight' strategy. BA 7 negative modulation also associates 'Improvisation' with a state of consciousness that has been linked to hypnagogia, sleep-states and being under anaesthesia.

Here we will present a few different studies that may build up a picture as to the right precuneus' role in our study as related to mental imagery and attention.

Firstly we will look at the visuo-spatial cognitive tasks that the precuneus has a role in. Relying on a lesion study, Suzuki *et al.*, (1998), described a case where a haemorrhage in the right medial parietal lobe mainly in the precuneus resulted in an inability to navigate in the real world despite being able to perform well on visuo-spatial learning tests. This indicates a selective impairment of mental navigation-related networks. This is indicative of a different form of mental imagery or navigation that is internally mentally navigated, for 'Interpretation' tasks which is not the case in 'Improvisation' as indicated by the negative modulation in the right precuneus.

The SPL especially in the right hemisphere has been considered a higher order area involved in controlling spatial aspects of motor behaviour [Grafton *et al*., 1996; Connolly *et al*., 2000; Seitz and Binkofski, 2003; Grefkes *et al*., 2004], and severe disturbances of visually goal-directed hand movements (such as could be attributed to 'Interpretation' tasks) not related to motor, sensory, visual acuity or visual field disorders have also been ascribed to lesions of the SPL.

Specifically for music, in a PET study of musical episodic memory [Platel *et al.,* 2003], melodic tunes recognition tasks contrasted with perceptive control tasks, resulted in activation of the episodic memory network, comprising the prefrontal cortex, the anterior cingulate gyrus and the precuneus. These activations were more prominent in the right hemisphere, although they were bilateral. Here, precuneus involvement was likely to be related to the success of episodic recall, as the musical material used in this experiment did not involve particularly imageable features and no subject had employed a specific mental representation strategy. This proves a likely model candidate for 'Interpretation' where the interpretation of composers' markings involves recall of technique employed elsewhere and learned in training, not to mention a note-for-note reproduction from reading of score to performance. This is further supported by a PET investigation that found the left precuneus and cuneus were the main areas active during detection of pitch changes [Platel *et al.,* 1997], where it was thought the pattern of activation was a consequence of the mental imagery strategy employed to perform the pitch discriminiation tasks via a 'mental stave'.

Finally we come to the important element of attention. Hugdahl *et al.,* (2000), showed that focussed attention decreased bilateral activation and an increase in the right precuneus especially for musical stimuli. This would imply that 'Interpretation' tasks involve more

focussed attention than do 'Improvisational' tasks. This is further supported by a PET study on the neural correlates of visual awareness using subliminal and supraliminal verbal stimuli [Kjaer *et al.,* 2001], where the right precuneus and dorsolateral prefrontal cortex were activated during visual-verbal stimulation that lasted long enough to elicit awareness. This indicated that these regions were critical for task-elicited and state-dependent awareness.

The most compelling evidence of the relationship between a negative modulation in the BA 7, attention and 'Improvisation' comes from a series of studies on altered states of consciousness such as slow-wave sleep (SWS), rapid eye (REM) sleep, the hypnotic state, induced-anaesthetic states and persistent vegetative states. All of these states show a profound deactivation in the BA 7 [Maquet *et al.,* 1997; Maquet *et al.,* 1996; Rainville *et al.,* 1999; Fiset *et al.,* 1999; Laureys *et al.,* 1999] . It seems there is an active participation of the precuenus in conscious processes, high order body and self-representation [Maquet *et al.,* 1999] which would make sense in light of the richly connected multimodal network that the precuneus belongs to. It would seem that the task of 'Interpretation' involves an internally guided attention and self-representation with episodic memory retrieval whilst that of 'Improvisation' involves more a loss of conscious self-awareness.

5.2.2 'Play' tasks

For these tasks, the EEG recordings were segmented as previously mentioned into four seconds at the beginning, middle and end. The end section was also segmented into an additional slightly longer segment of seven seconds which meant there were slightly fewer extracts that could be used, but it was done out of an interest to retain more of the performance. We will examine the pattern of activity with this seven second segment first.

When comparing performances of 'Improvisation' minus 'Interpretation', there are certain tendencies in positive/negative modulation in the middle Temporal Gyrus that have been dependant on the time evolution of the cognitive task, such that the initial and final parts (the four second segment did not present BA 37 in its activity pattern) of the performances were characterised by a positive modulation in BA 37 and the middle part by a negative modulation in the BA 37 suggesting a temporal dependance and role in 'Improvisation' on BA 37, see figure 5.14.

In addition, the negative modulation of BA 7 remained constant throughout, including in the first segment for the condition of comparing 'Improvise' to 'Play 1'. The negative

modulation of BA 7 did not present itself in the condition 'Interpret' to Play 1', strengthening the case that it is an area specifically related to 'Improvisation', see figure 5.15.

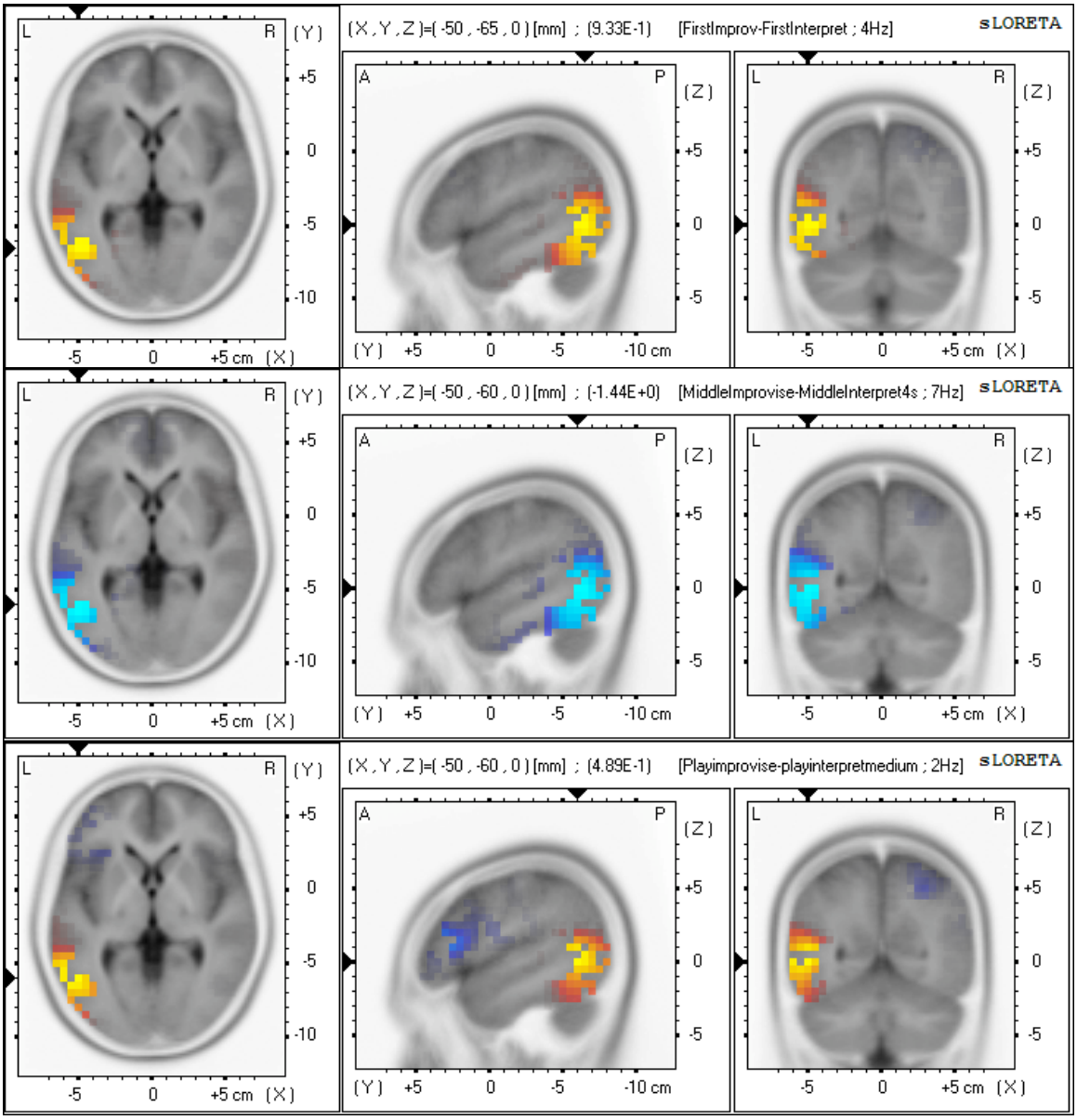
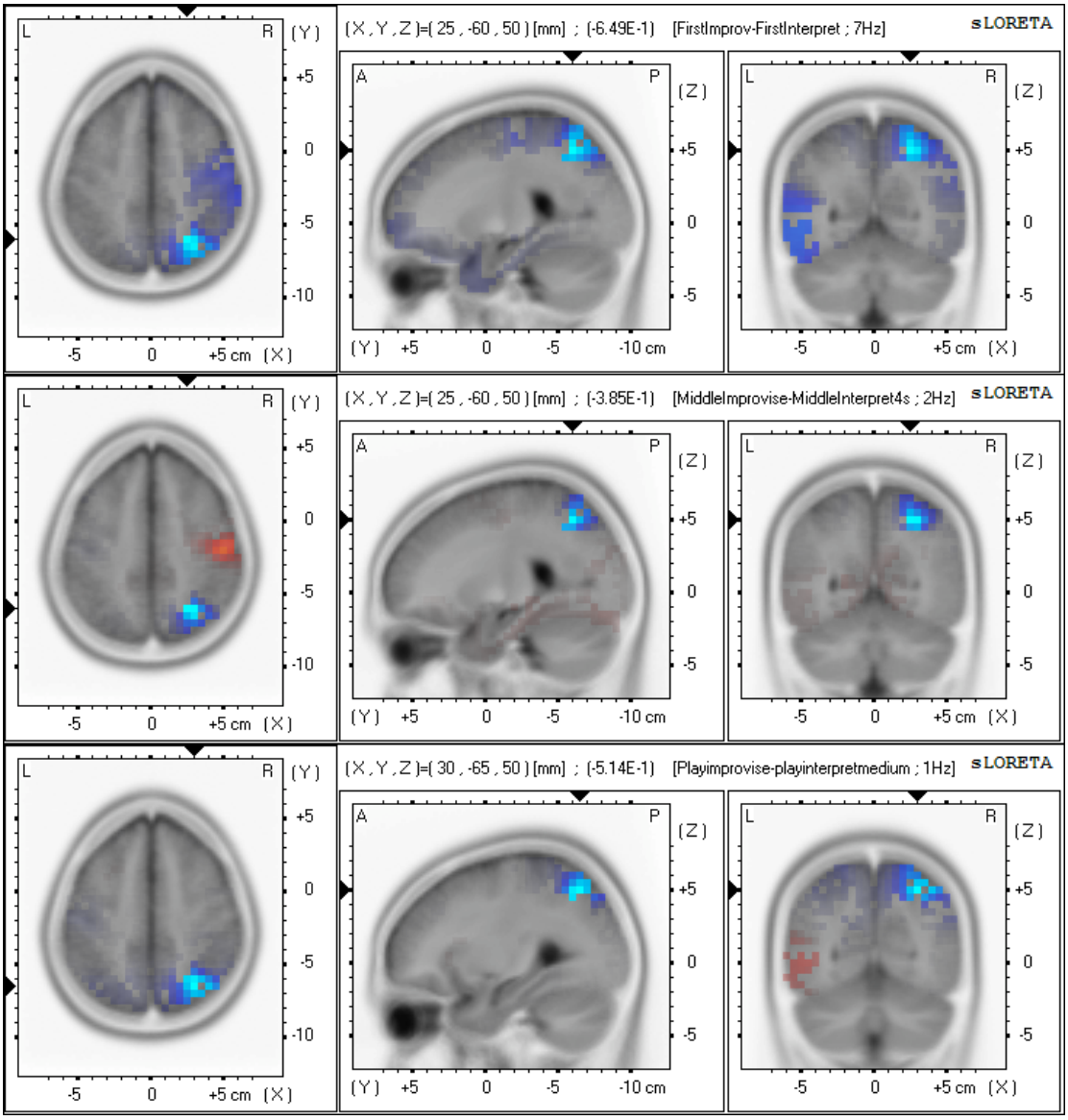
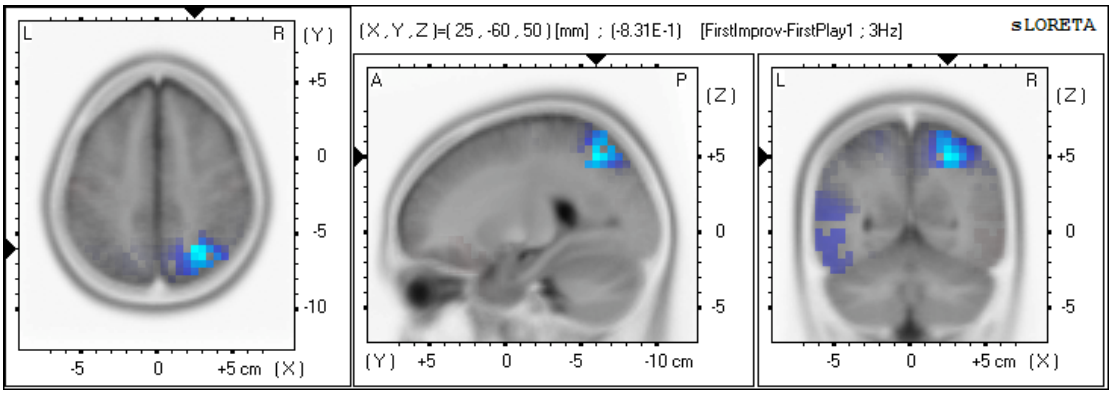


Figure 5.14 sLORETA images depicting a positive modulation in Brodmann Area 37, during the first four seconds and last seven seconds, and a negative modulation in the middle four seconds also in Brodmann Area 37, of performances in the comparison of improvisation versus interpretation. This implies a cognitive temporal evolution in the task of Improvisation with less semantic/metaphorical processing as linked to the function of BA 37 in the middle section of an Improvisation. As the instruction is to 'Freely improvise on the extract (or part thereof)', therefore perhaps there is a referral to the musical score of the extract, at the beginnings and ends of the improvisation.



(a)



(b)

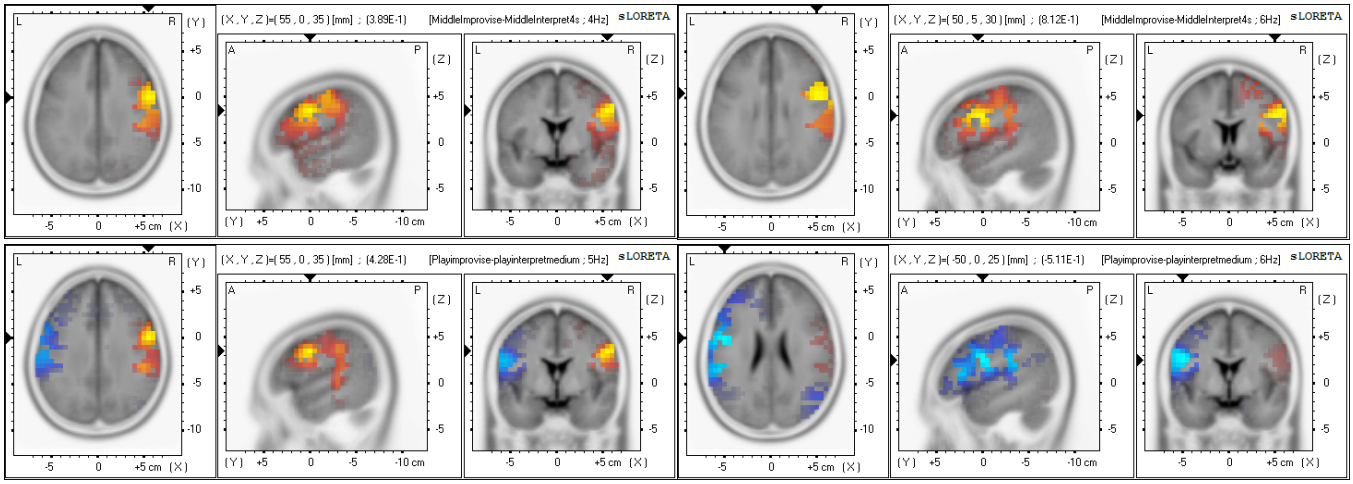
Figure 5.15 (a) Temporal evolution of the task of 'playing' the conditions of 'Improvise'-'Interpret' showing a constant negative modulation of BA 7 through beginning to end. (b) The task of 'playing' the condition of 'Improvise'-'Play 1' (baseline) also showing a negative modulation of BA 7 strengthening the possibility of its association to 'Improvisation'. This indicates that BA 7 plays a consistent role in the task of Improvisation only rather than the other musical tasks.

Another activity pattern that presents itself, dependant on the time evolution of the task are the positive/negative modulation pattern of the right and left hemispheric respectively, BA 6 and BA 9 for the middle and end segments (last seven seconds) and the positive modulation of the left hemispheric BA 42/45/46 in both the last four and seven seconds, see figure 5.16.

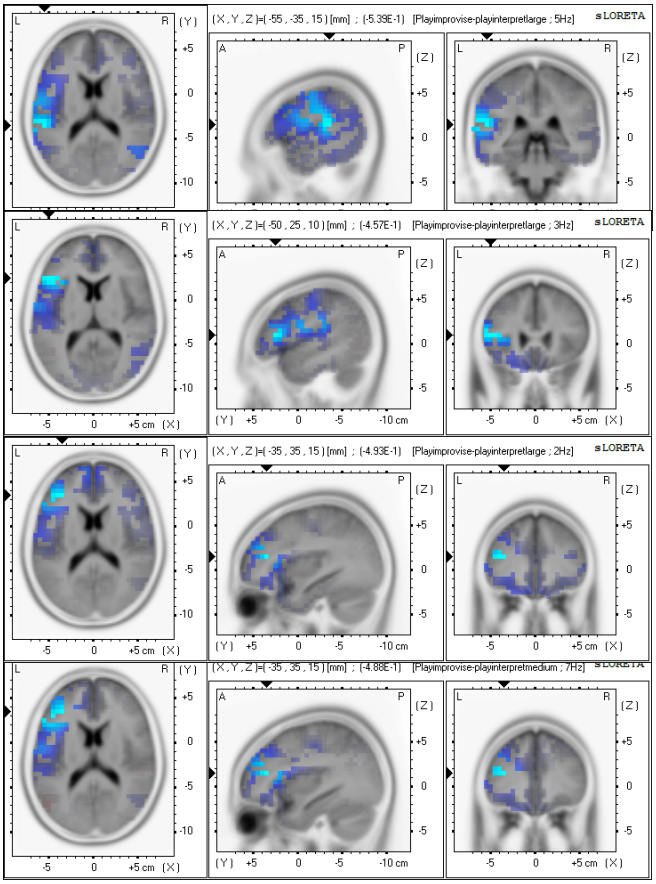
Positive modulations in the right hemispheric BA 6 and 9 are accompanied by a concurrent left hemispheric negative modulation in the same area and this is something that is also the case when 'Creative' extracts are compared to 'Non-Creative' extracts as assessed by participants and judges respectively. The involvement of BA 6 seems to support the findings of Brown *et al.* (2006), in their melody generation task though the activity pattern differs from ours in that theirs is a bilateral activation whereas ours is a hemispheric specific positive/negative modulation that is furthermore also found in the comparison of 'Improvisation' with 'Play 1' suggesting an association.

The negative modulation in the left dorsolateral prefrontal cortex (BA 9/45/46) for the 'Improvisation' task rather than 'Interpretation' task was hemispherically opposite to that found by Braun *et al.* (2012), though this could have something to do with the non-verbal nature of our 'Improvisation' task and the fact we were comparing this to a second creative task of 'Interpretation'. The same negative modulation pattern was found when comparing 'Creative' to 'NonCreative' tasks (both Judge and Participant assessed), where the 'Creative' set consisted 70-80% of 'Improvisation' tasks and the 'Non-Creative' set consisted 70% of 'Interpretation' tasks.

However, the negative modulation for 'Improvisation' in this comparison implies a greater positive modulation in the left dorsolateral prefrontal cortex during the task of 'Interpretation', whilst their study reported left hemispheric activation during their 'Improvised' task. Our condition of 'Interpetation' may be similar with their lyrical verbal 'Improvised' task as they are both goal-oriented.



(a)



(b)

Figure 5.16 The images show comparisons of 'Improvisation' to 'Interpretation'. (a) The first row depicts the positive modulation of the right BA 6 and 9 during the middle 4 second segment. The second row depicts the last 7 second segment where the pattern of concurrent negative modulation in the left BA 6 and 9 start to emerge. (b) In order of rows are the negative modulation of BA 42, 45 and 46 in the last four second segment and finally a maintenance of negative modulation in the BA 46 in the last seven second segment. This indicates a consistent pattern of positive/negative modulations in the pre-SMA and DLPFC during the middle and last sections of our 'Improvisation' task which is less goal-oriented than our 'Interpretation' task.

A final interesting positive/negative modulation pattern that emerged in the last four seconds of performance was the involvement of the insula (BA 13). It appears that there is a positive modulation in BA 13 that is specific to the condition of 'Interpretation' where a left hemispheric negative modulation occurs in the condition 'Improvisation'-'Interpretation' and a bilateral with a left hemispheric concentrated positive modulation when solely 'Interpretation' was compared to the baseline of 'Play 1', see figure 5.17.

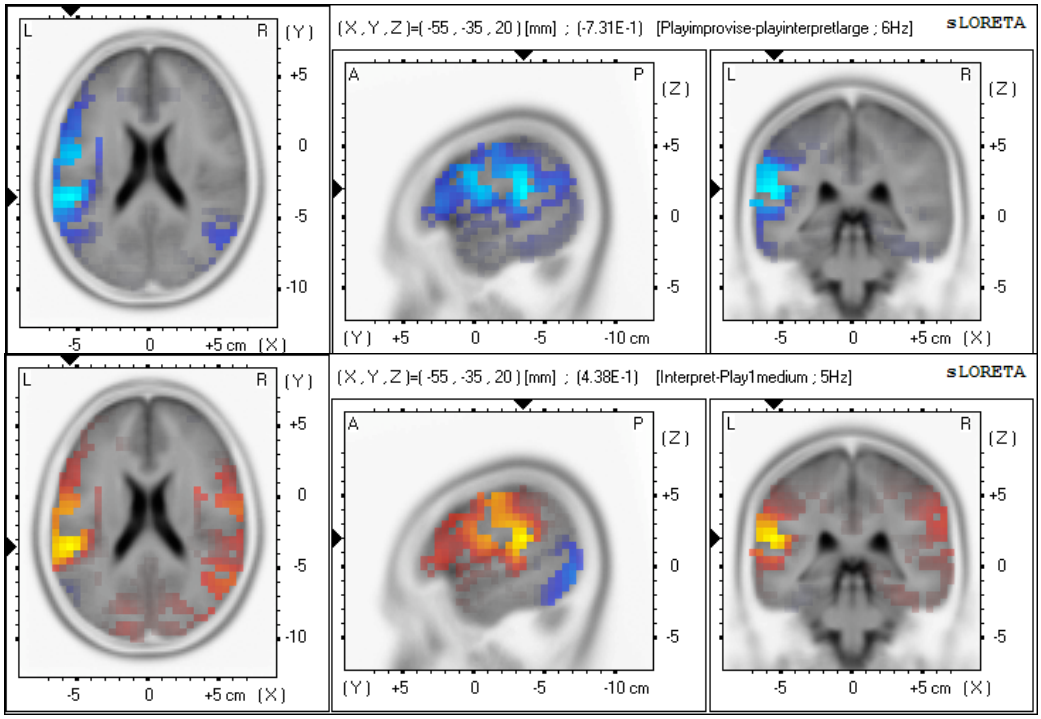


Figure 5.17 The first row depicts the comparison of 'Improvisation'-'Interpretation' showing a negative modulation in the left insula (BA 13) and the second row shows a positive modulation in the same area when 'Interpretation' is compared to the baseline 'Play 1'. This indicates that cognitively, 'Interpretation' requires more conscious error-monitoring, audio-visual integration, emotionally linked response inhibition and accurate rhythmic auditory processing than 'Improvisation'.

Anatomically, the insula appears to be a candidate for multi-modal emotional and motoric integration and processing as it receives information from 'homeostatic afferent' sensory pathways through the thalamus and outputs to limbic areas such as the amygdala, ventral striatum, orbitofrontal cortex as well as the motor cortices [Craig, 2002]. It is well placed to be a neurobiological candidate for embodied cognition, an idea proposed by philosopher, psychologist and physician William James (1842-1910), where subjective emotional experience, i.e., conscious feelings, arise from our brain's interpretation of bodily states that are caused by emotional events.

The association of the 'Interpretation' task to an increase in positive modulation in the insula could be feasibly linked to a mixture of conscious error-monitoring, emotionally linked response inhibition and audio-visual integration and temporal auditory processing as could be expected from the nature of the task.

Firstly, research by Shafritz *et al.,* (2006), on an fMRI study indicated an activation in the insula in participants when inhibiting responses to emotional faces whereas a task not involving emotional valence such as during a letter task, did not strongly engage this region. Music in itself provides an emotional context to the task of 'Interpretation' which by sticking to the rules of the particular extract performed, is creatively more goal-oriented, convergent and more inhibitive than 'Improvisation'.

Further research on the activation of the left insula, is a study by Klein *et al*., (2007), where activity in this region was stronger for conscious aware errors as compared to unaware errors, using an antisaccade task. What is of interest is that any post-error adjustments to do with speed and accuracy in performance was only observed after aware errors which is in keeping with the nature of 'Interpreting' a piece of music where accurately adhering to the notes and dynamic instructions is of utmost importance and requires a conscious awareness during error-monitoring.

A cross-modal study by Lewis *et al.,* (2000) involving the perception of speed of an auditory signal and the simultaneous identification of visual dots with the highest velocity, showed an enhancement of activation in the left insula. Lewis et al. theorised that this polymodal effect could have reflected specific task factors, such as attentional tracking of the target, selection/computation of the relevant motion parameter (speed), comparison of speeds, selection of response, or non specific task factors such as storage and retrieval of information from working memory, all of which are cogntive tasks collectively involved in the overall musical task of 'Interpretation'. The task of 'Interpretation' requires a greater integration of information from the visual cues of the musical score and the auditory sensory perception and monitoring of the actual music played, requiring an essential audio-visual integration that is not as necessary in the task of 'Improvisation', where participants are only required to use the visually presented musical score as a starting point for their performance and not as a continual reference required throughout their improvised performance. Participants could, if they wanted to, improvise with their eyes closed, whereas unless they memorised the extract in the few seconds it was presented for, they could not do so whilst interpreting it.

Finally, the left insula has been shown to be important in perceiving the regularity or irregularity of a temporal rhythm within a musical sequence [Platel *et al.,*1997]. The authors attributed the role of the left insula to memory processing whereas Collavita *et al.,* (1974), postulated that the insular-temporal region is crucial for discriminating temporal auditory patterns by attending to the entire pattern as a whole through their work in cats. Interpreting a piece of music certainly requires an awareness of the whole shape of the piece an an ability to temporally hold in the mind what has just been played, what is being played presently and preparing for what is about to be played in the future. It also requires an accurate knowledge of different time signatures and rhythms as indicated by the composer and the ability to carry this out with accuracy. Again in 'Improvisation', this is less externally goal-oriented and more an internal choice or preference, with the ability to change rhythms, tempi and time signatures at will and 'in their own time' if you will, whereas unless indicated by the composer, this is not the case with 'Interpretation'.

The involvement of the insula in the cognitive musical task of 'Interpretation' indicates that it is one which requires conscious awareness, emotionally related inhibition responses, error-monitoring, audio-visual integration and rhythmic temporal auditory processing suggesting a more integrated, inhibitive, conscious and convergent creative task than 'Improvisation'.

5.3 Linking assessments with sLORETA results

In this section we will be examining whether and how the assessments of the participants and the judges relate to the pattern of activations in the EEG recording.

Firstly, using the method of separating the participants into either Jazz or Classical background (see figure 5.9), we will see if there is a difference in the way that each group perform 'Improvisation' and 'Interpretation' tasks and whether any patterns of activation previously observed are in fact related to their background.

Secondly, we will be examining in more detail the relationship between the judges external assessments, the participants' self-assessments and the pattern of activity observed through sLORETA. Particularly, we would be interested in what constitutes as Creative for both parties and whether this is reflected in the EEG.

5.3.1 Jazz versus Classical

Participants were divided into two groups, Jazz or Classical, based on their background as calculated as an average of their own self-assessments and the mean judge scores on their performances across each type of extract. There were four in each group (see figure 31) and comparisons were made as according to Table 5.1. When comparing the two different background groups, they were classified as independent pairs for sLORETA settings.

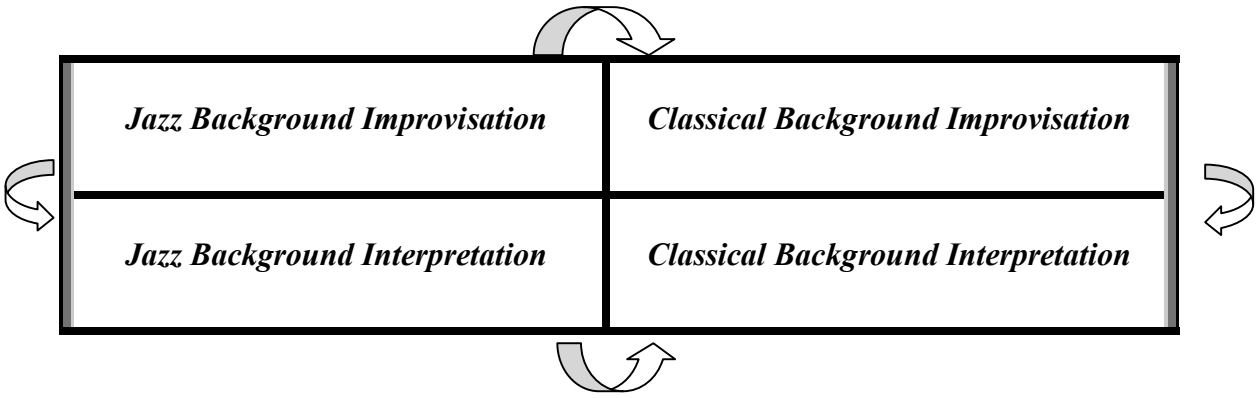


Table 5.1 A table of comparisons made for sLORETA analysis between Jazz and Classical background participants.

A robust pattern of positive/negative modulation appeared for BA 37, which only occurred when comparing performances from participants of a Classical Background, such that there was a left hemispheric positive modulation when comparing 'Improvisation' minus 'Interpretation' within a Classical background but a left hemispheric negative modulation when comparing the 'Improvisation' and 'Interpretation' performances between Jazz and Classical backgrounds, see figure 5.18. This suggests that for pianists of Classical background there is more use of this area possibly due to the reading from a pictorial representation of music and translating this into a musically meaningful output. They are more unfamiliar with 'Improvisation' performances than 'Interpretation' tasks and as such possibly adhere or refer back to the score more than possibly an improvising jazz musician would do. The same is true for 'Interpretation' tasks when comparing musicians from the two backgrounds. This is further supported by the negative modulation of BA 18 throughout any comparison of both 'Improvisation' and 'Interpretation' tasks between the Jazz and Classical participants, see figure 5.19. This area has been attributed to visual saccades [Darby *et al.,* 1996] and also to mental imagery during music perception of pitches [Platel *et al.,* 1997].

In addition, the pattern of right hemispheric positive modulation and left negative modulation in BA 6, 9 and 45/46 is found only during 'Improvisation'-'Interpretation' tasks in the middle and last 4 seconds when comparing participants of Jazz background (see figure 5.20). These patterns are also found with a right hemispheric negative modulation in BA 7 in the first and middle 4 seconds again only in the participants with a jazz background for the same tasks. This is consistent with the temporal pattern found earlier during this task suggesting an association specifically with the Jazz participants.

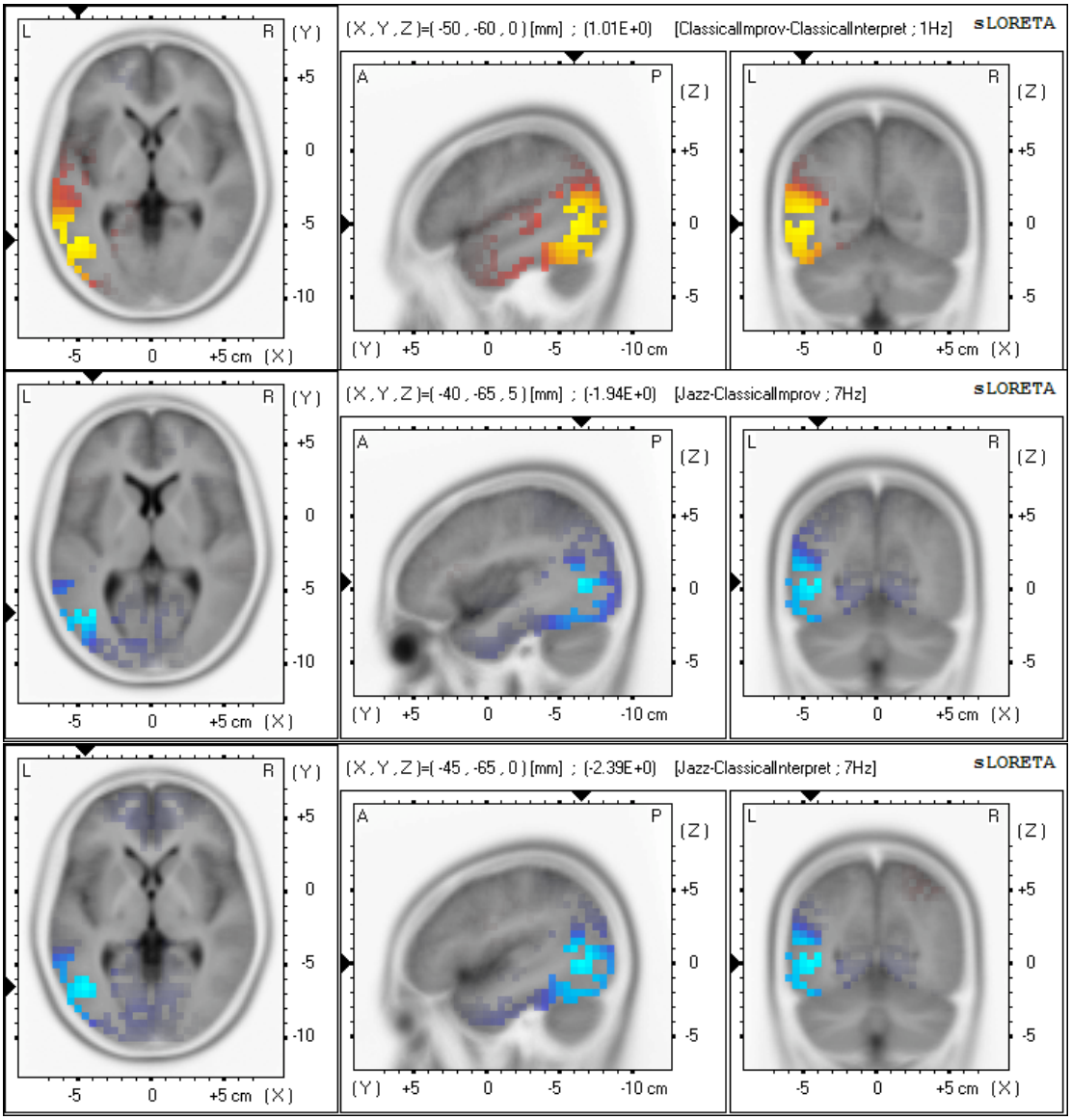


Figure 5.18. The first row depicts the condition of 'Improvisation'-'Interpretation' within participants from a Classical background, with a left hemispheric positive modulation of BA 37. The second and third rows depict comparisons between participants from Jazz and Classical backgrounds when comparing 'Improvisation' and 'Interpretation' tasks respectively. This indicates that the involvement of BA 37 only occurs when comparing performances from participants of a Classical background suggesting a reliance on the musical score as BA 37 is related to metaphorical/semantic processing.

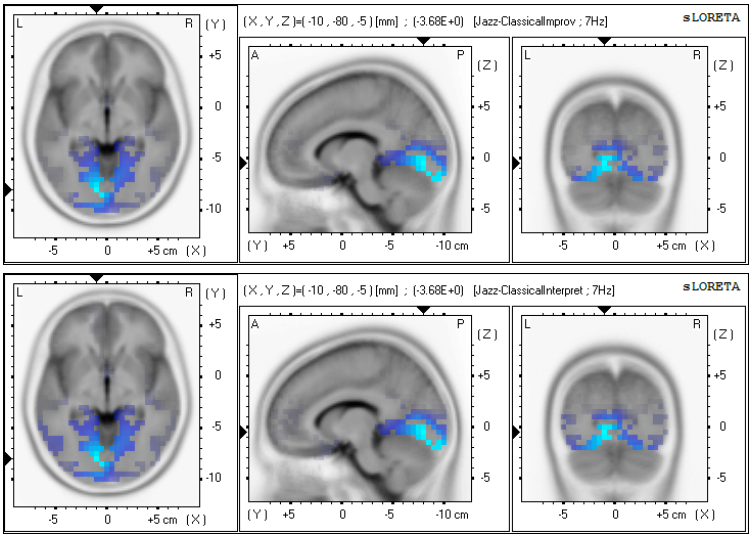


Figure 5.19 Negative modulation patterns in BA 18 for both tasks of 'Improvisation' and 'Interpretation' between participants of Jazz and Classical backgrounds. This indicates that participants from a Classical background adhere more to the visual musical score (visual saccades) and use a different form of mental imagery as compared to participants from a Jazz background.

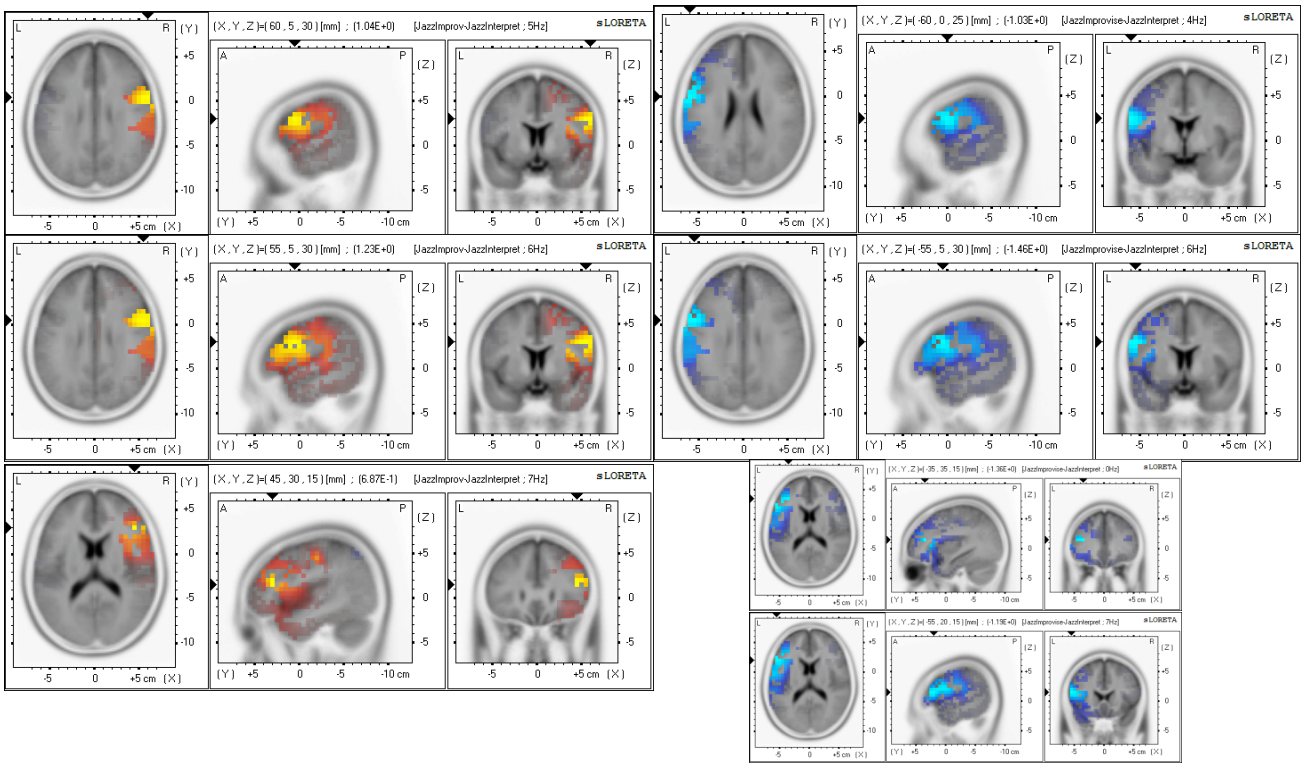


Figure 5.20 Activity patterns found when comparing the tasks 'Improvisation'-'Interpretation'. The first row depicts the right hemispheric positive modulation of BA 6 in the middle four seconds and left hemispheric negative modulation of BA 6 in the last four seconds. The second row depicts BA 9 in the same order of positive and negative modulation, and the third row, BA 46 along with the additional negative modulation of BA 45 in the last four seconds. These are only found within participants of a Jazz background suggesting other instances of this activity pattern are due to participants' pedagogical training.

5.3.2 Creative versus non-creative: Judge and self

Using the means of judge scores, the top Creative 78 extracts across Jazz and Classical genres and 'Improvisation' and 'Interpretation' tasks were chosen between the score range between 3.78 to 5.07 and the bottom Non-Creative 78 extracts were chosen in the range 1.86 to 2.86.

The results were remarkably consistent in the first and middle 4s with a positive modulation across all frequencies, of the left medial prefrontal cortex (MPFC), also known as the anterior cingulate or BA 32, see figure 5.21. In the middle 4 seconds we also see a negative modulation of the left BA 37 which we can now suggest is due to participants from Classical backgrounds in the sample set (see figure 5.21) and finally the persistent negative modulation pattern in the last 4 seconds of the left BA 6, 9 and 45/46 that we can now suggest is due to participants from Jazz backgrounds, see figure 5.21. The positive modulation in BA 32 has not been seen before and in so consistent a manner across many frequencies and temporally for the better part of the performances (first and middle sections). To examine whether this was due to (a) an objective assessment of creativity and (b) whether it was robust, we also compared extracts that were rated creative/noncreative by participants (completing the 3-way approach to this study) and three random extract sets chosen by a random number generator (see Appendix B for the distribution of judge means).

For the random sets, to keep the numbers of extracts consistent we simply took the top 78 Creative extracts and bottom 78 Non-Creative extracts as rated by participants themselves.

For the self-ratings, there was a positive/negative modulation pattern in BA 37 in the first and middle four seconds, similar to the temporal pattern for the tasks 'Improvisation' minus 'Interpretation' with participants from a Classical background, see figure 5.22. Similarly, in the last four seconds, the persistent right hemispheric positive modulation of BA 6, 9 and 45 is due to participants from Jazz backgrounds (see figure 5.22) for the same task comparison, thus suggesting an element contributable to the type of task rather than 'Creativity' per se.

Furthermore, both positive and negative modulation patterns for BA 6, 9, 45/46 did not occur simultaneously, but rather the negative modulations occurred in the Judge set and the positive modulations occurred in the Participant set. Judge and Participant 'Creative' datasets were both primarily 'Improvisation' (80% and 70% respectively), and 'Non-Creative' sets 'Interpretation' (70%), but with an overall overlap of only 40% in extracts in both sets for both 'Creative' and 'Non-Creative' extracts, this could possibly be attributed to

the element of participant subjectivity, showing a specific right hemispheric positive modulation for Improvisational performances.

This overlap of 40 % could also support the positive modulation of BA 32 being due to the Judges choosing extracts that were objectively 'Creative' the majority of the time (i.e the other 60% of the extracts), whereas the Participants own self-assessments could be hit and miss.

The three 'Random' extract sets compared as such: 'Random 1'- 'Random 2', 'Random 1'- 'Random 3' and 'Random 2' – 'Random 3', showed a fluctuation of positive and negative modulations of Brodmann areas between frequencies and temporal evolutions of the performances. These were in the areas that have been mentioned before which is unsurprising as we are using extracts from an overall dataset that is from the same cognitive musical pool, but there was not a consistent pattern.

A positive modulation of BA 32 was *not* found in the Random or participants' datasets' comparisons.

This positive modulation of the left MPFC supported the findings from Braun *et al.*, (2012) for their 'Improvisation' versus 'Conventional' comparisons and makes for a good candidate for creative performances when compared to those that are non creative as the area has many afferent and efferent connections suggesting an integration of motoric and emotional communication. As mentioned earlier, it allows a maintenance of executive control, consciously monitoring and implementing adjustments in an ongoing performance [Miller and Cohen, 2001; Tanji and Hoshi, 2008].

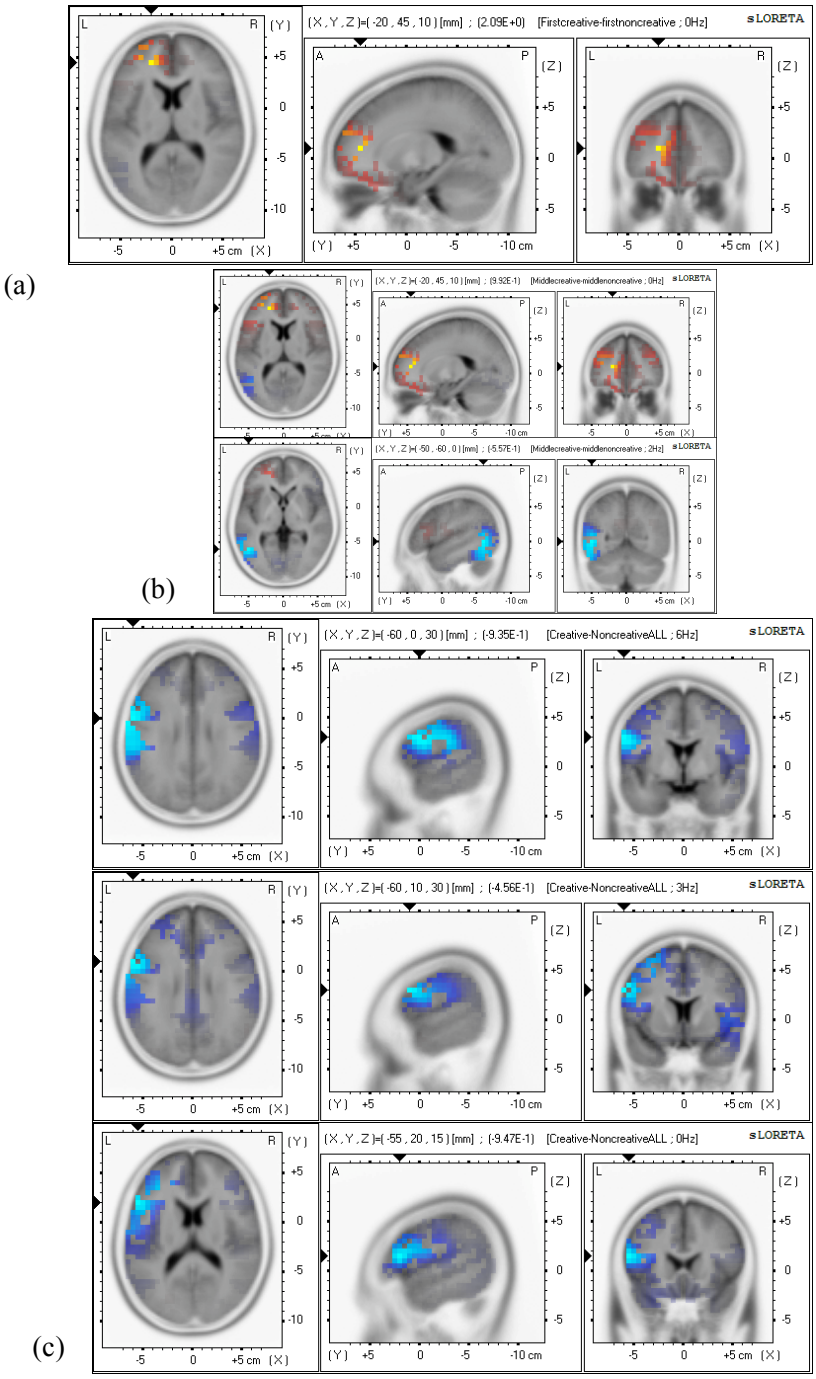


Figure 5.21 Positive and negative modulation patterns of Judge assessed comparisons of 'Creative' versus 'Non-Creative' extracts. (a) The first four seconds of performances, showing a positive modulation in the left BA 32 for the Judges. (b) The second and third rows depicts the middle four seconds of performances, showing a positive modulation in the left BA 32 and negative modulation in the left BA 37 for the Judges. (c) The last four seconds of performances, showing the negative modulations of the left hemispheric BA 6, 9 and 45 for the Judges' dataset. Of note is that BA 32 is a robust consistent indicator of creativity in the initial and middle stages of performance using an objective external assessment. The left negative modulation of the DLPFC accompanies Jazz background creative 'Improvisations' versus 'Interpretations' as per the 'Creative' (80% 'Improvisation' tasks) and 'Non-creative' sets (70% 'Interpretation' tasks).

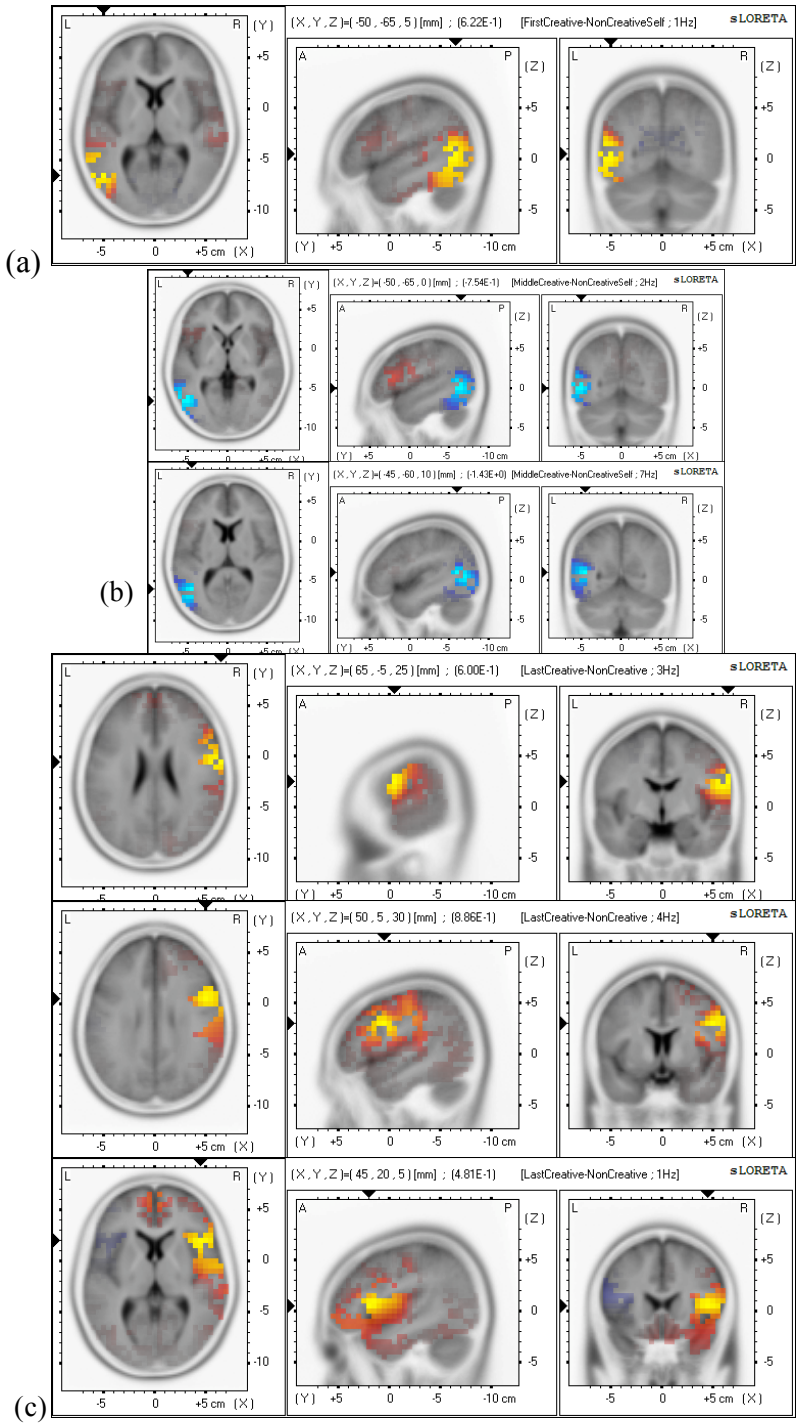


Figure 5.22 Positive and negative modulation patterns of Self-assessed comparisons of 'Creative' versus 'Non-Creative' extracts. (a) The first four seconds of performances, showing a positive modulation in the left BA 37 for Self-assessments. (b) The second and third rows depicts the middle four seconds of performances, showing a negative modulation for the left BA 37 and the left BA 39 for the Self-assessments. (c) The last 4 seconds of performances, showing the right hemispheric positive modulation in the same areas for the Self-assessments. Unlike for the Judges assessments there is no pattern that cannot be attributed to the participants' background with BA 37 to Classical and the DLPFC to Jazz. In addition, there was more fluctuation in the involved areas dependant on frequency bands, unlike BA 32 which was consistent across many frequency bands.

5.4 Summary and discussion of results

Firstly, we will recap the analyses and results of the Judges and Self assessments. After an initial calibration correcting for the Jazz Judges' tendency to systematically mark both Jazz and Classical extracts harsher, both Jazz and Classical Judges' assessments sat on an identity, x=y, for both types of extracts. Analyses revealed a judge and participant inter-rater reliability at participant level and an equal agreement between judges at genre level (Jazz and Classical) across the tasks of 'Improvisation' and 'Interpretation', increasing confidence for further analyses on the extracts themselves. There was a non significant tendency for a higher disagreement amongst judges for 'Classical Improvisation' which could be attributed to the pedagogical unusualness of this task on classical extracts and the difficulty level of the extracts themselves compared to the relatively simpler jazz extracts. Furthermore, it was possible to partition the participants into their corresponding Jazz and Classical backgrounds for further sLORETA analyses based on the ratings which agreed with the phenomenological interview information taken from the participants themselves.

Now we will summarise the major findings of the sLORETA analyses and the anatomical areas of modulation that are suggested to be involved in different musical processes. We are examining the tasks 'Interpret' and 'Improvise' which are in themselves different types of creativity within music but we go a step further of what constitutes as more or less creative within these tasks.

During the tasks of 'thinking' about 'Improvising', an important distinction in the type of mental imagery used to 'Interpretation', emerged in the form of Brodmann Area (BA) 40 rather than BA 37, indicating 'Improvising' having an 'Insight' strategy. This area has previously been implicated in verbal creativity for this 'Insight' strategy but not for music.

Both 'Improvise' and 'Interpret', require more of the semantic processing associated with BA 37 when compared to the baseline of 'thinking' about the task 'Play', suggesting a different form of technical musical processing with the extra cognitive load than just playing the bare bones of the extract presented. On closer inspection, BA 37 is an area that is specifically positively/negatively modulated in Classical musicians which makes sense in light of their close adherence to the score both from an educational training perspective and as a prerequisite of the task certainly when it comes to 'Interpret'. A constant in the activity pattern for BA 37 is the negative modulation in the middle segments of performance when comparing 'Improvisation' to 'Interpretation' in general and also during more creative tasks (assessed by judge and self), indicating a loss of reference to the score even with their

Classical pedagogical background. The role of BA 37 in musical cognitive processing and its association specifically with musicians from a Classical background is a new finding.

BA 7 negative modulation is present strongly in all Improvise comparisons during 'thinking' and 'performing' and is revealed to be something specific to Jazz musicians which also makes sense to the task from anecdotal evidence of being 'in the zone' as it is present during altered states of consciousness such as hypnagogia, sleep states and being under anaesthetia. From section 1.4.2, previous research has linked the hypnagogic state and its corresponding frequency of theta to creativity An activation of BA 7, also corresponds with tasks of focussed attention and decreased bilateral activation which is linked to the integrated task of 'Interpretation'. This area and its negative modulation are suggested to be a strong feature of 'Improvisation' which probably uses conceptual combinations of thoughts and ideas not readily accessible at the conscious level. BA 7 also refers to less episodic memory recall and adherence to an internal mental navigation to the musical notes presented. The role of BA 7 in 'Improvisation' amongst Jazz musicians is a new finding.

The positive/negative modulation pattern of BA 6,9,45 and 46 from the right to left hemisphere respectively, occurs in 'Improvisation' minus 'Interpretation' comparisons only for Jazz musicians, temporally in the last segments of performance, with BA 6 specifically linked to Improvisation. Previous research has linked BA 6 to melody generation (though bilaterally) and the dorsolateral prefrontal area which comprises of BA 9, 45 and 46, to lyrical creativity which our research also supports by the involvement of these areas in the comparison of 'Creative' minus 'NonCreative' datasets. However, our patterns of positive modulation are in the opposite hemisphere possibly due to a combination of the type of creativity (musical rather than verbal) and task comparison ('Improvisation' versus 'Interpretation'). Our 'Interpretation' task seems more similar to their 'Improvisation' task as both are more goal-directed than our task of 'Improvisation'. Interestingly, in the 'Creative' minus 'NonCreative' comparisons there was a constant negative modulation in the left hemisphere for these areas only in the extracts chosen with the Judges' assessments whereas there was a constant positive modulation in the right hemisphere only in the extracts chosen with the Participants' assessments. This might be a possible contender for the subjective experience versus the objective assessment in what constitutes as creative.

The positive modulation of BA 13 or the insula during the task of 'Interpretation' over 'Improvisation', indicates a task that is more goal-orientated utilising conscious error-monitoring, emotionally related inhibition responses, audio-visual integration and rhythmic

temporal auditory processing suggesting a more integrated, inhibitive, conscious and convergent creative task than 'Improvisation'. This is a new more detailed finding in the cognitive differences between the two types of creativity that is investigated further in the behavioural experiment outlined in Chapter 6.

Most importantly, BA 32 is suggested to be an objective indicator of creativity and is robustly present across many frequency bands in the beginning and middle sections of the 'Creative' minus 'NonCreative' comparisons for the extracts chosen as per Judges' assessments and not as per the self-assessments. BA 32 is not present in any other comparisons and is a likely contender to be linked to creativity, from the nature of its functional roles and anatomical links to other parts of the brain. It allows an integration of motoric and emotional communication with a maintenance of executive control, consciously monitoring and implementing adjustments in an ongoing performance.

This finding supports previous research in lyrical verbal creativity, but is novel in musical creativity also because it suggests that judges make their decision for a highly creative performance early within hearing a performance and this is also reflected in the EEG of the performers themselves. This suggests that performances that are more creative are more co-ordinated from the beginning and is supported by recent phenomenological research presented by Lubart and Botella (2013, MIC Conference) on the creative processes of art students characterised from interview and working-diary analyses. Functionally, BA 32 seems to be a good contender as an early indicator as it has in previous research been seen to operate at the surface of intention and action, synthesising information, encoding goals and guiding self-generated, stimulus-independent behaviours. The early recognition by both assessors and the participants (indicated by their EEG pattern of positive modulation) lends weight to the original premise behind our choice of creative assessment in trusting the ability of both performer and audience to know instantly if an inspired performance was to ensue, by simply asking both the question of 'How creative did you think that was ?'. This was on advice of Imperial College Conductor and Member/Director of the Associated Boards of Music, Richard Dickins.

This association between the judges' assessments and EEG completes a loop by confirming an objective psychological impression with neurobiological evidence which could act as an early biomarker in the investigation of ecologically valid musical creativity and is a novel finding. Using sLORETA, we have been able to highlight a few anatomical areas that functionally contribute to the musical brain.

6. Analyses, Results and Discussion of Behavioural Study

In this chapter we are going to describe a behavioural experiment done to augment our picture of the musical creative process and its' subprocesses, done in collaboration with Professor Joydeep Bhattacharya. Referring back to Wallas' classic qualitative model of Creativity (1926) in Chapter 1.2.1., we were specifically interested in the 'Incubation' period which is the second stage in his model and wondered if this is a subprocess also found in the musical creative process of either 'Improvisation' or 'Interpretation'.

Though the case of musical creativity is not a problem-solving one, there is some indication from the results in Chapter 5, that an Insight strategy or 'Aha!' moment exists in 'Improvisation' with the activation of Brodmann Area 40. If there is an indication of an 'Insight' stage in the creative musical process, perhaps this might suggest the existence of an 'Incubation' period.

The 'Incubation' period is a phase when the problem is internalised and is said to be the cradle of creativity as often, famous creative minds report they get their best ideas when not actively working on the problem.

The 'Insight' stage is the third stage in Wallas' proposed model and anecdotally, from these famous creative case studies, seems to emerge out of no conscious forewarning i.e., 'not actively working on a problem', pointing both towards a prior second stage of 'Incubation' and the role of 'unconscious' thought in it.

In fact, Dikterhuis and Meurs (2006), have formulated a theory that unconscious thought processes play a crucial role in generating creative ideas. They suggest that though conscious thought is used to focus on the task at hand, it is less useful for associations which occur more during 'unconscious' thought, using less obvious and easily accessible information and thought systems. This conceptual combination would have obvious benefits for creativity and is suggestive that unconscious thought is a prominent feature in the 'Incubation' period.

'Unconscious' thought can be closely related to 'mind-wandering' also known as 'task-unrelated thought'. It involves a shift of attention away from the primary task, to process some other information that is not obviously goal-directed. This decouples attention from the immediate task, engaging us in internal cognition unrelated to the demands of this external task. It is a very common phenomenon with research suggesting that up to 50% of

waking thought is task unrelated [Killingsworth and Gilbert, 2010]. Unsurprisingly then, the wandering mind correlates with a specific 'default' neural network consisting of cortical and subcortical stuctures that include the posterior cingulate cortex/precuneus, medial prefrontal cortex and the temporoparietal area [Mason *et al.*, 2007] along with the executive network [Christof *et al*., 2009]. As was discussed in Chapter 5, many of these regions also appear to be involved in the musical creative process, specifically of 'Improvisation'.

Through this behavioural experiment, we hope to shed some more light on the subprocesses involved in musical creative thinking. Firstly we can infer whether the 'Incubation' period exists by detecting an effect on performance on inclusion of a 'mind-wandering' task if we accept the prominent contribution of 'unconscious' thought to the 'Incubation' period. Secondly, if it does exist, we can suggest whether this 'Incubation' period, can therefore be the cause of some of the neural activity we have observed in Chapter 5, unveiling a more detailed process for both 'Improvisation' and 'Interpretation'.

Taking the close association of the process of 'mind-wandering','unconscious' thought and the 'Incubation' period as a starting point, we decided to design an experimental protocol that would a) involve a 'task-unrelated' activity (so in this case the task is thinking about and executing a performance) and b) explore what if any effect this had on a musical performance whether 'Improvisation' or 'Interpretation'. The 'task un-related' activity was chosen to be a 'distractor' task used very commonly in psychophysical experimental studies called an 'N-Back' task which involves the use of working memory whilst participants view a sequence of numbers and note a specific number ,'N' places back within the sequence. The experimental design is described in more detail in the 'Methods' section in 6.1.

We hypothesised that the distractor task would be beneficial to the musical creative process and specifically, more beneficial possibly to 'Improvisation' which we suggest is a 'divergent' creative task rather than 'Interpretation' which we suggest is a more cognitively integrated and convergent task as indicated by results in Chapter 5.

This was based on the previous creativity research described above, linking creativity to 'unconscious' thought/'mind-wandering', but also research where performances in creativity tests were positively influenced by mind-wandering [Sawyer, 2011] and specifically in divergent thinking [Sio and Ormerod, 2009 ; Baird *et al*., 2012].

Furthermore, there has been other research linking neural activities (high frequency gamma band power) in participants prior to achieving an 'Insight'-ful solution through tranformative thinking [Seth *et al.*, 2009] and before the 'a-ha' experience whilst solving a

remote associate problem, standardly related to creative thinking [Sandkuhler and Bhattacharya, 2008]. This illustrates both that there is some empirical support for the existence of the 'Incubation' period through these neural activities, but also that it is related to 'Insight'-ful solutions which is a likely subprocess in 'Improvisation'.

6.1 Methods

There were seven participants with an equal ratio of gender and Jazz or Classical Background. Participants are presented with 10 short musical extracts that they were instructed to think about and play by 1) interpreting the piece with the composer's markings and, 2) improvising freely on the extract or some aspect therein such that the extract is still recognizable to the listener. It is important to note participants have to strictly adhere to only *think* of playing the extract as instructed for a finite period of time and then subsequently *play* it as instructed.

Each extract and set of manipulations was presented twice (total number of four times) via two tasks: conscious and unconscious. The conscious task involves the participant specifically thinking about playing the extract in a focused manner for two minutes and then asked to play it. The unconscious task involves dividing the thinking section into thinking about playing the extract for 30 seconds, doing a 2-back 'distractor' task for 85 seconds and the remaining 5 seconds is back to thinking about playing the extract before the participant is subsequently asked to play as instructed.

The 2-back task is done by presenting a sequence of numbers displayed for a second each and the participant is asked to indicate whether every 2nd number is identical, i.e., whether the number, two numbers previously is the same as the one being currently presented. If not fast enough or missed, they are informed with a message of Incorrect. Participants' performance at the 2-back task is recorded and seen as an indication of how well their attention has been focused on the task and thus distracted from the instruction of thinking about playing the extract.

After each manipulation, participants are asked to rate their own performance by judging their creativity from a scale of 1 to 5, (1 being very poor, 2 being poor, 3 being neutral or ambivalent, 4 being good and 5 being excellent).

The 10 extracts were composed entirely for the purpose of the experiment in order not to be recognized by the participant. This is so as not to have a memory component during 'Interpretation' and 'Improvisation'. The extracts are varied in style, rhythm and key so as to

avoid bias due to preference and are for two hands on piano with composer's markings. We are grateful to composer Matthew Lee Knowles, for composing these extracts, see figure 6.1 for two examples.

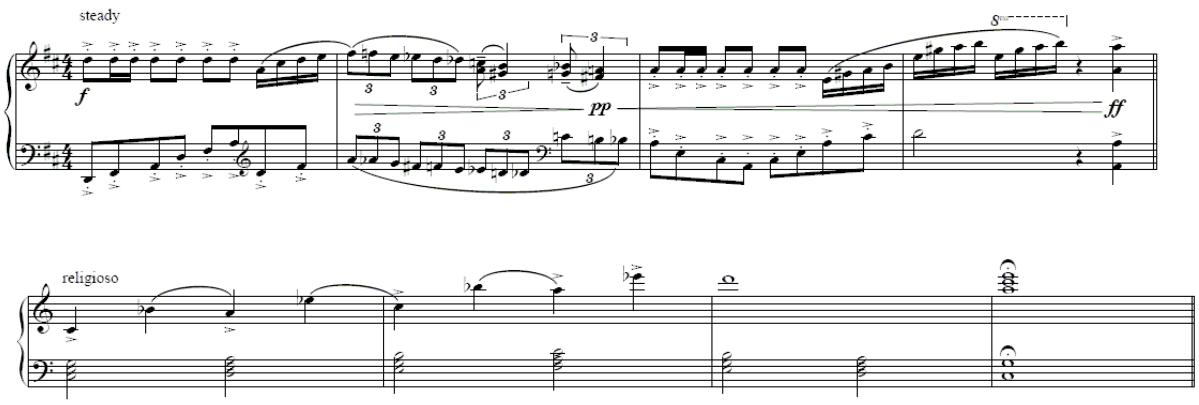


Figure 6.1 Two examples of the ten musical extracts presented to participants during the 'conscious' and 'unconscious' tasks.

6.2 Results

A statistical test, 'Analysis of Variance' (ANOVA), to investigate the significance of any differences on performances due to the different attentional tasks, was applied on the self-ratings of the participants. Briefly, an ANOVA is used to test for significant differences between means of multiple groups by comparing variances. The null hypothesis would be that there are no mean differences between groups in the population so therefore the variance estimated based on within-group variability should be about the same as the variance due to between-groups variability. Comparing the two estimates of variance via the *F* test, examines whether the ratio of the two variance estimates is significantly greater than 1 as we would expect some minor random fluctuations within a small sample size. The *p*-value indicates the significance of the *F* value if above 1 (normally $p<0.05$ to allow for 5% chance) and the eta^2 is a measure of the degree of association between the effect and the dependent variable and is calculated by the proportion of variance in the dependent variable that is attributable to each effect within the sample.

We performed a 2x2 factorial repeated measures ANOVA with two factors: Task with two levels ('Improvise' versus 'Interpret'), and Attention with two levels ('Unconscious' versus 'Conscious'), see figure 6.2.

The interaction between Task and Attention was found to be marginally significant (F(1,7)=4.43, p = 0.073, eta^2 = 0.388). No main effect was found to be significant, but using a t-test, which compares significances between two groups, for the Interpretation task, focused 'conscious' attention led to a significantly better performance than distracted 'unconscious' attention (t(7)=3.44, p=0.011). For the improvisation task, no significant difference was observed between the two attention conditions (p>0.7).

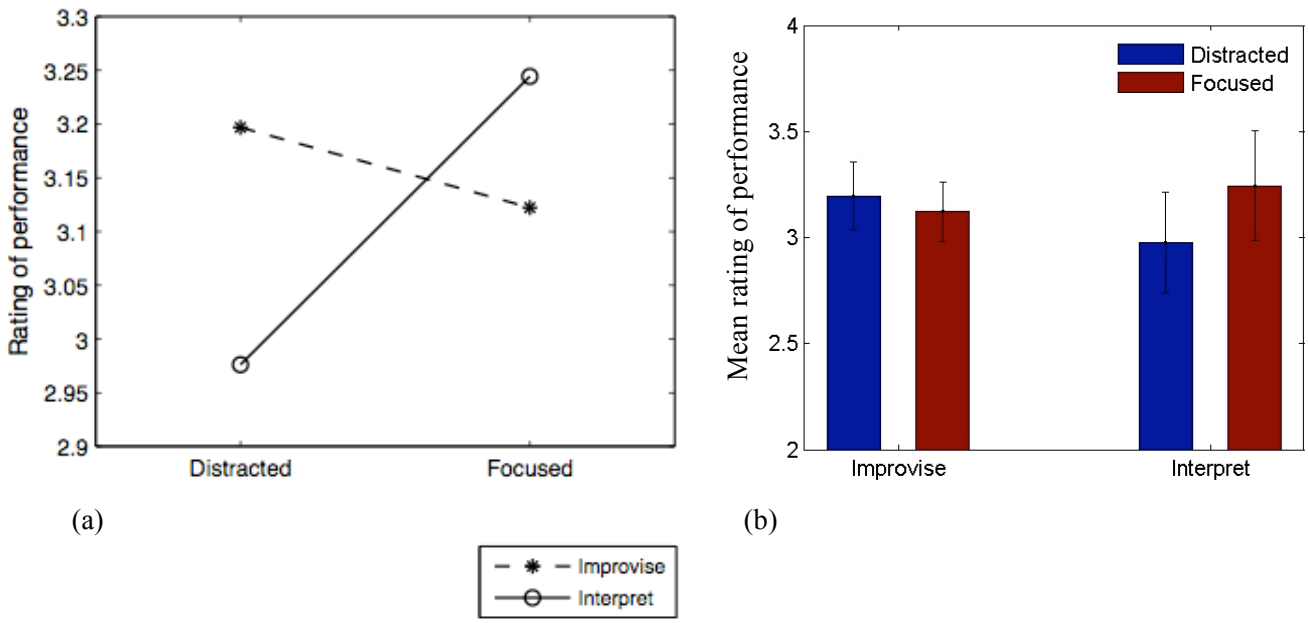


Figure 6.2 (a) A 2x2 factorial repeated measures ANOVA with two factors was performed: Task with two levels (Improvise versus Interpret), and Attention with two levels ('Unconscious' versus 'Conscious'). Notably, for the 'Intepretation' task, focussed 'conscious' attention led to a significantly better performance and there was a marginally significant interaction between Task and Attention. (b) Bar graphs of the mean participants self-ratings of performances during the different tasks and attentions showing one standard error of mean.

6.3 Discussion

The data suggests that as compared to focussing, distraction impairs musical performance (subjectively perceived) only during the creative musical task of 'Interpretation'. For musical tasks like 'Improvisation', distraction leads to a similar performance.

This supports the second half of our hypothesis with regards to 'Interpretation' not being positively contributed to by distractor tasks (and the implied 'Incubation' period). It also supports other research where, the 'Incubation' period specifically aids divergent

thinking and not convergent thinking and in our case has even resulted in a negative contribution implying that the 'Incubation' period is not a sub-process for the musical creative tasks of 'Interpretation'.

However, does the 'Incubation' period contribute to the musical creativity process at all and specifically the divergent creative process that is 'Improvisation' ? Though not significant, there is an indication of a better performance after a distracted task and there is a marginal significance in the interaction between Task and Attention. This could mean several things that could be clarified by further research.

Baird *et al*. (2012) report that the benefits of incubation intervals are greater in divergent thinking tasks when individuals are distracted by less demanding mind-wandering tasks. The 'N-back' distractor task was a very mentally occupying task and perhaps a less demanding distractor task is required to allow more mind-wandering. If a greater positive effect is seen with this new distractor task, one could suggest that mind-wandering and the closely associated 'unconscious' thought does indeed contribute to the subprocess of 'Incubation' within the musical creative process of 'Improvisation'.

However, if this does not result in a greater positive affect, then one needs to ask a further question of whether it is 'unconscious' thought that is contributing to the 'Incubation' period. In this case, the 'N-back' distractor task could be conserved but more participants should be added to the study to increase the sample size to see if this would make the effect of the distractor task on 'Improvisation' more significant. Equally, adding the element of 'objective' judge assessments as in the EEG study, could also influence the statistics (also in the case of 'Interpretation'), as participants' self assessments could simply be a case of rating difficulty and the resultant frustration with their performance rather than the creativity. This could especially be the case for 'Interpretation' where participants have more overt goals to achieve such as adhering to accuracy of sight reading and the composer's markings and a distractor task does not aid in a task that requires conscious attention.

Given the slight tendency of improvement in 'Improvisation' with the distractor task, if the above two modifications in experimental design still do not lead to a significant positive effect, only then could one suggest that the musical creativity task of 'Improvisation' does not involve a subprocess of 'Incubation'. As it stands however, it is still open to interpretation whether the deactivation seen in the precuneus specifically for 'Improvisation' is due to the 'Incubation' period and related to the default network suggested by Mason *et al.*, 2007. Given the marginal significance in the interaction betweeen Task and Attention, the temporal

evolution and shape of the 'Improvisation' task with the deactivation of the precuneus being present only in the beginning and middle segments, suggests a possible 'Incubation' period leading to a final 'Insight'-ful completion of a 'creative' performance.

6.4 Summary

In this chapter, we outlined a behavioural study that investigated the existence of a sub-process of 'Incubation' within the musical creative tasks of 'Improvisation' which we suggest to be divergent and 'Interpretation' which we suggest to be convergent based on results found in Chapter 5.

We simulated the 'Incubation' period by presenting participants with a distractor task within the two musical tasks, hypothesising that there would be no effect on 'Interpretation' but expecting to see an improvement in 'Improvisation' as measured by participants self-assessments.

Analysing the results showed a significant decrease in performance in 'Interpretation' tasks when participants were presented with the distractor task implying that 'Incubation' was not a sub-process for a conscious convergent creative musical task such as 'Interpretation'.

Though the difference in performance due to the distractor task for 'Improvisation' was not significant, there was a tendency and moreover the interaction between Task and Attention was marginally significant. Given the experimental findings in Chapter 5 of the temporal role of the precuneus in 'Improvisation' we suggest further experiments that would either increase the sample size or use an easier distractor task.

7. FINAL STUDY: NETWORK ANALYSES

Having explored the anatomical and associated behavioural foundations of musical creativity in the previous chapters, in the following chapter we will outline a characterisation of the functional connections in these brain areas via some network analyses. Hearkening back to the pilot study, we'll be looking at the measure of phase synchrony between electric signals corresponding to each of the 64 electrodes used in the EEG recordings. This work was done in collaboration with Ernesto Pereda and Joydeep Bhattacharya my co-supervisor.

7.1 Methods

7.1.1 Data segments

For each of the eight subjects, one segment of the first 4 seconds each, downsampled at 512 Hz (2048 data samples), was selected for each of the 10 extracts of the two genres of music (Jazz and Classical) and the three 'Performance' tasks of 'Play', 'Interpret' and 'Improvise'.

7.1.2 Phase synchronization indexes

For the assessment of phase synchronization between the signals of two electrodes, it is first necessary to estimate the phases of each EEG signal, a procedure that consists of two steps. First, the raw data $x_i(t)$ were band pass filtered in the frequency band of interest (say, the alpha, α, band) using a finite impulsive response (FIR), zero-phase distortion filter. Then, this real-valued filtered data $x_{i\alpha}(t)$ is converted into a complex-valued one as described in Chapter 5,

$$x_{i,\alpha}(t) + jx_{i,\alpha}^{H}(t) = A(t)e^{i\varphi(t)} \tag{8.1}$$

where j = is the imaginary unit, A(t) is the instantaneous amplitude, φ is the instantaneous phase, and $x_{i,\alpha}^{H}(t)$ is the Hilbert Transform of the filtered data, namely:

$$x_{i,\alpha}^{H}(t) = \frac{1}{\pi} p.v. \int_0^N \frac{x_{i,\alpha}(\tau)}{t-\tau} d\tau \tag{8.2}$$

where p.v. stands for the Cauchy principal value and the instantaneous phase $\varphi_{i,a}(t)$ is then defined as:

$$\varphi_{i,\alpha}(t) = \arctan\left(\frac{x_{i,\alpha}^{H}(t)}{x_{i,\alpha}^{H}(t)}\right) \tag{8.3}$$

The cyclic relative phase (i.e., restricted to the interval [0,2π] between EEG electrodes *i* and *k* (*i*, *k*=1,…, 64) is finally obtained as:

$$\varphi_{ik,\alpha}(t) = |\varphi_{i,\alpha}(t) - \varphi_{k,\alpha}(t)| \bmod 2\pi. \tag{8.4}$$

Assessing the degree of phase synchronisation between two electrodes comes down to an estimate of whether the distribution of (2.1), which is a circular variable, is different to what would be expected for two independent data signals. This estimation can be done in different ways (see, e.g., [Pereda *et al.*, 2005; Vinck *et al.*, 2011]). Here, we used the mean phase coherence (also termed Phase Locking Value, PLV, [Mormann *et al.*, 2000]), which is a measure of how homogeneously spread the relative phase is over the unit circle:

$$PLV_{ik,\alpha} = \frac{1}{n_s}\left|\sum_{\tau=1}^{n_s} e^{j\varphi_{ik,\alpha}(\tau)}\right| \tag{8.5}$$

This index ranges between 0 (no phase synchronisation) and 1 (complete phase synchronisation) and has been used many times in M/EEG analysis (see, e.g., [Pereda *et al.*, 2005]). The PLV index was calculated using the recently released Matlab® toolbox HERMES [Niso *et al.*, 2013].

In our case, the data were filtered in non-overlapping consecutive frequency bands of 4 Hz bandwidth in the range 4-50 Hz, and the values of PLV were then averaged to estimate PS in four of the "traditional" frequency bands θ: (4-8 Hz), α: (8-16 Hz), β: (16-30 Hz) and γ: (30-50 Hz).

7.1.3 Estimation of graph theoretical measures

Once the degree of phase synchronisation between any two electrodes was assessed by means of the PLV, the corresponding interdependence matrix:

$$A = \begin{pmatrix} PLV_{11} & \cdots & PLV_{1n} \\ \vdots & \ddots & \vdots \\ PLV_{n1} & \cdots & PLV_{nn} \end{pmatrix} \tag{8.6}$$

where n=64.

In the context of multivariate EEG analysis this matrix can be regarded as the weighted adjacency matrix of a complex network, where the electrodes are considered as nodes and the PS indexes measure the strength of the links between them [Rubinov and

Sporns, 2010]. From this adjacency matrix, it is possible to estimate different measures, which give insight into the brain network's structure and function.

7.1.4 Thresholding

The first step in this direction consists of determining which of the PLV values should be considered significant. There are different approaches for this largely unsolved question [Fornito *et al*., 2013; Langer *et al*., 2013]. Here, we used the fixed density approach [Fornito *et al*., 2013], in which the values of PLV_{ij} are rank ordered for each adjacency matrix, and the k*N_{LINKS} highest values are considered significant (where $0<k<1$ is the fixed density of significant links, and N_{LINKS}=Nchan*(Nchan)/2=2048 is the total number of possible links). In line with recent studies (e.g., [Kim *et al*., 2013; Quraan *et al*., 2013]), we calculated the network measures for different values of k to check that the results were robust against this parameter.

7.1.5 Network measures

To characterize the structure of the weighted undirected functional connectivity brain network so constructed, we calculated three different measures: the *strength*, the *clustering* and the *efficiency*, which characterize network centrality, segregation and integration, respectively [Rubinov & Sporns, 2010; Newman, 2010].

The average strength of the network, S, is defined as:

$$S = \frac{1}{N}\sum_{i\in N} S_i = \frac{1}{N}\sum_{i\in N}\sum_{j\neq i\in N} PLV_{ij} \tag{8.7}$$

where S, the strength of each individual node, is the sum of weights of the links connected to the node, and provides a simple estimation of the importance of the node within the network.

The clustering coefficient C quantifies the tendency of network elements to form local clusters. The presence of network clusters indicates segregated functional dependencies in the brain. In its weighted version [Onnela *et al.*, 2005], it is defined as:

$$C = \frac{1}{n}\sum_{i\in N} C_i = \frac{1}{n}\sum_{i\in N}\frac{2t_i}{k_i(k_i-1)} \tag{8.8}$$

where k_i is the density of node i, (i.e., the number of nodes it connects to normalized to the total possible number of connections), C_i is the clustering coefficient of node i (C_i =0 for d_i <

2), and t_i is the number of triangles around a node i, defined by the geometric mean of triangles around it:

$$t_i = \frac{1}{2} \sum_{j,h \in N} \left(PLV_{ij} PLV_{ih} PLV_{jh} \right)^{1/3} \tag{8.9}$$

Finally, the measure of integration is the local efficiency [Latora and Marchiori, 2001], which can be understood as a measure of how well each subgraph communicates when the index node is eliminated [Achard and Bullmore, 2007].

$$E_l = \frac{1}{N} \sum_{i \in N} \frac{\sum_{\substack{j,h \in N \\ i \neq j}} \left(w_{ij} w_{ih} - \left[d_{jh}^{w}(N_i) \right]^{-1} \right)^{1/3}}{k_i \, (k_i - 1)} \tag{8.10}$$

where $d_{jh}(N_i)$ is the length of the shortest path between nodes j and h, that contains only neighbours.

All network measures were calculated using the Brain Connectivity Toolbox for Matlab® [Rubinov and Sporns, 2010].

7.1.6 Statistical Tests

The comparison of brain networks can be carried out at two different levels: global and local [Meskaldji *et al.*, 2013]. Indeed, the three network measures described above are calculated locally (at each node) and then averaged to produce a global estimation of the corresponding feature. Consequently, we perform the statistical test at these two levels.

7.1.6.1 Global comparisons

At the global level, we used a 2x3 repeated measures ANOVA test, with *Music* (Jazz vs. Classical) and *Performance* ('Play', 'Interpret' & 'Improvise') as dependent factors to check for differences in the values of the measures in each of the four frequency bands. When any of the factors (or their interaction) was significant at the $p<0.05$ level (Bonferroni corrected for multiple comparisons due to the four bands), differences were further analysed using appropriate post-hoc comparisons.

7.1.6.2 Local comparisons

Local comparisons at the electrode level were carried out to elucidate the topography of the global differences, in those cases where the corresponding ANOVA test was significant. In that instance, a paired t-test was applied to the three local measures at each electrode, and then

corrected for multiple comparisons using a type I False Discovery Rate (FDR) [Benjamini and Hochberg, 1995] at the q<0.1 level.

7.2 Results

7.2.1 Global level

At the global level, there were significant differences between the two levels of the *Music* factor, Classical as compared to Jazz, for the three network indexes (S, C and E) and the three values of *k* analysed ([0.8 0.6 0.4]) for the three highest frequency bands α, β and γ. The whole picture is presented in table 7.1. As an example, figures 7.1 to 7.3 show the values of the indexes for the β band (k=0.8), which presented the greatest increases when comparing Classical music over Jazz.

	Strength			*Clustering*			*Efficiency*		
k \ Freq	*a*	*b*	*g*	*a*	*b*	*g*	*a*	*b*	*g*
0.8	*	**	*	**	**	**	*	**	*
0.6	*	**	*	*	**	*	*	**	*
0.4	*	**	*	*	*	*	*	*	*

Asterisks indicate the level of significance, with *: p<0.05, **: p<0.01

Table 7.1: Differences between the two music types (Classical vs. Jazz) for each network index averaged across playing styles for the three densities considered and the three highest frequency bands. The β band consistently shows the highest significance in difference in *strength, clustering* and *efficiency* revealing an increase in this frequency band for Classical music as compared to Jazz music for these three network measures.

7.2.2 Local level

As commented above, we further analyse the topography of the differences for the *Music* factor for the α, β and γ bands. As a representative example, figure 8.2(a) presents the results for the S index shown in figure 8.3(a). The most important differences are localized in the fronto-central region, with a clear right hemisphere lateralization.

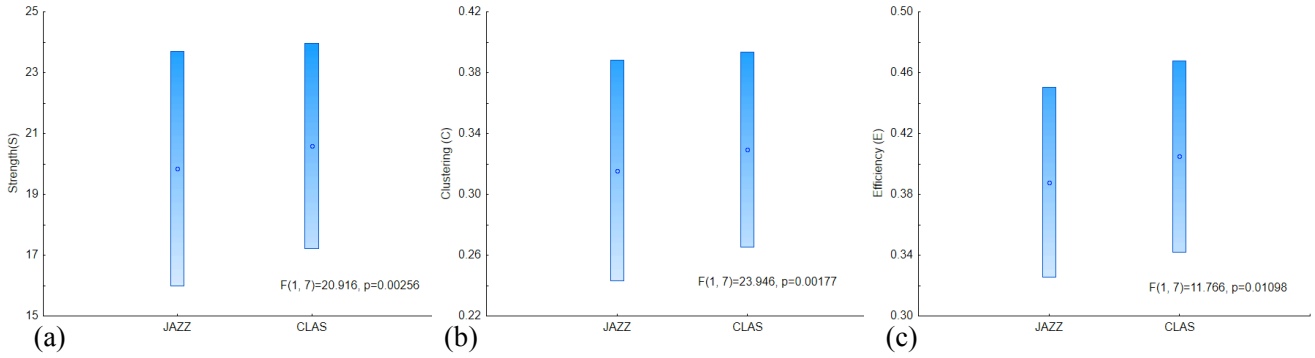


Figure 7.1 The (a) Strength (S) (b) Clustering (C) and (c) Efficiency (E) averaged across electrodes, subjects, performance type and excerpts for the two genres of music (Jazz and Classical) for the β band (k = 0.8). The bars indicate 95% confidence interval for the mean value. The corresponding F and p values are indicated in the right bottom corner of the figure.

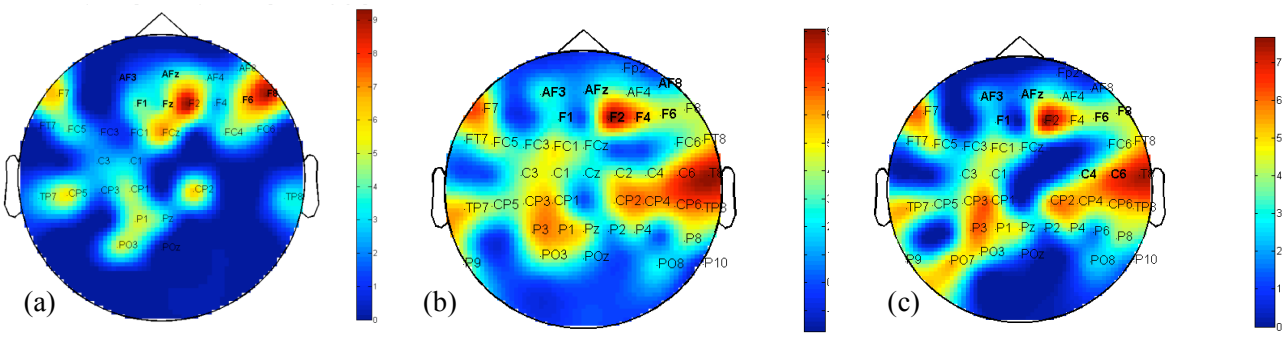


Figure 7.2 Topography of the differences for the (a) S index (b) C index and (c) E index (as shown in figure 7.1: β band, k = 0.8) between the two genres of music (Jazz and Classical), averaged across subjects, extracts and performance types, and expressed as the percentage of increase with respect to the Jazz condition. The labelled electrodes are those showing significant differences at the q<0.1 level (FDR type I test) and the ones in bold were some of the electrode positions that corresponded to activation patterns in the comparison of 'creative' minus 'non-creative' datasets using sLORETA.

7.3 Discussions

The results above indicate that the brain network is more efficient and more strongly synchronised and integrated when participants are playing Classical extracts as compared to Jazz extracts.

Curiously for the complementary sLORETA results when comparing Classical extracts to Jazz extracts averaged across all participants and playing tasks, we actually found

a greater activation in the same right hemispheric fronto-central region but for Jazz extracts over Classical extracts for the bands α and β, see figure 7.3.

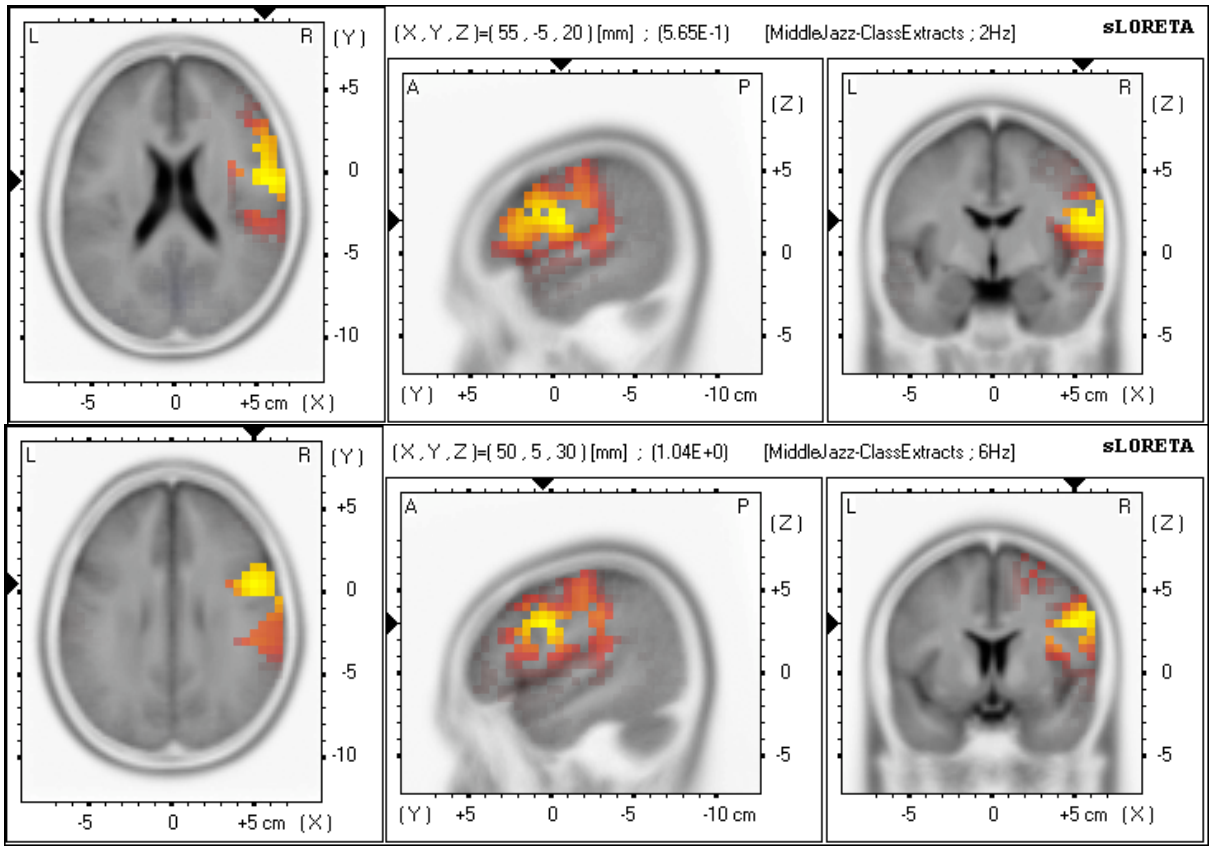


Figure 7.3 Two panels indicating a greater activation in the right fronto-central area whilst participants performed Jazz extracts over Classical. The top panel shows the α band and the bottom, the β band.

This indicates that though there is an increase in β activity (current density amplitude) during the performance of Jazz extracts, this is more phase locked and integrated suggesting an increase in connectivity, during the performance of Classical extracts.

With the combination of the sLORETA results and some preliminary network analyses we can begin to reveal a more comprehensive picture of not only what brain areas are involved in musical creativity but also how they interact. In this vein, more network analyses matching both Judge and Self assessments to network measures could yield novel results. In addition, other measures could be used such as Mutual Information which is a stricter measure than correlation and discounts spurious connections due to scalp conduction, to reveal a more robust functional connectivity. Further down the line it would be very useful to assess an effective connectivity that takes into account the direction of connectivity perhaps by using measures such as Granger Causality.

7.4 Summary

In this chapter we outlined a connectivity measure of phase synchrony called Phase Locking Value (PLV) with which we then constructed an adjacency matrix in order to form a network using three different thresholding values, k. At each k value, we calculated three network measures of strength, clustering and efficiency at the node (electrode) level and then averaged to produce a global estimation of the measure.

Using a 2x3 repeated measure ANOVA test, a significance was detected at the global level, between the two types of music, such that the brain network when playing Classical music rather than Jazz, was more efficient, strongly synchronised and was organised in more local clusters implying segregated functional dependencies. These were found to be mostly in the frequency band, β across all three threshold, k values, in the right fronto-central region.

When investigated, with respect to the current density amplitudes and areas of activation with sLORETA, the same right fronto-central region was shown for the β band. However, the pattern of activation was for Jazz music over Classical music leading to the tentative suggestion that though there is an increased β activity during the performance of Jazz extracts, this is more phase locked and integrated during the performance of Classical Extracts.

SUMMARY AND OUTLOOK

The study of creativity is an important challenge for complexity science. It requires a breadth and depth of understanding that needs to be reflected in the comprehensiveness of any experimental design of research done into it. Coloured by as many disciplines and genres that can manifest creativity, there is also the question of the many branches of academia that pursue it, from neuroscience to musicology and philosophy to mathematics, creativity rests under the heading of a complex system as a truly interdisciplinary endeavour. Our challenge has been to integrate the many avenues and approaches into an ecologically valid study of musical creativity in particular.

In order to characterise a topic that is in danger of almost being too vast to contain or even conceptualise, we thought to pinpoint a few key markers that are both creativity's drivers and its manifestations, by in the first instance attempting to quantitatively note agreements between a generator and an observer of creativity. These agreements are inherently self-referential inside the creative system by its very nature, and thus both participants and external judges were given the same assessment ratings of 1 through to 5 (1 being very poor and 5 being excellent), and asked the same question based on a gut instinct assumed to be felt by both, of 'How creative did you think that was?'. The simplicity of this approach was justified as both judges and participants showed an inter-rater reliability at participant level with no significant differences of opinion amongst judges with respect to the genres of Jazz and Classical music across all extracts and the different creative tasks of 'Improvisation' and 'Interpretation'. This reliability, along with the ability to partition the participants into their corresponding Jazz or Classical pedagogical and performance backgrounds, from the ratings alone, increased our confidence for further analyses on the EEG of the extracts themselves.

Which brings us to the third key marker of detecting a signature with no prior assumption of the underlying neurobiological mechanism but a dearth of qualitative and some quantitative observational knowledge from other researchers. By investigating extracts that were deemed to be creative by judge assessments, we completed a loop, confirming an objective psychological impression with the neurobiological evidence of source localisation activation in the left hemispheric Brodmann Area (BA) 32 as an exciting early indicator of creativity within a performance. This was a novel indication in the context of musical creativity and was supported by research into verbal lyrical creativity [Braun *et al.*, 2012]. It

is also a novel neurobiological finding that suggests that performances which are more creative are more co-ordinated from the beginning and is supported by recent interview and working-diary analyses done on art students [Lubart and Botella, 2013]. Strategically placed anatomically, BA 32 has many afferent and efferent connections allowing a motoric and emotional integration. Also known to be a part of the medial prefrontal cortex (MPFC), it has previously been linked to operating at the surface of intention and action, synthesising information, encoding goals and guiding self-generated, stimulus-independent behaviours [Soon *et al.*, 2008 ; Ramnani and Owen, 2004 ; Tsujimoto *et al.*, 2010 ; Passingham *et al.,* 2010; Haggard, 2008]. All of which seem important characteristics of creativity.

Using the source localisation software, sLORETA, on our EEG recordings, in addition to BA 32, we were able to highlight a few other anatomical areas that functionally contribute to the musical brain. These include BA 40, 7, 37 and 13.

Having investigated the *where* it was time to look at the *how* by (a) attempting a classification of the different musical creativity tasks, through an identification of sub-processes in referral to the original qualitative models, and (b) by investigating the mechanisms of functional connectivity in these tasks through network analyses.

BA 40 was activated during the task of 'thinking' about 'Improvisation' which is novel for musical creativity though it has previously been linked to an 'Insight' strategy in verbal creativity [Betchereva *et al.*, 2004]. This finding could suggest a possible type of creativity that 'Improvisation' may be, because in Wallas' seminal qualitative thought model, the 'Insight' stage is preceded by an 'Incubation' period which is characterised by 'Unconscious' thought [Dikterhuis and Meurs, 2006] and said to be present in 'divergent' creative tasks [Sio and Ormerod, 2009 ; Baird *et al*., 2012]. Building upon this, BA 7, also known as the precuneus, was another novel result found to be consistently deactivated during both thinking about and performing 'Improvisations' by Jazz musicians. This area has previously been linked to a default 'wandering mind' network and altered states of consciousness such as sleep states, being under anaesthesia and notably hypnotic hypnagogic states which has previously also been linked to creativity [Green *et al*., 1970; Dietrich, 2004; Maquet *et al.*, 1997; Maquet *et al.,* 1996 ; Rainville *et al.,* 1999; Fiset *et al.,* 1999; Laureys *et al.*, 1999; Mason *et al*., 2007] .

We conducted a behavioural study that introduced distractor tasks within the cognitive musical tasks, to investigate whether if a sub-process of 'Incubation' contributed to 'Improvisation' and whether this then could be related to the involvement of BA 7. There was

a marginally significant interaction between the task and the attention factors and a non-significant tendency to improve in 'Improvisation' after a distractor task, as per self-assessments. The collective findings may suggest that 'Improvisation' is a divergent creative task with a sub-process of an 'Incubation' period but further investigation is certainly warranted to stake a conclusive claim.

On the other hand, there was a significant increase in performance for 'Interpretation', as per self-assessments, after conscious, focussed conditions within the task. This finding along with the involvement of BA 13 activation during 'Interpretation' performances, which has previously been linked to conscious error-monitoring, emotionally related inhibition responses, and audio-visual integration [Shafritz *et al*, 2006; Klein *et al.*, 2007; Lewis *et al.*, 2000], strongly suggests that 'Interpretation' is a convergent goal-oriented creative task that is more integrated, inhibitive and conscious than 'Improvisation' and does not involve a sub-process of 'Incubation'. These combinations of results allow us to classify the musical creative task of 'Interpretation' into an accepted general type of creativity using convergent thinking, with more detailed information about its subprocesses which has hitherto not been done before.

Conventionally speaking, Jazz musicians usually improvise and Classical musicians interpret, but in our study we have placed them out of their comfort zones by asking them to do the other musicians' normative tasks. However, we can infer from the suggestive results that the type of musical creative task is closely linked to the genre of music as can be seen by the activation of BA 7 only for Jazz musicians whilst improvising which favours lower states of attention and divergent thinking processes, the activation of BA 13 only during interpretation which favours conscious error-monitoring and integrated convergent thinking processes, and the activation of BA 37 only for Classical musicians that underlies semantic processing and a close adherence to the musical score.

Subsequent network analysis using the phase synchrony connectivity measure, of phase locking value, PLV, also shows a brain network that is significantly more integrated during the performance of Classical music, a feature that is suggested for the creative task of 'Interpretation' itself. Network analysis also showed an increased clustering indicating segregated functional dependencies again pointing to a more convergent functionality.

Difficulty in handling continuous unequally durationed time series in complex analyses, meant we had to take a step back and resort to more conventional neuroscientific methods involving localisation and modality to help narrow our field of search. In order to

investigate global mechanisms and patterns we had to start at a more local functional scale. Promisingly, when investigating the same genre comparisons of Classical music with Jazz across all tasks with sLORETA, as in the network analysis, the same areas of activation were found. Excitingly, a more detailed possible mechanism emerged with this complementary analysis as though there was significantly increased β frequency band activity (16-30Hz) whilst performing Jazz music, this activity was more integrated and phase locked during the performance of Classical music.

The complementary procedure of network analyses would certainly be an avenue to pursue further by including other measures, to PLV, that investigate the *effective* connectivity in addition to the *functional*. One could examine a more detailed network by focussing on direction of activation by measures such as Granger Causality and also matching individual participant and judge assessments to their corresponding brain networks during extract performances and noting the differences in a quantitatively coherent manner.

As an example, the presence of the left BA 32 in extracts deemed to be objectively creative by external judges, also indicates a role of integration in the initial stages of a creative task. BA 32 being anatomically well-connected, indicates that it acts as an important hub in the musical brain network that allows access to disparate areas and therefore possibly subsystems. Therefore, the directionality and temporal characteristics of BA 32 connectivity should be further investigated with network analyses using Granger Causality and directed Mutual Information as measures for the adjacency matrix. Having seen a temporal evolution in activations within the different types of performances, it would certainly be worthwhile to investigate temporal network dynamics in more detail now that we have localised key functional areas of BA 7, 13, 32 and 37.

To further pursue the findings from this study, I would re-design the experiment knowing what we do now. First and foremost, I would limit the performance of ‘Play’, ‘Interpret’ and ‘Improvise’ to all be of the constant time duration of 15 seconds. This is a compromise, drawing from the distribution of durations of performances during these different tasks (figure 5.1) and certainly to give enough time for ‘Improvisation’ tasks so as not to rush the participant.

The reasons for this are three-fold:

a) To be able to comparatively analyse the different tasks with one another given the same time duration as this would allow a second per second, one-to-one temporal mapping between

the tasks and give us the opportunity to investigate the temporal dynamics in a clearer fashion.

b) To make it intrinsically easier to assess for both external judges and participants which it would be the shorter the performances are, but in addition to then allow the assessments for 'Interpretation' and 'Improvisation' be more on a par with each other and allow a more direct neurobiological indication of creativity with the recorded EEG, rather than having an open-ended question as to which section of the performance (beginning, middle or end) was related to the final assessment.

c) For 'Improvisation', to give participants the ability to shape their performances in a limited time frame so that one might even see an activation pattern similar to what has been found in the EEG in this study, but more intensely and coherently in a shorter time span.

I would also choose the extracts differently such that both Jazz and Classical extracts would have a similar difficulty level for a performer. The desire would be for all the extracts to be easy to perform, which would require the Classical extracts to decrease in difficulty level to match the Jazz extracts. This would be beneficial to the assessment inter-rater reliability, drawing from the 'Max-Min' profile of the judges across the different genres, where 'Classical Improvisation' had the greatest disagreement and 'Jazz Interpretation' the least, see figure 5.4.

Looking at the close link between genre and type of creative task, for any future investigation I would divide participants into their pedagogical and performance Jazz and Classical backgrounds and only present them with their normative tasks and genre extracts, such that Jazz musicians would be asked to improvise on Jazz music and Classical musicians to interpret Classical music. This would allow us to concentrate more deeply on each type of musical creative task and increase sample size for each genre/task cohort. Statistically speaking, the activation patterns from both can then be compared by taking the maximum activations using sLORETA of each task on their own (e.g. 'Jazz improvise' or 'Classical interpret' or 'play' for both) rather than comparing tasks within the sLORETA software. These activations can then be compared as 'between' the groups of 'Jazz improvise' and 'Classical improvise' using a non-parametric statistical test for independent sample populations, to lend more statistical weight to any activation patterns found.

Finally, I would combine the behavioural experiment and EEG investigations into one study by introducing a distractor task (easier than the 2-back) and allowing a focussed period, for each instance of Jazz improvisation or Classical interpretation whilst recording EEG. This

is in order to record neurobiological data during the so-called ‘Incubation’ period and also to detect any changes in activation pattern during performances after a distractor task to give us a more objective quantitative measurement than the participants’ self-assessments.

Creativity is a complex problem which we have begun to scratch the surface of by refining and attaining a balance in our scientific approach of conventional reductionist experimental design whilst simultaneously integrating and monitoring several ecologically valid factors in the examination of a real-life process. Similarly looking forward in analyses, a combination of neuroscientific localisation methods, and global and temporal state characterisation complexity methods, only one of which is network analysis, seems to be most promising.

Similarly looking forward in analysis, what seems most promising is a combination of neuroscientific localisation methods, with global state and temporal complexity characterisations. So far in our study, the latter that has been more realistically approachable is that of network analysis.

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Appendix A

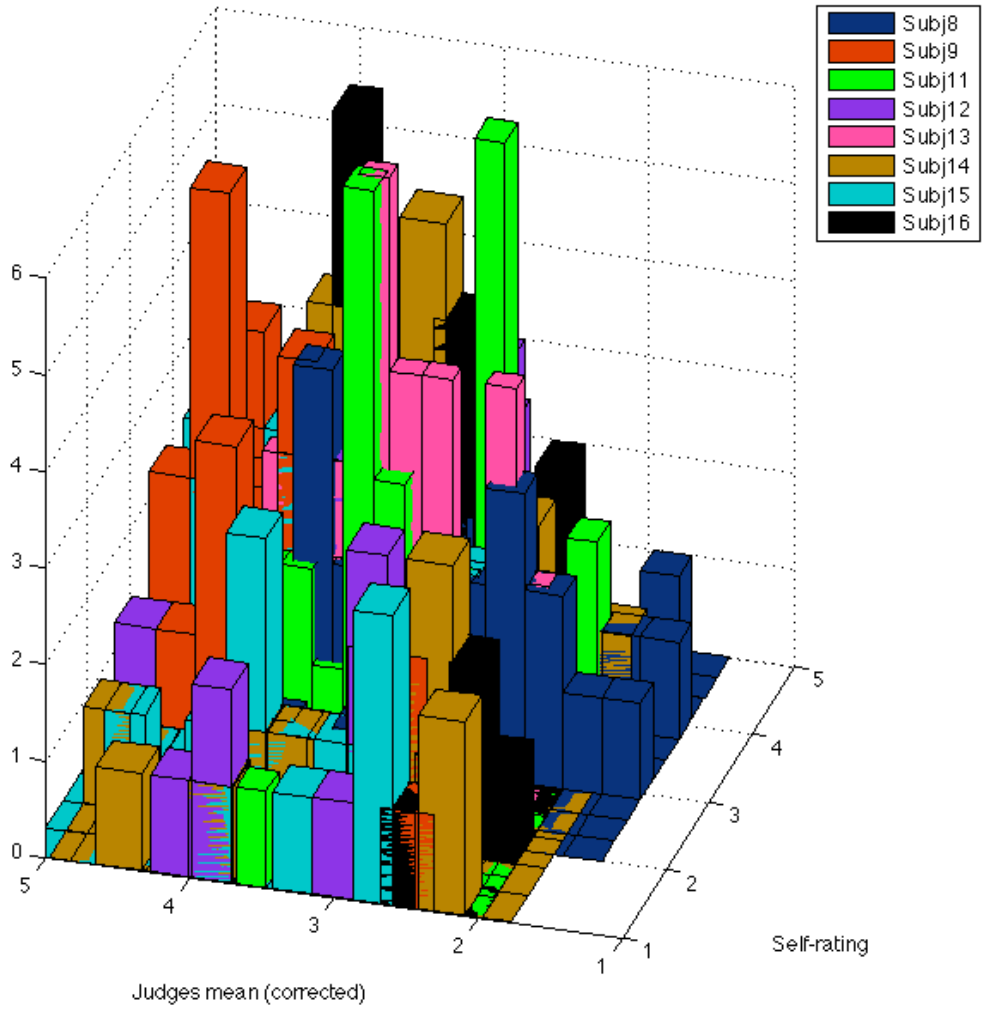


Fig 1. Bivariate histogram of corrected judge means vs self assessments colour-coded per participant. (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

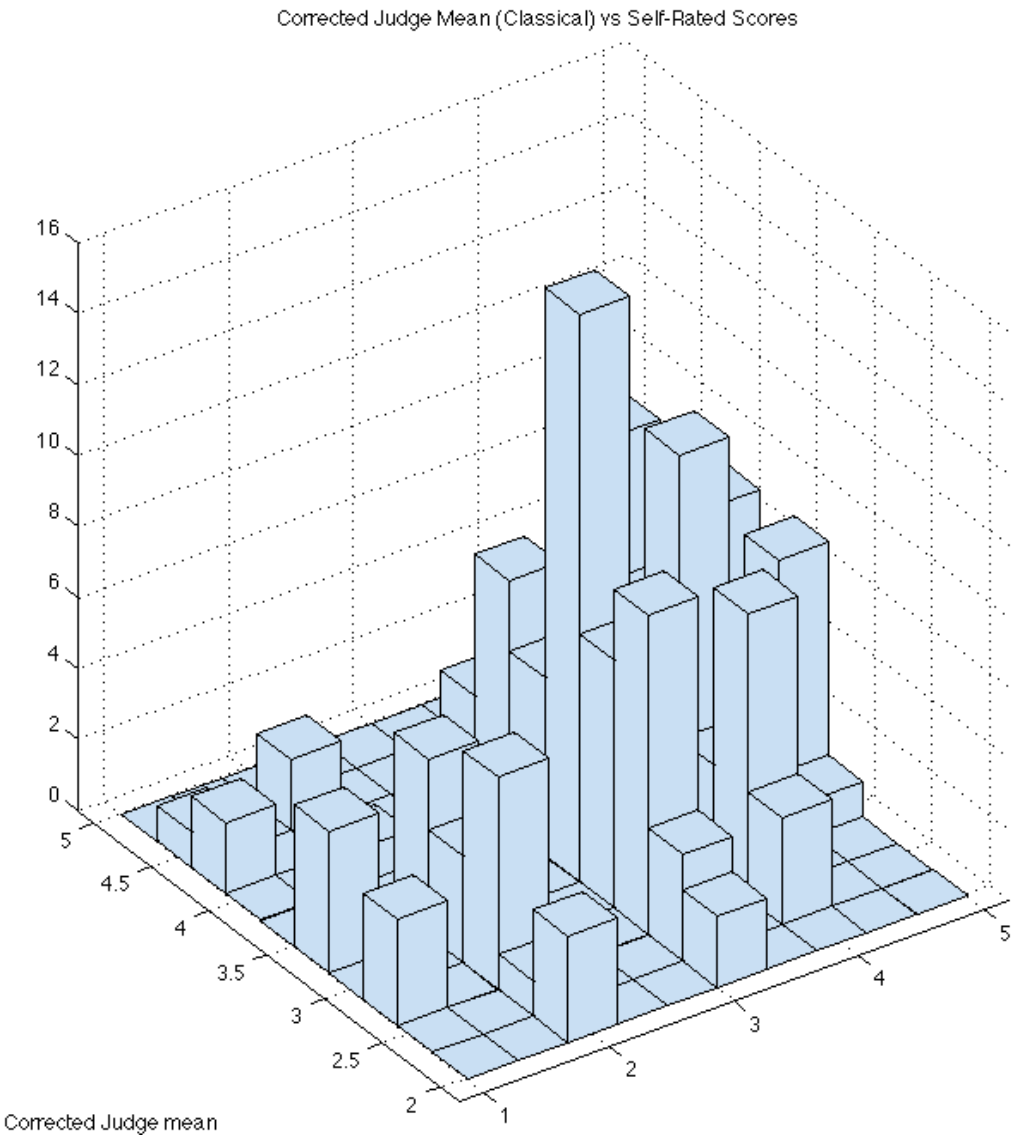


Fig 2. Bivariate histogram of corrected judge means vs self for classical extracts.

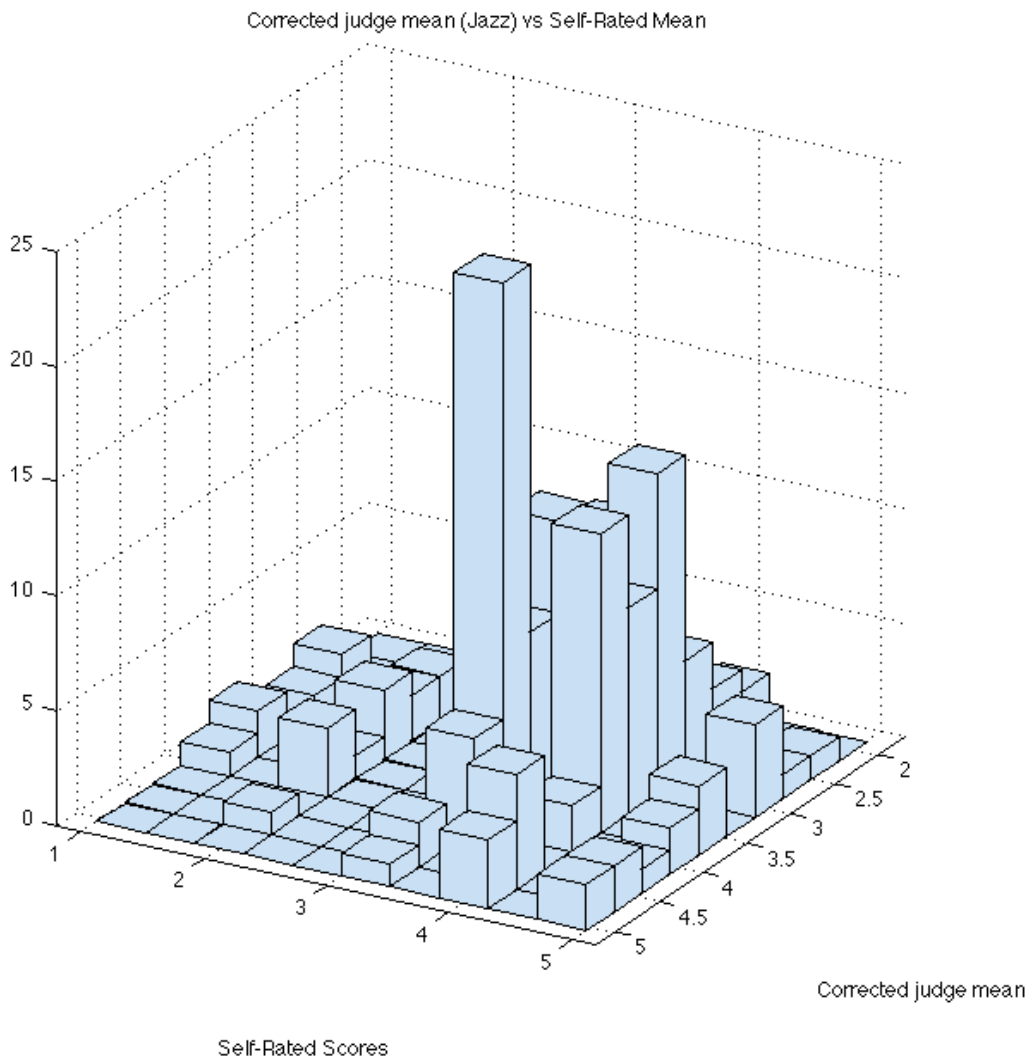


Fig 3. Bivariate histogram of corrected judge means vs self for jazz extracts.

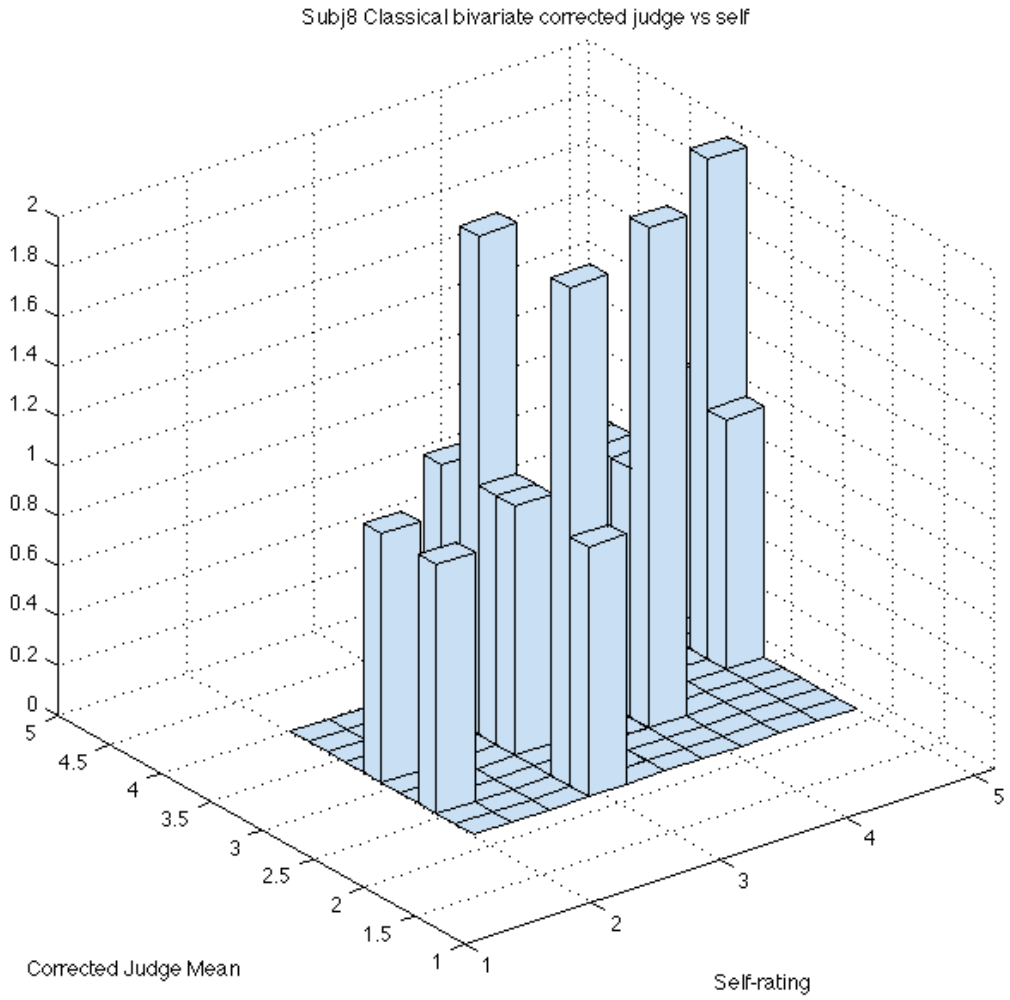


Fig 4. Bivariate histogram for Subject 8 of corrected judge means vs self for classical extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

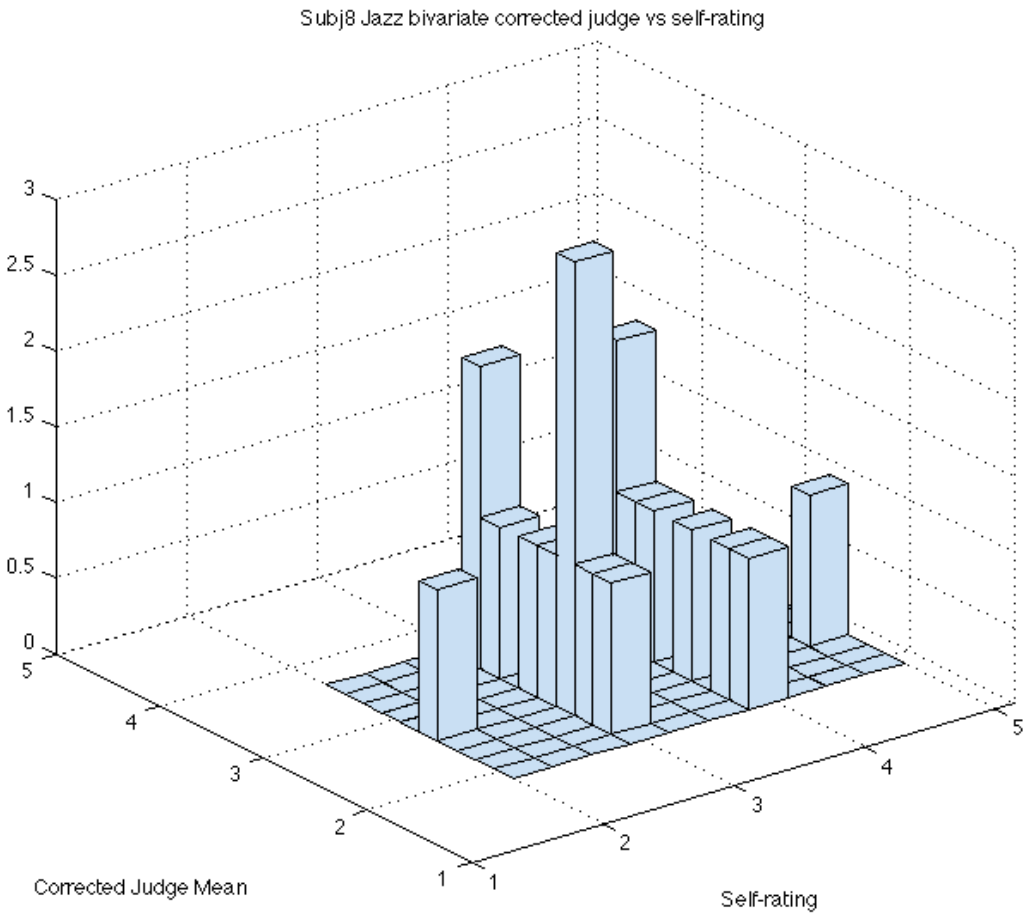


Fig 5. Bivariate histogram for Subject 8 of corrected judge means vs self for jazz extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

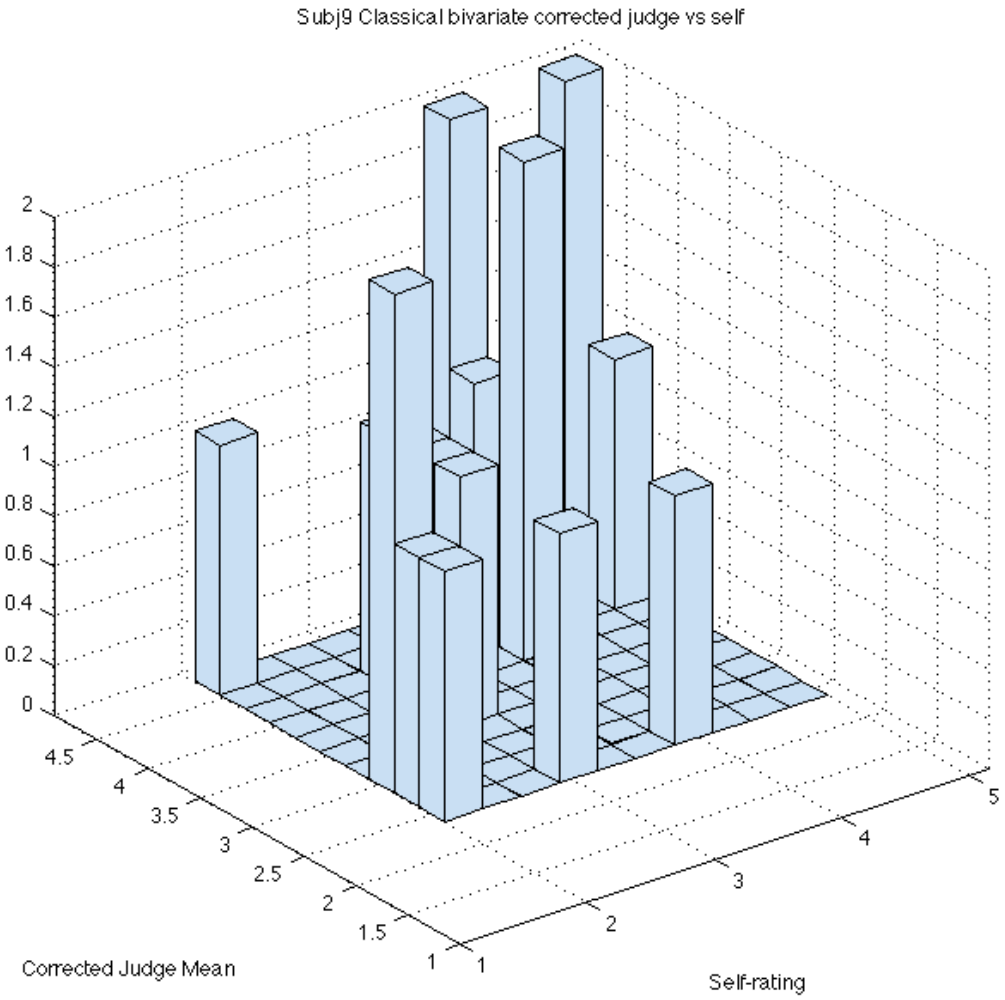


Fig 6. Bivariate histogram for Subject 9 of corrected judge means vs self for classical extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

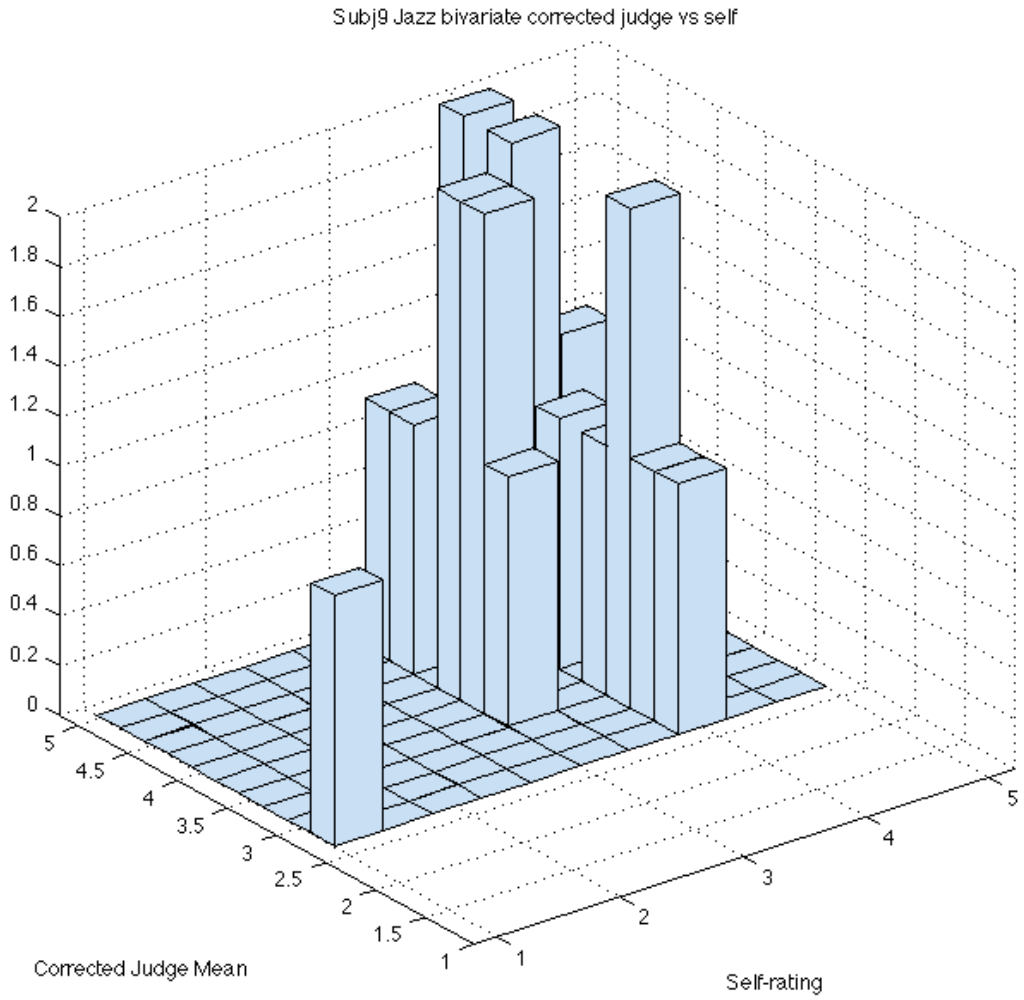


Fig 7. Bivariate histogram for Subject 9 of corrected judge means vs self for jazz extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

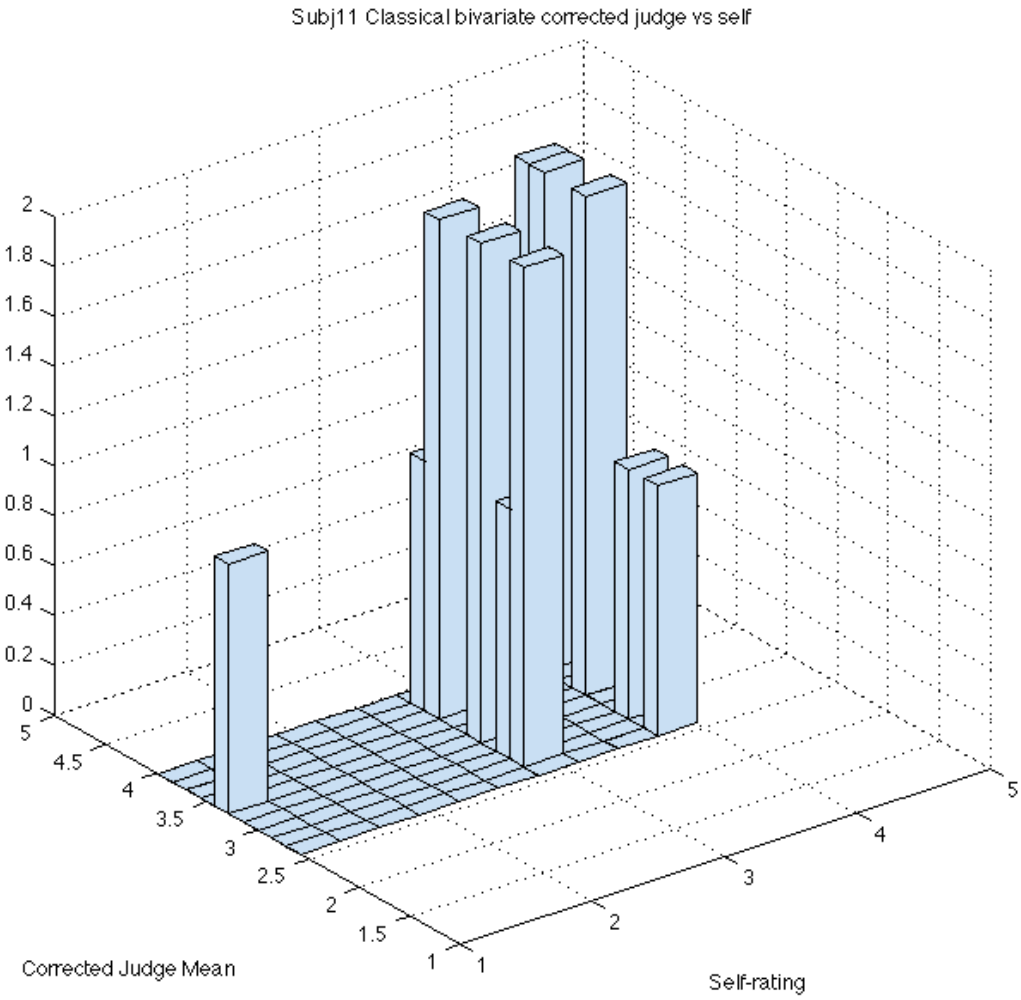


Fig 8. Bivariate histogram for Subject 11 of corrected judge means vs self for classical extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

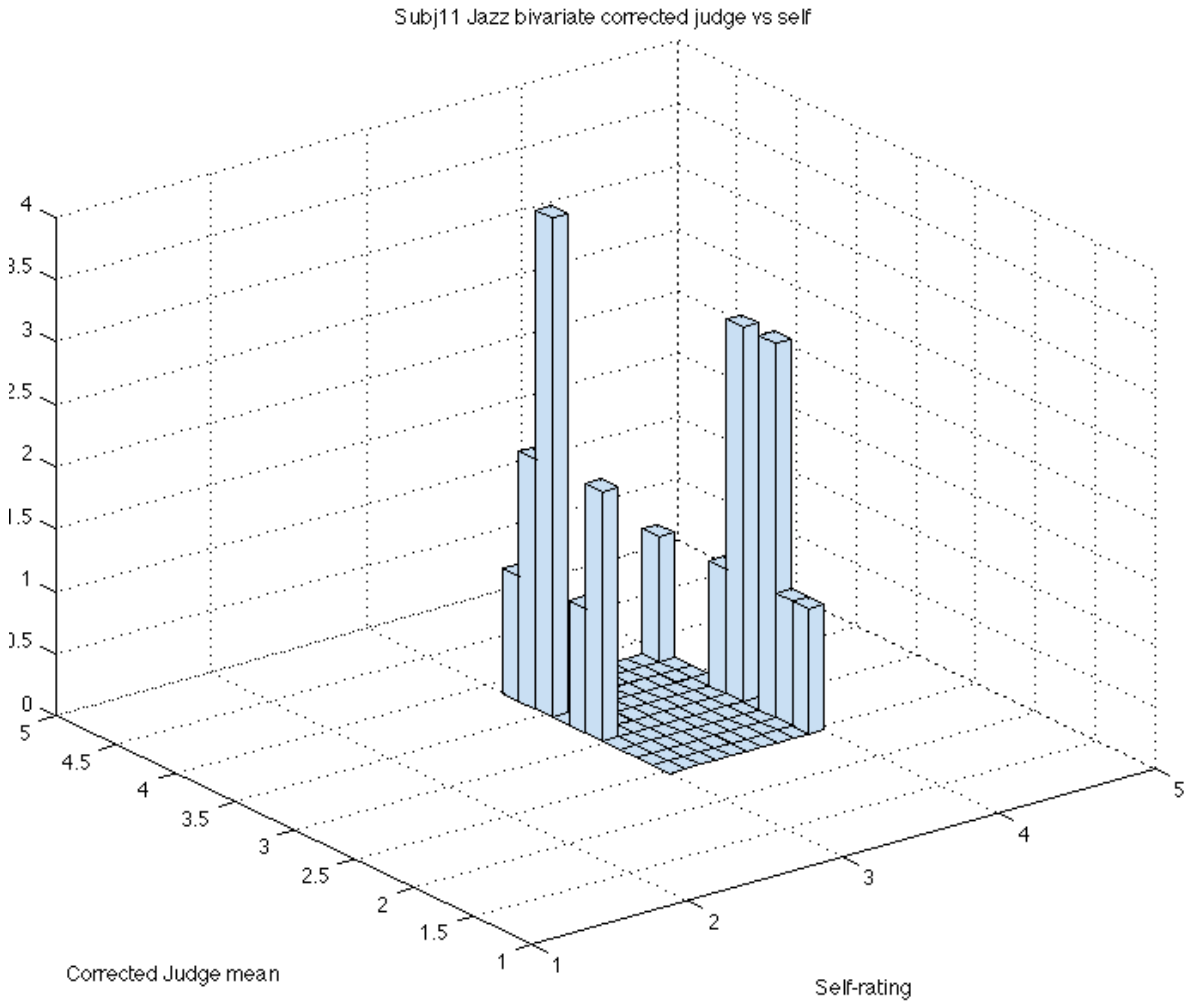


Fig 9. Bivariate histogram for Subject 11 of corrected judge means vs self for jazz extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

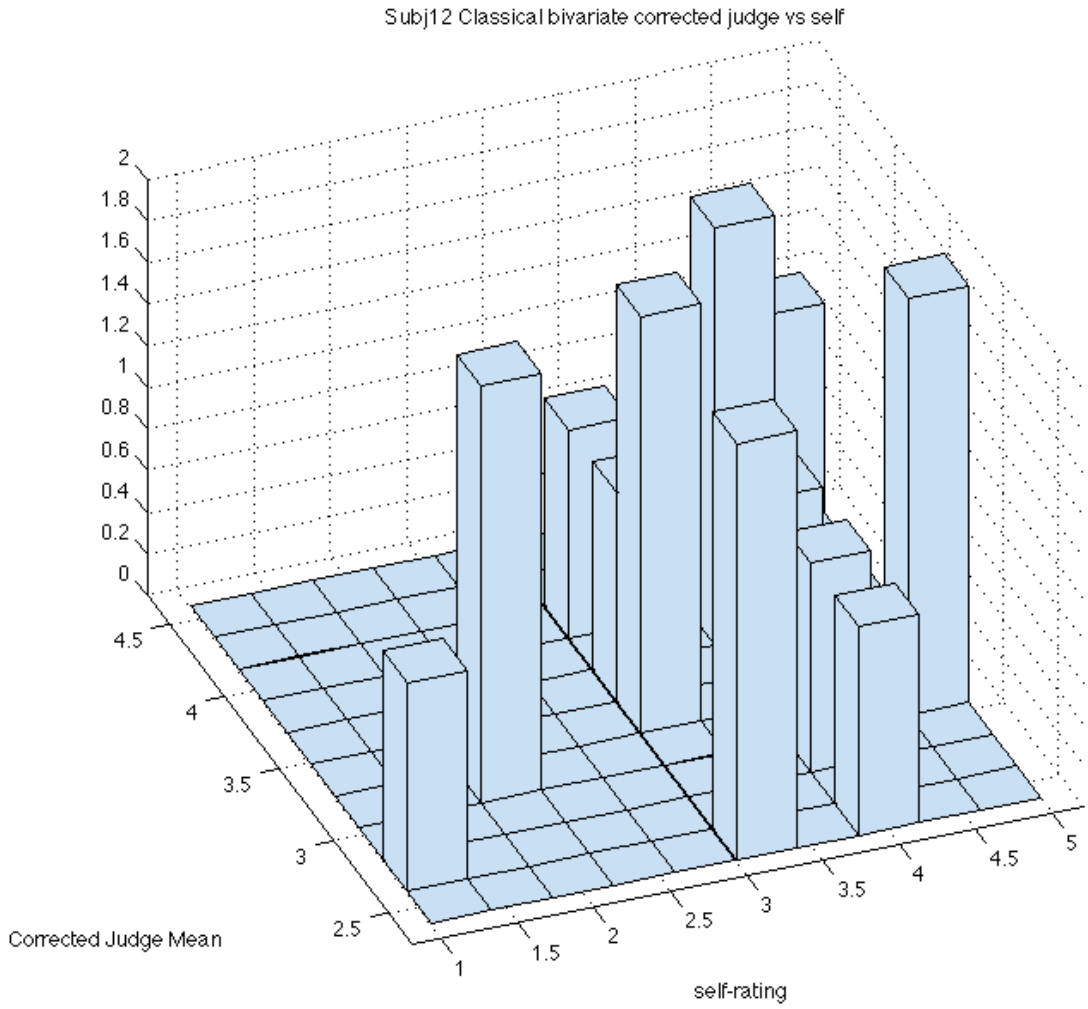


Fig 10. Bivariate histogram for Subject 12 of corrected judge means vs self for classical extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

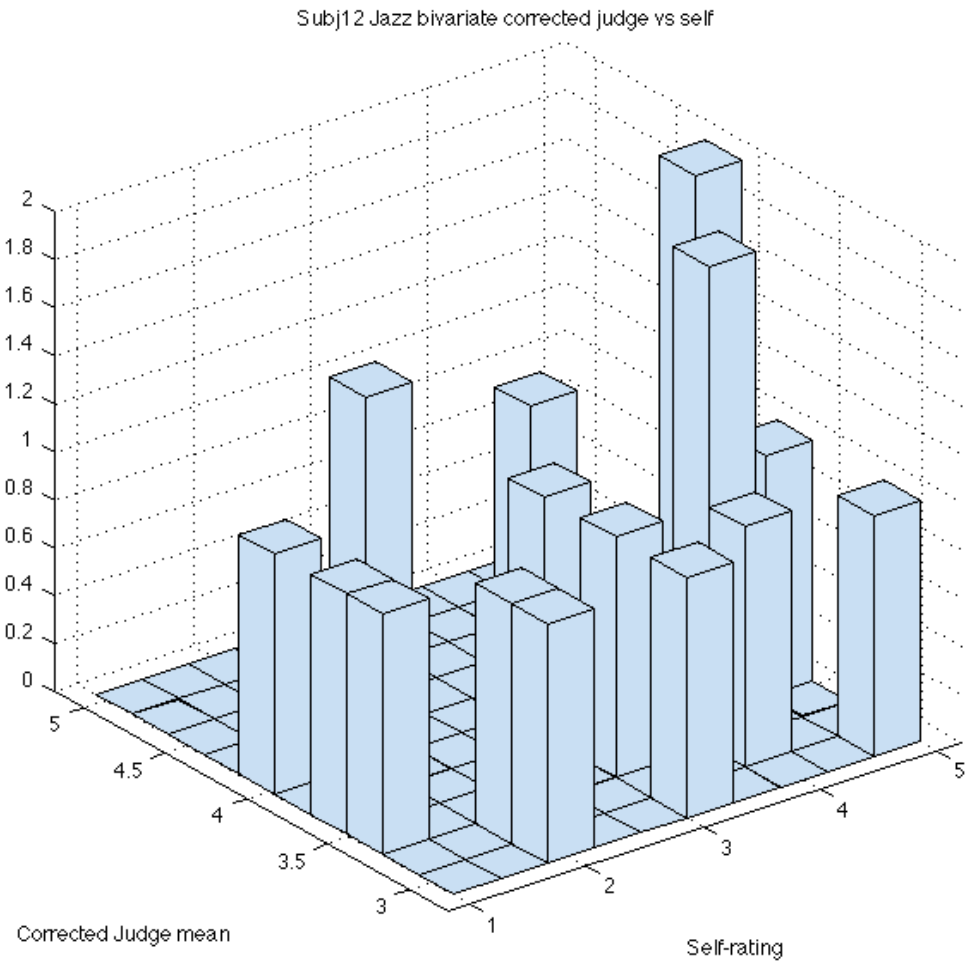


Fig 11. Bivariate histogram for Subject 12 of corrected judge means vs self for jazz extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

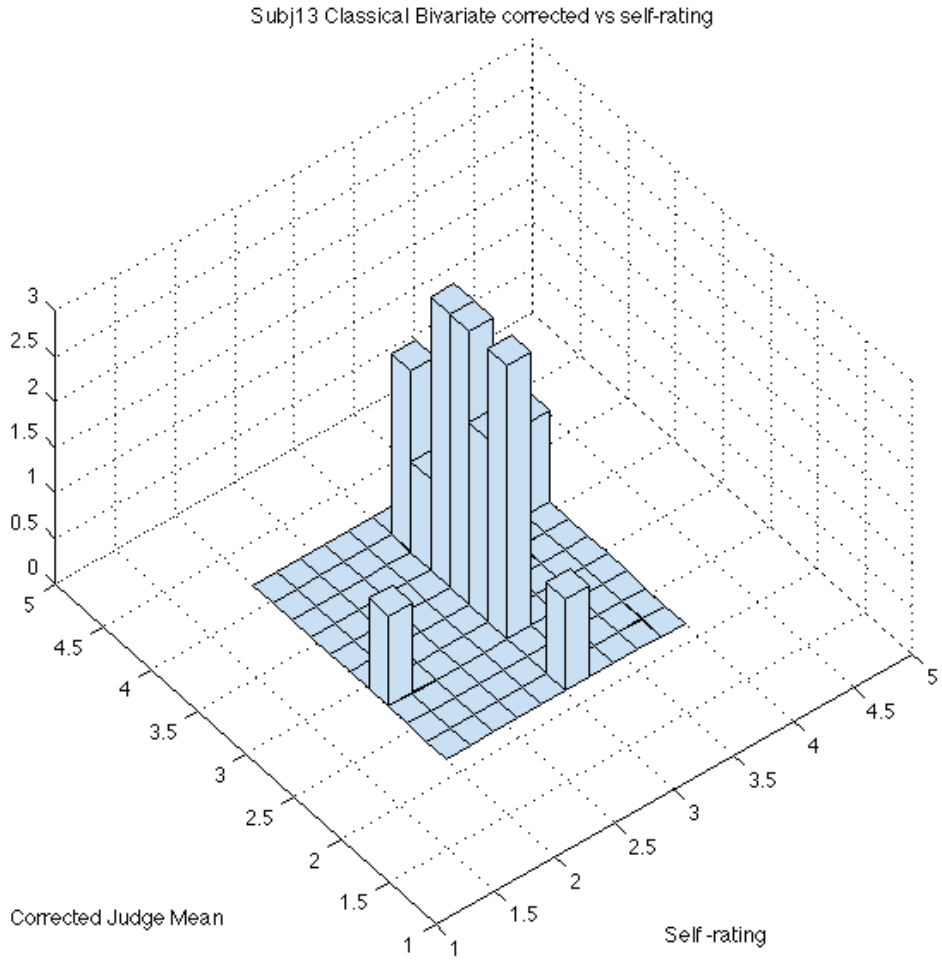


Fig 12. Bivariate histogram for Subject 13 of corrected judge means vs self for classical extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

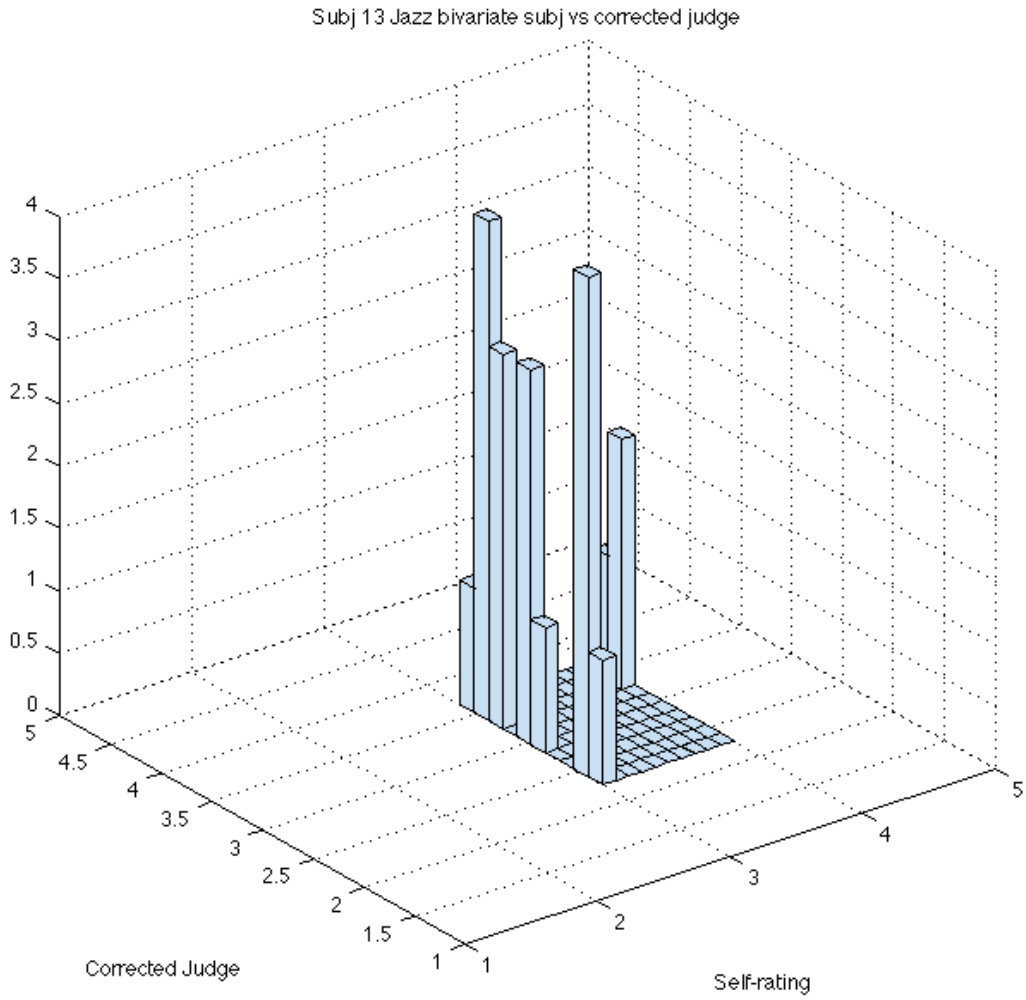


Fig 13. Bivariate histogram for Subject 13 of corrected judge means vs self for jazz extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

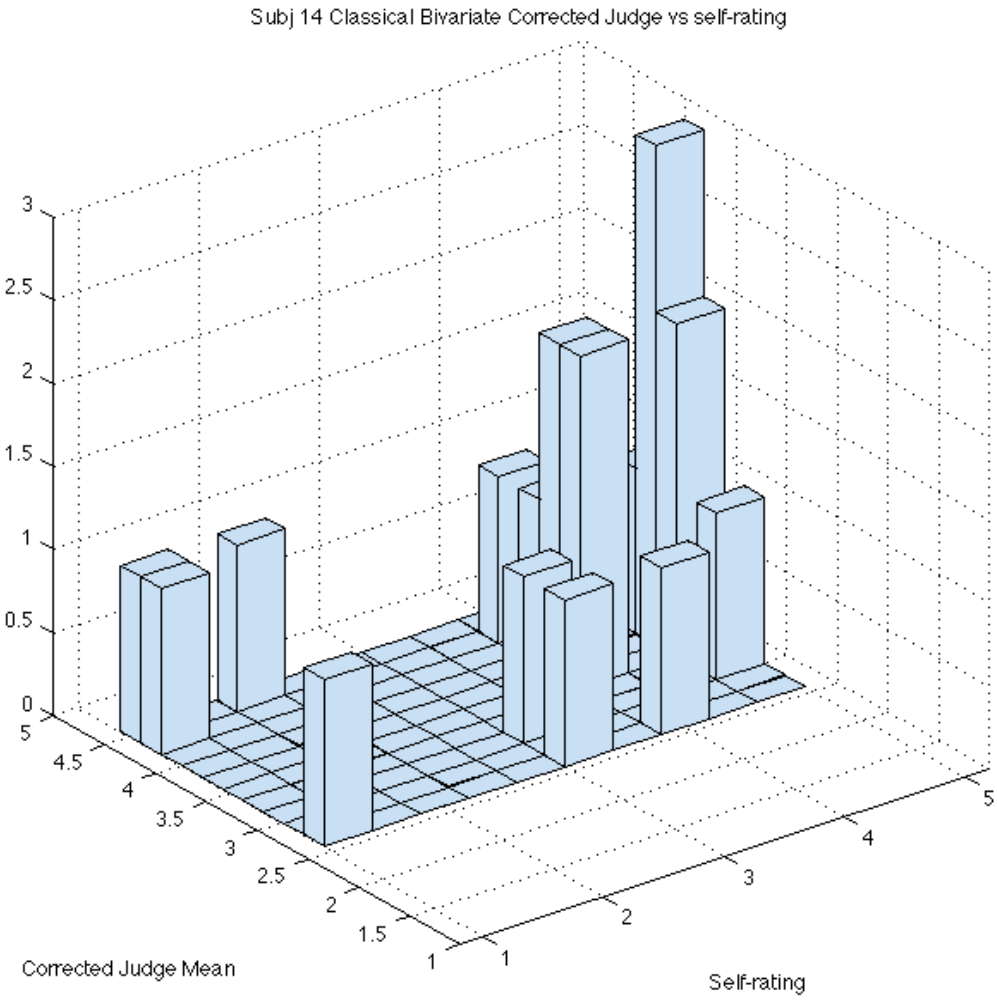


Fig 14. Bivariate histogram for Subject 14 of corrected judge means vs self for classical extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

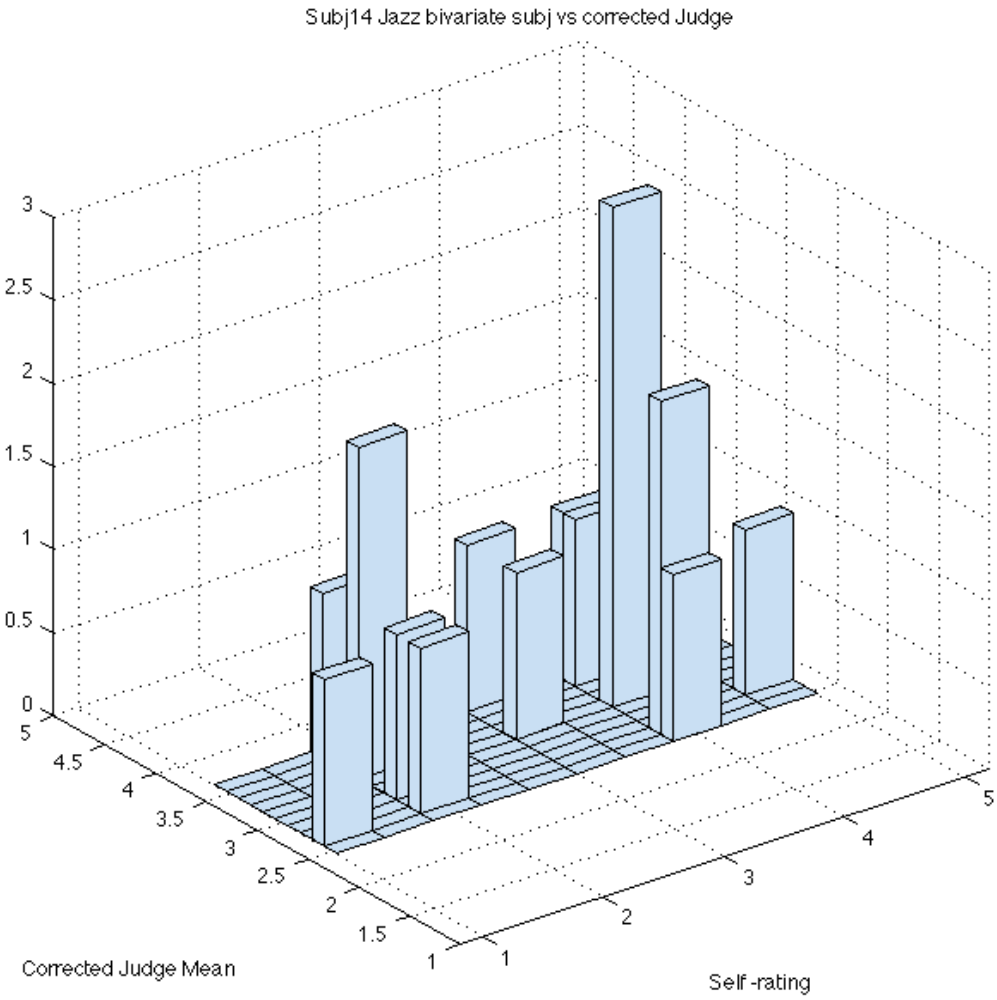


Fig 15. Bivariate histogram for Subject 14 of corrected judge means vs self for jazz extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

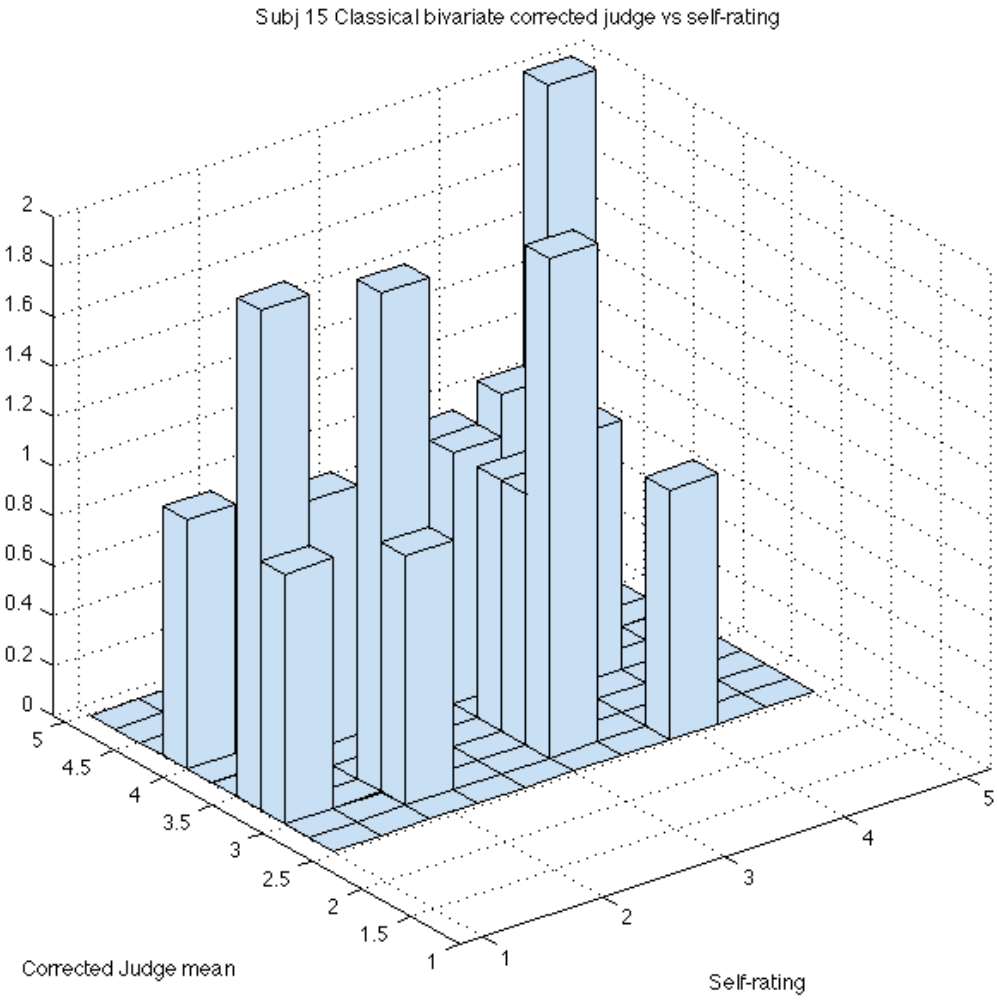


Fig 16. Bivariate histogram for Subject 15 of corrected judge means vs self for classical extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

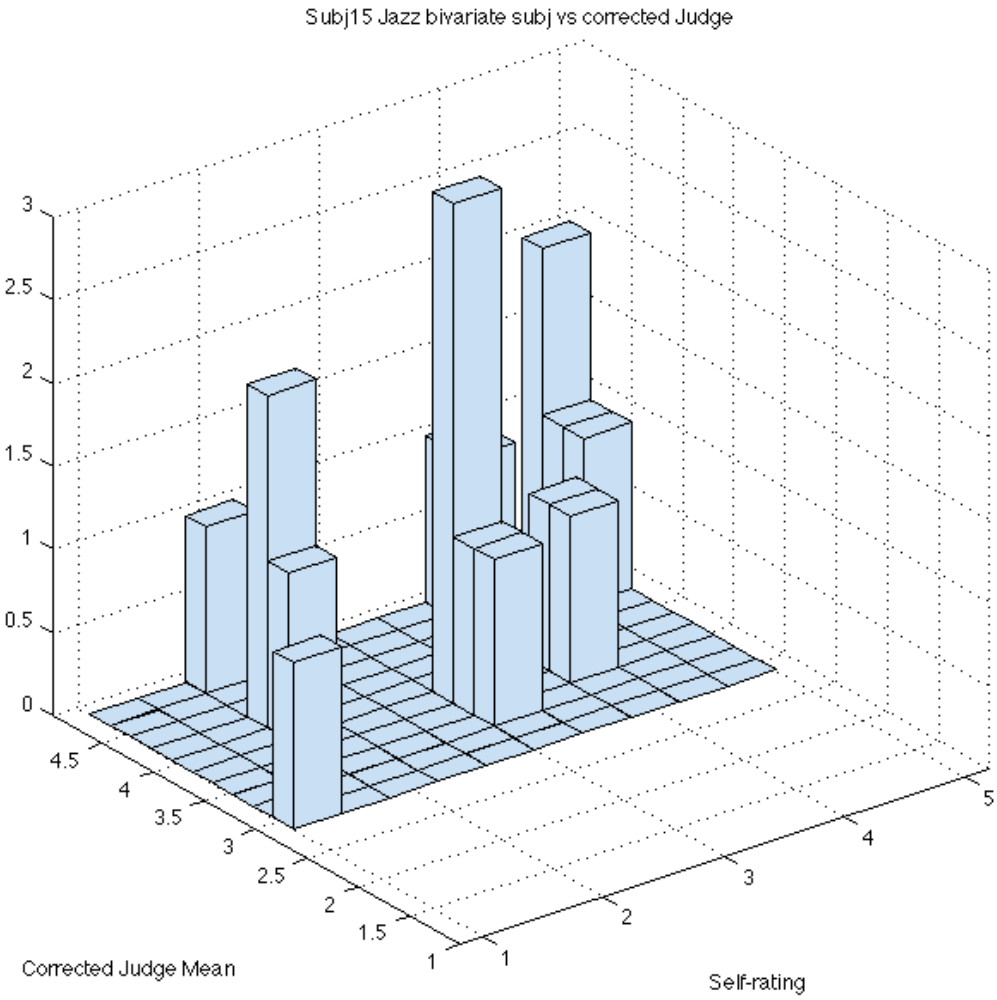


Fig 17. Bivariate histogram for Subject 15 of corrected judge means vs self for jazz extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

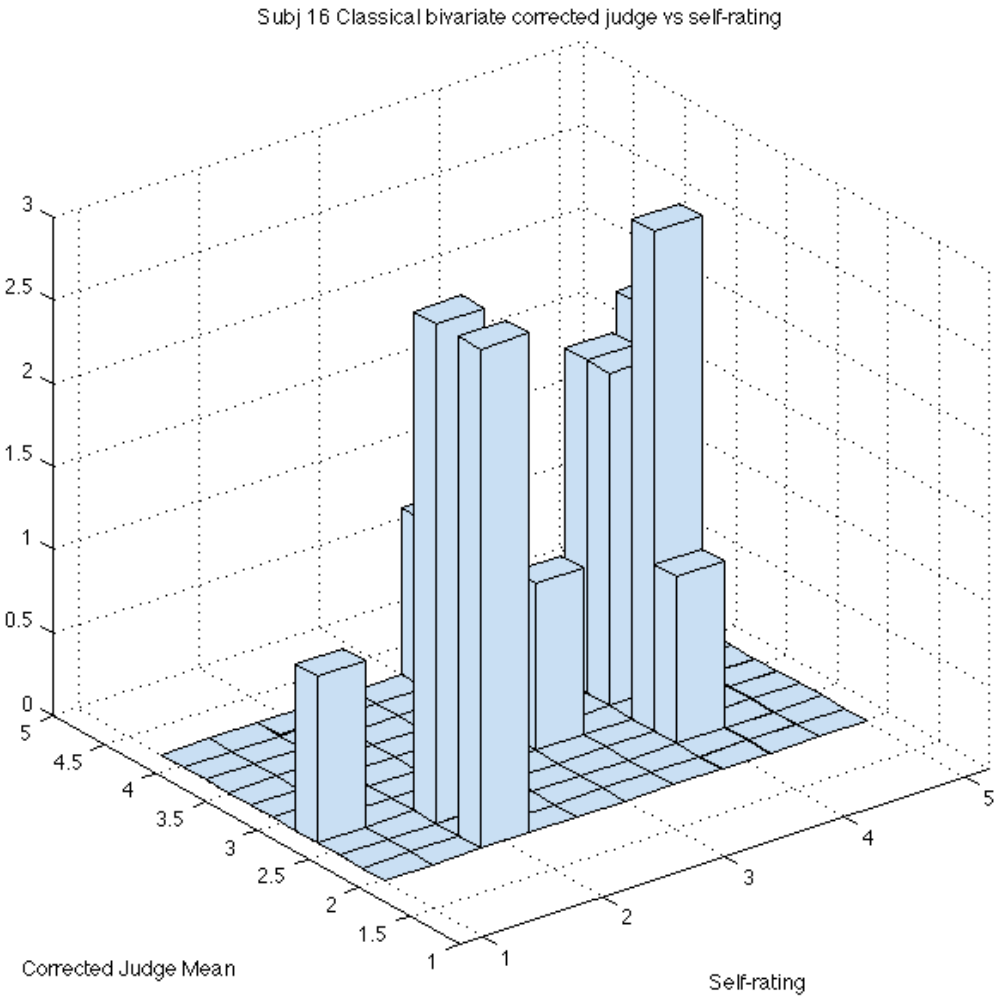


Fig 18. Bivariate histogram for Subject 16 of corrected judge means vs self for classical extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

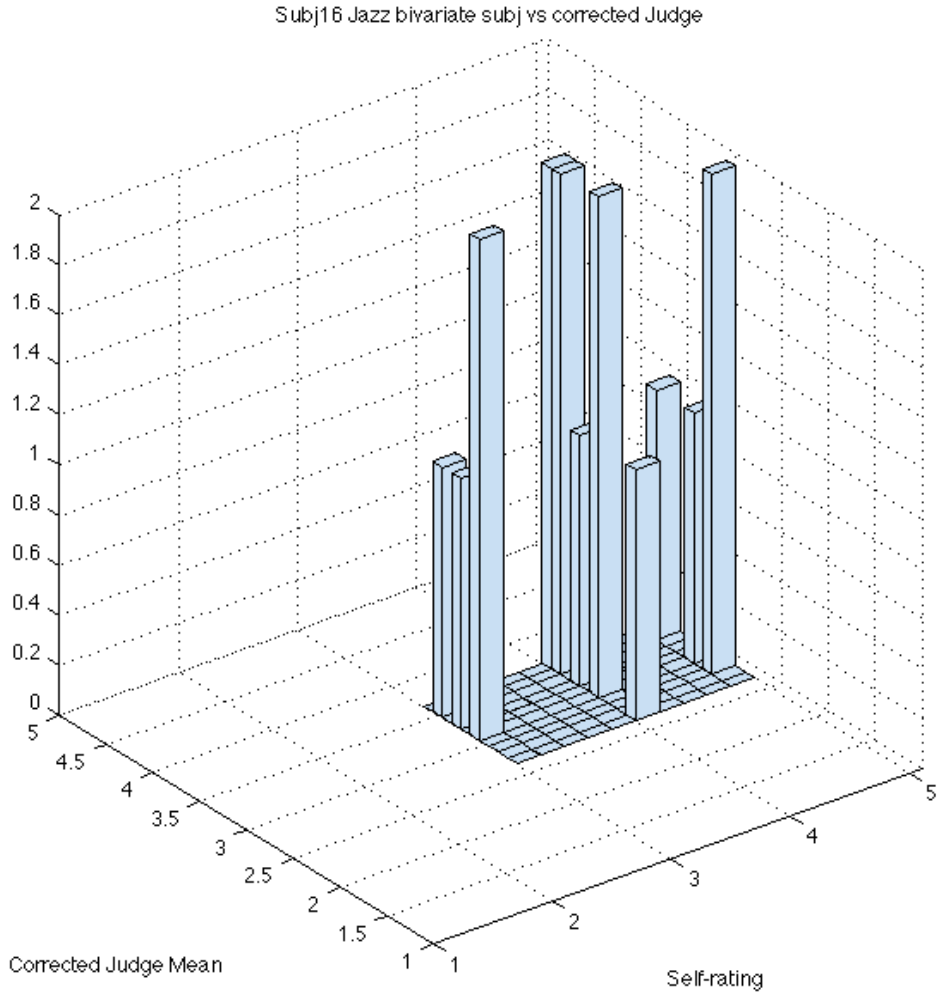


Fig 19. Bivariate histogram for Subject 16 of corrected judge means vs self for jazz extracts (the numbering reflects carrying the final study on from the pilot study such that Subject 8 is equivalent to Participant 1 as indicated in the body of the thesis; we did not use the recordings for Subject 10).

Appendix B

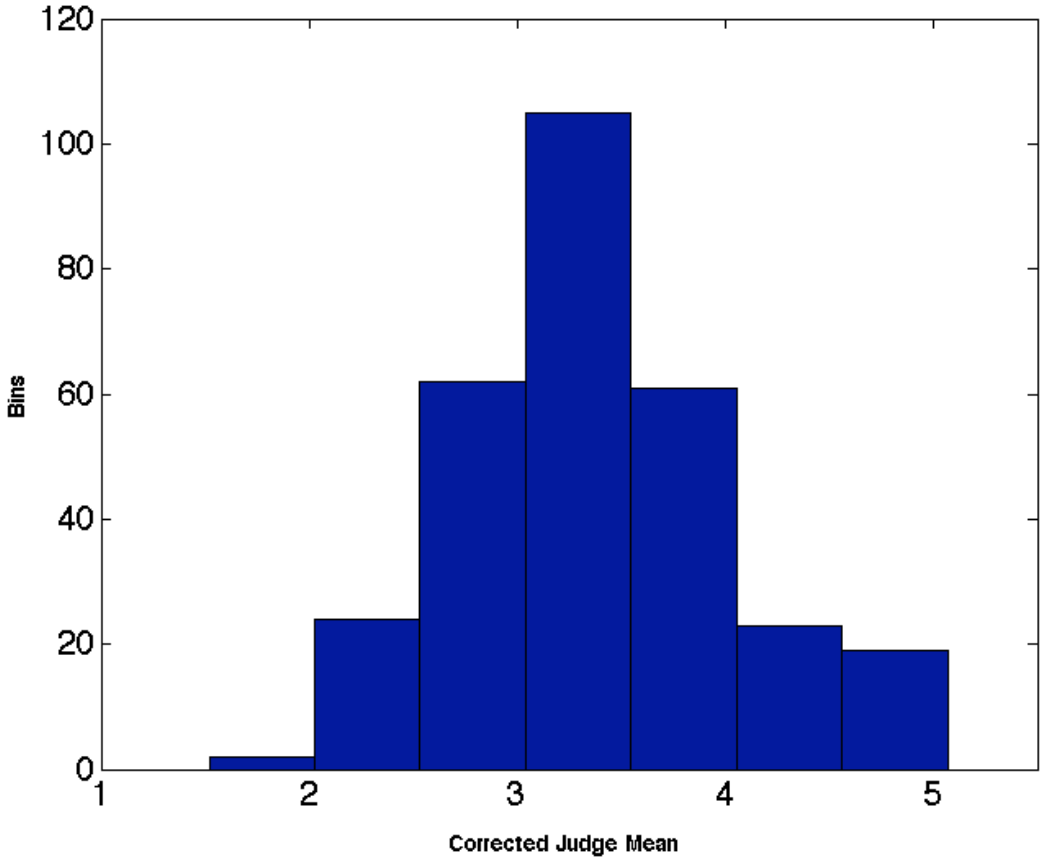


Fig 1. Distribution of Judge Means (corrected) across all Subjects and Extracts (Normal Distribution)

Appendix C

We performed standard multivariate analysis on the judges' and participants' assessments datasets using the Pearson's Correlation Coefficient, r:

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

where X and Y are the values of two different assessment datasets e.g. X could be Judge 1 and Y could be Judge 2. We cross-correlated all 5 judges with each other and then subsequently each judge with each of the 8 participants across all extracts (correlation matrix C1), jazz extracts (correlation matrix C2) and classical extracts (correlation matrix C3).

	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	0.2598	0.2171	0.1387	0.2407	0.1279	0.4121	-0.3694	0.1034	0.2495	0.0354	0.4100	0.0399
2	0.2598	1	0.5026	0.3183	0.1108	0.2150	0.5360	-0.0637	0.4084	-0.0451	0.1276	0.3685	0.4399
3	0.2171	0.5026	1	0.1870	0.4086	0.4294	0.4073	-0.1570	0.1806	0.0723	-0.1070	0.4323	0.3957
4	0.1387	0.3183	0.1870	1	0.2540	-0.2119	0.2521	-0.1812	-0.4275	0.4038	0.0301	0.5587	0.0923
5	0.2407	0.1108	0.4086	0.2540	1	0.3176	0.3797	0.3925	0.3264	0.1698	-0.1507	0.1501	0.5984
6	0.1279	0.2150	0.4294	-0.2119	0.3176	1	0	0	0	0	0	0	0
7	0.4121	0.5360	0.4073	0.2521	0.3797	0	1	0	0	0	0	0	0
8	-0.3694	-0.0637	-0.1570	-0.1812	0.3925	0	0	1	0	0	0	0	0
9	0.1034	0.4084	0.1806	-0.4275	0.3264	0	0	0	1	0	0	0	0
10	0.2495	-0.0451	0.0723	0.4038	0.1698	0	0	0	0	1	0	0	0
11	0.0354	0.1276	-0.1070	0.0301	-0.1507	0	0	0	0	0	1	0	0
12	0.4100	0.3685	0.4323	0.5587	0.1501	0	0	0	0	0	0	1	0
13	0.0399	0.4399	0.3957	0.0923	0.5984	0	0	0	0	0	0	0	1

Fig 1. Correlation matrix C1 cross-correlating judges and participants across all extracts. Columns/ rows 1 to 5 correspond to the 5 judges and columns/rows 6 to 13 correspond to the 8 participants.

	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	0.2598	0.2171	0.1387	0.2407	-0.0363	0.0404	-0.4804	-0.0054	0.1967	0.1378	0.4217	-0.3814
2	0.2598	1	0.5026	0.3183	0.1108	-0.1206	0.3916	-0.6727	0.4007	0.0077	0.2072	0.2296	-0.4472
3	0.2171	0.5026	1	0.1870	0.4086	0.5028	0.0618	-0.6405	-0.0781	-0.0662	-0.0406	0.3358	0.1270
4	0.1387	0.3183	0.1870	1	0.2540	-0.2607	0.4399	-0.2325	-0.4701	0.4031	0.0421	0.5798	0
5	0.2407	0.1108	0.4086	0.2540	1	0.0184	0.3306	0.3737	0.3705	0.0251	-0.2941	0.2656	0.7127
6	-0.0363	-0.1206	0.5028	-0.2607	0.0184	1	0	0	0	0	0	0	0
7	0.0404	0.3916	0.0618	0.4399	0.3306	0	1	0	0	0	0	0	0
8	-0.4804	-0.6727	-0.6405	-0.2325	0.3737	0	0	1	0	0	0	0	0
9	-0.0054	0.4007	-0.0781	-0.4701	0.3705	0	0	0	1	0	0	0	0
10	0.1967	0.0077	-0.0662	0.4031	0.0251	0	0	0	0	1	0	0	0
11	0.1378	0.2072	-0.0406	0.0421	-0.2941	0	0	0	0	0	1	0	0
12	0.4217	0.2296	0.3358	0.5798	0.2656	0	0	0	0	0	0	1	0
13	-0.3814	-0.4472	0.1270	0	0.7127	0	0	0	0	0	0	0	1

Fig 2. Correlation matrix C2 cross-correlating judges and participants across jazz extracts. Columns/ rows 1 to 5 correspond to the 5 judges and columns/rows 6 to 13 correspond to the 8 participants.

	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	0.2598	0.2171	0.1387	0.2407	0.1791	0.6144	-0.2877	0.3875	0.2928	-0.1696	0.3737	0.3277
2	0.2598	1	0.5026	0.3183	0.1108	0.4496	0.6321	0.3879	0.4297	-0.0300	-0.0946	0.4192	0.6854
3	0.2171	0.5026	1	0.1870	0.4086	0.3728	0.5949	0.2133	0.5204	0.2457	-0.2850	0.4174	0.4553
4	0.1387	0.3183	0.1870	1	0.2540	-0.2017	0.0611	-0.1200	-0.4214	0.5021	-0.0166	0.4784	0.1626
5	0.2407	0.1108	0.4086	0.2540	1	0.5309	0.4640	0.4464	0.3197	0.2929	-0.1130	0.0469	0.5272
6	0.1791	0.4496	0.3728	-0.2017	0.5309	1	0	0	0	0	0	0	0
7	0.6144	0.6321	0.5949	0.0611	0.4640	0	1	0	0	0	0	0	0
8	-0.2877	0.3879	0.2133	-0.1200	0.4464	0	0	1	0	0	0	0	0
9	0.3875	0.4297	0.5204	-0.4214	0.3197	0	0	0	1	0	0	0	0
10	0.2928	-0.0300	0.2457	0.5021	0.2929	0	0	0	0	1	0	0	0
11	-0.1696	-0.0946	-0.2850	-0.0166	-0.1130	0	0	0	0	0	1	0	0
12	0.3737	0.4192	0.4174	0.4784	0.0469	0	0	0	0	0	0	1	0
13	0.3277	0.6854	0.4553	0.1626	0.5272	0	0	0	0	0	0	0	1

Fig 3. Correlation matrix C3 cross-correlating judges and participants across jazz extracts. Columns/ rows 1 to 5 correspond to the 5 judges and columns/rows 6 to 13 correspond to the 8 participants.

Amongst the judges, the highest cross-correlation values were between judges 3 and 2, and 3 and 5, whilst the lowest cross-correlation values were between judges 2 and 5, and 1 and 4 (see figure 4). Amongst the judge/ participant cross-correlations, the highest positive correlations were between judge 5 and participant 8 across all and jazz extracts and between judge 2 and 8 for classical extracts. The highest anti-correlations were between judge 4 and participant 4 across all and classical extracts and between judge 2 and 3 for jazz extracts. Zero correlations (or near zero) were found between judge 4 and participant 6 for all and classical extracts and between judge 4 and participant 8 for jazz extracts (see figure 5 for judge/participant comparisons).

As can be seen, due to the low number of data points (down to 40 points for the judge/participant comparisons) and their discreteness this traditional statistical method may not be optimal for the main purposes of our study i.e. relating the assessments to the EEG recorded to ascertain high and non-creative extracts across all participants. Neither does it aid in quantitatively distinguishing accurately the participants' jazz or classical backgrounds whereas we used a simple method to deduce the phase space occupied by the combined judge and participant scores per genre for each participant, below or above their corresponding mid-line which makes them fall in one or the other genre category.

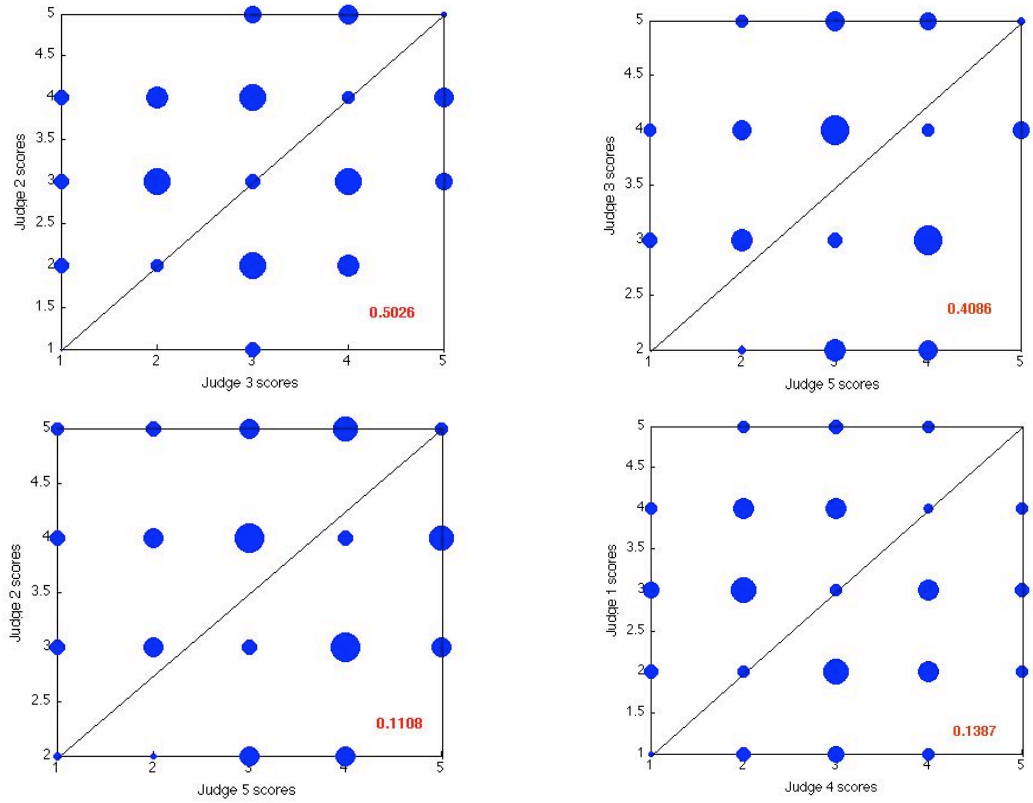


Fig 4. Scatter plots of judge scores with their correlation coefficient in red. The top row consists of the two highest positive cross-correlations and the bottom row the two lowest.

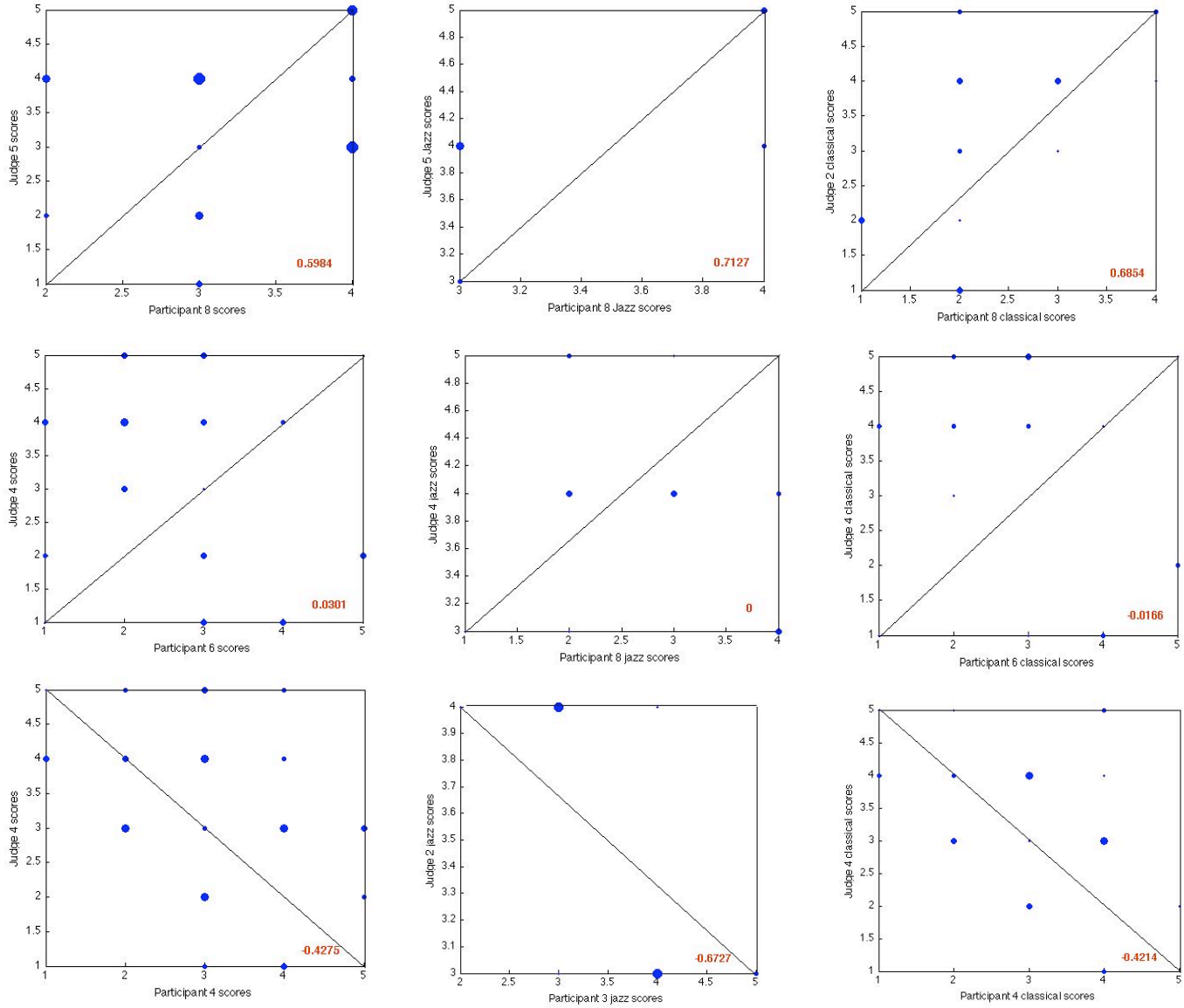
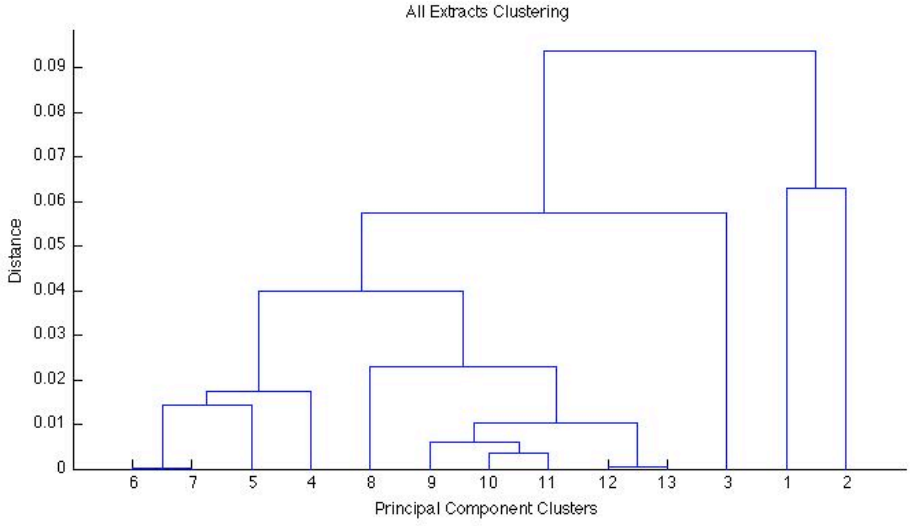


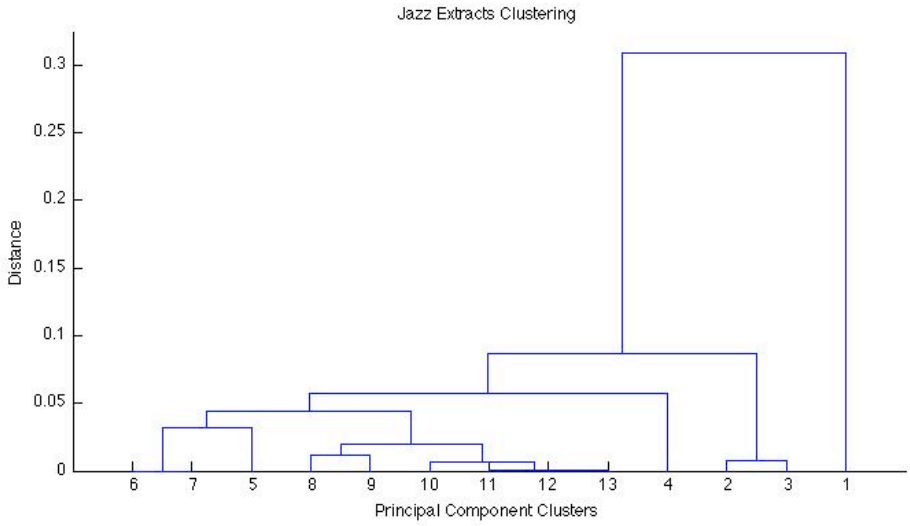
Fig 5. Scatter plots of judge and participant scores with their correlation coefficient in red. The top row consists of the three highest positive cross-correlations, the middle row the three most non-correlated and the bottom row the three highest negative cross-correlations.

A Principal Component Analysis (PCA) was performed on each of the correlation matrices in order to orthogonally transform them into a set of values of linearly uncorrelated variables or 'principal components' that are equal to the original number of variables i.e. 13. In order to detect any patterns of clustering between subsets of judges and/or participants, we created a corresponding Euclidean distance matrix y for each correlation matrix from which a clustering matrix was calculated using a nearest neighbours method. These were then visualised using dendrograms (see fig 6). There seem to be fewer major clusters for judges across jazz extracts implying a uniformity in assessments further supported by figure 5.4 and the plots of (Max-Min) for the jazz genre across the interpretation and improvisation tasks.

a)



b)



c)

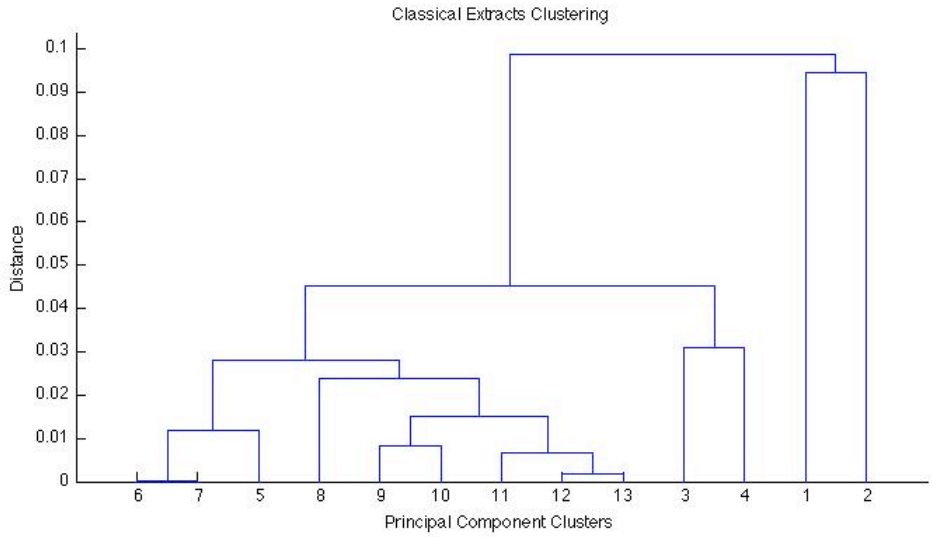


Fig 6. Dendrograms of principal component clusters from correlation matrices for a) all extracts, b) jazz extracts and c) classical extracts. Components 1 to 5 correspond to 5*5 judge cross-correlations and components 6 to 13 correspond to 5*8 judge/participant cross-correlations.

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