Neurocognitive Aspects of Musical Improvisation and Performance

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Musical Creativity: Its Elusive Nature

What does musical creativity entail? What are the cognitive processes involved? Does it have distinct neurobiological correlates? Many people, hearkening to 19th century Romantic views, believe that artistic creativity is a mystery forever beyond the reach of empirical science. There is a strong belief that musicianship is a special faculty, confined to a tiny elite, and in fact the very word *music* is derived from the Greek word *mousikē* i.e. of the muses, a divine source. In Plato's view, musicians are not creative per se, but rather they merely imitate the muses as the latter are the original sources of creative inspiration. This view is no longer accepted as tremendous progress in the field of neuroimaging has convincingly demonstrated that all mental functions, from very mundane to highly complex ones, are represented by specific neural correlates (Gazzaniga 2004). Yet musical creativity still remains a very difficult problem to shed light on for neuroscientists as it is seen to be enormously complex (too many attributes of musical creativity), unpredictable (difficult to predict the onset/offset of musically creative ideas), undefinable (no one single definition exists), and lacking introspection (musicians often cannot explain the process of being creative). Nevertheless, neuroscientific research on musical creativity offers an immense promise to reveal the hidden spatio-temporal intricacies of neuronal dynamics of the creative brain in action, which complement traditional behavioural research methods. In this Chapter, we

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G.E. Corazza and S. Agnoli (eds.), *Multidisciplinary Contributions to the Science of Creative Thinking*, Creativity in the Twenty First Century,
DOI 10.1007/978-981-287-618-8_15

provide an overview of the current research, albeit at its infancy, on the neurocognitive aspects of musical creativity. First, we provide a brief description of the available neuroimaging techniques to study musical creativity. Next we explain various facets (i.e. stage, type, model) of general creativity. The topic of flow experience, an optimal experience of an intense reward during pursuit of an activity such as music performance, is discussed next. Subsequently, we present the principal findings of neuroimaging research of musical creativity, mainly of musical improvisation. Finally we provide some concluding remarks and introduce a few open questions for future research.

Neuroimaging Techniques

Before we detail various types, models of creativity, we briefly describe the available neuroimaging techniques to study (musical) creativity. Currently two techniques are used most often in neuroscience, namely functional magnetic resonance imaging (fMRI) and electroencephalogram (EEG). fMRI has high spatial resolution useful for localising brain functions, but it has a low temporal resolution in the range of a few seconds. On the other hand, EEG has limited spatial resolution but offers excellent temporal resolution in the order of milliseconds. 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 is an indirect indicator of neural activity. It detects differences in magnetism in deoxygenated and oxygenated blood i.e. BOLD (Blood Oxygen Level-Dependent). Blood flow through the brain is closely linked to neural activity but oxygen-rich blood displaces deoxygenated blood 2 s later than activity and rises to a peak over 4–6 s before returning to the original level, thus having a limited temporal resolution and explains why fMRI is poor at detecting communication between brain areas in real-time (Logothetis 2008). Nevertheless, fMRI offers the best results, among the techniques available for noninvasive neuroimaging, in terms of localising brain areas.

EEG, on the other hand, is a direct indicator of neuronal activity. It primarily reflects the summation of a large number (in the order of thousands to millions) of post-synaptic potentials recorded on the surface of the scalp (Nunez 1995). One scalp electrode can integrate activity from neurons across 10 cm^2 of cortical surface (Nunez et al. 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.

EEG activity measured at the scalp is a mixture of spectral components that have historically been divided into various frequency bands: delta (<4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (>30 Hz) (Donner and Siegel 2011). There exists a rich body of literature on the functional roles of these oscillations in diverse cognitive tasks [see for review (Ward 2003)].

Creative moments are often spontaneous and dynamic in time and therefore EEG may be better suited to capture it. Additionally, there is widespread evidence that brain areas do not work in isolation for processing a cognitive task, instead they form a functional (as well as structural) network by exchange of information on a dynamical basis (Varela et al. 2001), and one could investigate this underlying network by using EEG (note that fMRI also allows a reveal of brain networks but its temporal sluggishness prohibits tracking the fast changes in network configurations). Yet as discussed earlier, a major drawback of EEG is that it is a measurement of electrical brain activity at the neocortex level and does not provide 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 cortical sources and is travelling and spreading through the bone of the skull which is conductive, giving rise to spurious synchrony.

For both techniques there are some serious practical issues that have impeded the progress of neuroscientific research on musical creativity. For example, during brain imaging, participants are usually instructed to stay in a relatively fixed position during the entire recording, either lying on a bed inside a fMRI scanner or sitting on a chair for EEG. Strict requirement on immobility is imposed to minimise movement related artefacts as both techniques (more so for fMRI) are quite sensitive to minute head (and body) movements. This is ecologically an inappropriate (and unusual) situation for a musician to perform. Furthermore, there are other restrictions on the type of instruments to be used, e.g., any metallic instrument is not possible to use inside a fMRI scanner. Therefore, the neural correlates of musical creativity, in its true colour, are indeed quite difficult to capture. Nevertheless, there are some recent pioneering efforts, thanks to new innovations in fMRI compatible instruments and clever experimental designs, investigating the musical brain in creative action, and these will be discussed in the later section.

Stages and Neuroscience of Problem-Solving Creativity

Most of the neuroscientific research on musical creativity, or on creativity in general, is about revealing the underlying processes. Before we begin probing the creative Process [as per Mel Rhodes well-established 4P model (Rhodes 1961)], it would be useful to outline broad stages of creativity in order to understand the basis of subsequent neurobiological investigations. There is almost a century of qualitative explorations into the realm of creativity that could be related to artistic performance and these are, therefore, important shoulders to stand on. In 1926, Wallas put forward a qualitative model of creativity focusing on problem-solving, with four distinct stages as follows (Wallas 1926).

Preparation: This is the first stage where the problem under consideration is formulated and attempts are made to solve it.

Incubation: This refers to the stage where the problem is left aside to work on other unrelated tasks; it is the process of internalising the problem into unconscious mind.
Illumination: This refers to the moment of inspiration or the moment of insight (Aha!) where the solution is arrived without any conscious forewarning.
Verification: This is the final stage when the solution is consciously confirmed and applied.

Some recent neuroscientific research have explored these various stages of creative problem solving. For example, Sandkühler and Bhattacharya have studied different stages of problem-solving by focussing on the insightful nature of the solution rather than the nature of the problem (Sankuhler and Bhattacharya 2008). They have found that functional fixedness or a mental impasse (a state when the problem solver gets mentally stuck on an inappropriate construct of the problem and any further progress is therefore prohibited) at the preparation stage is associated with a higher gamma band response over parieto-occipital and occipital areas, which might be related to excessive attentional focus on an inappropriate representation of the problem. Interestingly, they also investigated the role of 'hint processing' for insight, which could shed new light into how we process new information to solve creative problems. Higher alpha (10–12 Hz) power over the right temporal and lower gamma power over the parieto-occipital areas were predictive of successful utilisation of hints. This suggests that a diffuse attentional focus, as opposed to a focused attentive state, may be more beneficial for processing and integrating new incoming information to produce a creative solution (Martindale 2004). Furthermore, the reported right hemispheric dominance is also aligned with many previous studies on creativity (Parncutt 1994). Interestingly, gamma power at the temporal region is again associated with subjective moments of insight and the verification stage is associated with a higher gamma power at the parieto-occipital region. Altogether it seems that brain oscillations at alpha and gamma frequencies over many brain areas (e.g., temporal, parieto-occipital) are associated with various stages of creative problem-solving.

On reaching a mental impasse leading to incubation, a solver may be forced to remove the problem from their conscious awareness. It is widely accepted that conscious thought has limited processing capacity, yet unconscious thought could process a vast amount of information (Dijkterhuis and Nordgren 2006). Previous research has demonstrated that spontaneous unconscious thought is beneficial for making an optimal choice in a complex decision that requires consideration of multiple attributes (Dijkterhuis et al. 2006). Interestingly, this beneficial effect of unconscious spontaneous thought holds only for complex decisions, whilst conscious or deliberate thought outperforms unconscious thought for simple decisions that involve only a few attributes. Unconscious thought is also associated with better performance on a creativity task (Dijkterhuis and Meurs 2006). This suggests that spontaneous thought may facilitate access to unconventional or non-dominant information in long term memory, thereby, potentially removing any mental impasse by promoting remote creative associations (Zhong et al. 2008).

Neuroanatomically, cognitive spontaneous insights may have its origin in the posterior association cortex, and basal ganglia, given its role in operating outside conscious awareness. During the period of down-regulation of the frontal attentional network, information from the unconscious processing enters into the working memory network.

Additionally, research has shown that working memory, temporal integration and sustained and directed attention are key cognitive functions that provide the underlying framework to compute even higher cognitive functions because they act as buffers, simultaneously maintaining *in-the-moment* information in consciousness and ordering it in space-time as associations proceed (Damasio 1990). Damasio suggests that a working memory buffer is critical for creative thinking because it allows for the retention of relevant knowledge while problem solving; it allows us not only to retrieve and create internal representations but also to actively hold, rearrange and restructure these representations. A crucial signature of creativity is the ability to manipulate concepts and parts of concepts to create new and surprising combinations from active representations held in working memory. A recent study indeed suggests that across trials musicians with higher working memory capacity perform significantly better creative improvisations than musicians with lower working memory capacity (De Dreu et al. 2012).

It is hypothesised that through long-distance phase synchronisation of electrical brain activity and neuronal clusters, 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). Synchrony appears to allow the binding of sensory attributes and the overall integration of multiple 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 cognitive acts contribute to a musician's creativity and thus synchrony could be a possible mechanism to be analysed in order to find a signature for musical creativity (see section "Neural Correlates of Musical Improvisation").

Neuroscience of Types of Creative Processes

There are two commonly known types of creative processes: convergent and divergent thinking. Convergent thinking refers to finding the single best, or most often correct answer to a problem, leaving no room for ambiguity, i.e. answers are either right or wrong such as in riddles. It emphasises speed, accuracy, and logic, and focuses on recognising the familiar, reapplying techniques, and accumulating stored information. It is most effective in situations where an answer readily exists and simply needs to be either recalled or worked out through decision-making strategies. These strategies are often useful after an initial bout of divergent thinking which generates creative ideas by exploring many possible solutions in a spontaneous, free-flowing and emergent cognitive manner. With divergent thinking, many possible solutions are explored in a short amount of time, and unexpected connections are drawn.

Beeman et al. (2004) have found that participants working on a convergent problem showed burst of high frequency gamma oscillations (~40 Hz) over the right temporal brain areas, 300 ms prior to the moment of insight.

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, as 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 (Carlsson et al. 2000). 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). 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).

Models of (Musical) Creativity

Of course, not all creative activities are of a problem-solving kind and can also make use of mental and thought models. There are two main kinds of performed musical creativity, *Interpretation* in Western Classical music and *Improvisation* which is most commonly found in Jazz and Indian Classical music.

Interpretation refers to the ability of the performer to interpret the composer's markings of dynamics, tempo and emotionality without changing the written score in their performance. *Improvisation* refers to the ability of the performer to change the structure of a musical phrase by modifying its key, melodic contour, the very notes, rhythm and time signature. The improviser may seem to have an unlimited set of choices but they are not necessarily unconstrained. Musical improvisation does implicitly depend on a specific musical style, and therefore, is constrained by the rules and constraints of that musical style e.g. orthodox modern jazz (Johnson-Laird 2002). It is conceptually similar to language as a speaker can produce an infinite number of possible sentences with a finite number of words and finite set of syntactical rules.

Improvisation also involves a wide range of complex cognitive processes along with strong emotional components as "the improvisers must effect real-time sensory and perceptual coding, optimal attention allocation, event-interpretation, decision making, prediction, memory storage and recall, error correction, and movement control, and further, must integrate these processes into an optimally seamless set of musical statements that reflect both a personal perspective on musical organisation and a capacity to affect listeners" (Pressing 1998). In fact, improvisation can be likened to real-time composition where a musical phrase is entirely generated from the mind perhaps with a theme or visual imagery which is a form of mental model, thus simulating processes in the real-world.

The Geneplore model (Finke et al. 1992) is one such mental model that divides creativity into a generative and exploratory phase. Within the generative phase, the construction of mental representations, called pre-inventive structures, occur with certain specific properties. In the exploratory phase, these properties are used to elucidate a better sense of the pre-inventive structures. Johnson-Laird elaborates on this further, proposing a mixture of multi-stage neo-Darwinian and neo-Lamarckian algorithms as a model for jazz improvisation, where the former uses *some* criteria to guide the generative process and the latter uses *all* the criteria acquired from experience to govern the generative stage. His theory proposes that these strategies are split between the generation of chord sequences requiring working memory for intermediate results (multi-stage neo-Darwinian algorithm) whereas the improvisation of melodies would have to fit the chord sequences and can be generated as rapidly as the musicians fingers would allow (Neo-Lamarckian algorithm).

Another model is Boden's *Improbabilistic* and *Impossibilistic* forms of creativity (Boden 1990), where the former involves novel combinations of the familiar, that is, associative or analogical thinking and the latter refers to 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 and are radical, can emerge. For the purposes of musical creativity, *Interpretation* could be likened to the *Improbabilistic* model and *Improvisation* could be likened to the *Impossibilistic* model.

Flow Experience in Music

Most of us, musicians or naïve listeners, have experienced a period of focused concentration associated with an intense positive experience whilst performing or listening to music (Diaz 2013). This type of psychological state is termed *Flow* (popularly known as "being in the zone") by positive psychologist Csikszentmihalyi (1990); it describes an optimal experience associated with an intensely positive emotion of being fully engaged in the successful pursuit of an activity. Flow experience is assumed to be closely related to creativity (Csikszentmihalyi 1996). Furthermore, due to its intrinsically rewarding nature, flow is often considered to be the primary motivating factor for a training musician to invest a disproportionate amount of time in learning musical skill and meeting greater challenges.

Flow is characterised by nine dimensions as follows (Csikszentmihalyi 1990): a balance of challenge and skill, merging of action and awareness, clear goals, unambiguous feedback, full concentration on the task, sense of control, loss of self-consciousness, transformation of time, and extremely rewarding.

Flow has been positively related with high achievement of music performance (O'Neill 1999), quality of group compositions (Sawyer 2006), meaningfulness of songs created during therapeutic songwriting (MacDonald et al. 2006), reduction of performance anxiety (Fullagar et al. 2013), and emotional (more than cognitive) aspects of subjective well-being (Fritz and Avsec 2007).

As the flow state is highly emotionally rewarding, and music is an effective medium of communicating emotions, achieving a flow state during creative music performance may be related to the intrinsic ability to effectively deal with (musical) emotions. Recently we (Marin and Bhattacharya 2013) have explored this issue by investigating whether there is something inherent in the emotional personality of the professional musicians that could explain why some musicians experience flow states more easily and often compared to others. We studied 76 professional pianists and evaluated their flow experience in piano performance and measured their trait emotional intelligence, a personality trait defining the ability to effectively process and manage emotional information (Petrides and Furnham 2001). We have found that flow experience can be significantly predicted by the amount of daily practice and trait emotional intelligence (Marin and Bhattacharya 2013). This is in line with some recent evidence that individual proneness to flow experience is associated with personality traits that are under dopaminergic control and be represented in low impulsiveness, more openness, stable emotion and positive affect (Ullen et al. 2012).

The neuronal correlates of flow experience during musical performance is not yet properly investigated but Dietrich (2004) has suggested a theoretical framework of flow experience based on explicit-implicit distinction. At the initial stages of acquisition of a skill (i.e. musical in this context) explicit processes are involved with associated activities at the medial temporal lobe and frontal attentional network, promoting cognitive flexibility. Once the skill is learned, implicit processes are more involved with associated activities of the subcortical structures like basal ganglia. The optimal flow experience is achieved when the practiced skill that is represented by the implicit system is exercised without any interference from the explicit processes that are temporarily suppressed; therefore, a necessary condition for flow is suggested to be the transient deactivation of the prefrontal network exerting attentional and cognitive control (Ulrich et al. 2014).

Neural Correlates of Musical Improvisation

Neuroimaging studies on musical creativity have predominantly focused on aspects of jazz improvisation, as jazz is a contemporary Western musical form in which improvisation plays a paramount role, and being tonal in nature is easier to analyze for its music content.

Limb and Braun (2008) performed a seminal fMRI study in which jazz musicians 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 during improvisation but using the same chord structure of the original composition and the same auditory accompaniment as the basis for improvisation. The principal finding was that improvisation, as compared to the production of over-learned musical sequences, was consistently characterised by a dissociated pattern of activity in the prefrontal cortex, specifically the deactivation of the dorsolateral prefrontal cortex and lateral orbital frontal cortex with focal activation of the medial prefrontal cortex. Interestingly the transient deactivation of DLPFC, the center of executive functioning and control, during spontaneous musical improvisation is aligned with the earlier neurocognitive framework of flow experience (section "Flow Experience in Music"). Note that as the study used accompaniment as a basis for improvisation, the feel is more towards interpretative goal-oriented creativity. Furthermore, the significant role of memory cannot be ruled out either.

In another fMRI study, Bengtsson and colleagues (2007) investigated musical creativity, especially piano improvisation, by employing three experimental conditions. In *improvise* condition, pianists (all males) were instructed to improvise on 8 bars of a visually presented piece of music; in *reproduce* condition, the pianists had reproduced their earlier improvisation from memory, and in *free improvisation* condition, they were asked to simply improvise but without committing to memory. To isolate the neural correlates of musical creativity, the authors first compared the brain activations during improvise with those during reproduction, and identified those differences in the comparison above that are common to activations during free improvisation. A broad network of brain regions, including sensorimotor cortex (presupplementary motor area, the rostral part of the dorsal premotor cortex), superior temporal gyrus, and the prefrontal cortex, specifically the right DLPFC were found to be associated with the piano improvisation. Other fMRI studies on the generation of musical structures have identified similar (and even a broader range of) brain regions including the language areas (Parncutt 1994).

Although pioneering in nature, these fMRI studies may suffer from one principal limitation, i.e. poor ecological validity. Inside a fMRI scanner, the pianists are asked to play whilst lying down, which might have involved different motor skills and cause different perceptions and reactions than usual, as pianists usually perform sitting upright. Interestingly, EEG does not pose such limitations, and here, we briefly describe some of our own experimental findings on musical creativity in pianists.

In a pilot study, we recruited 5 pianists (1 female) from a classical background with at least Grade 8 level (minimum requirement for a university degree in music) with four of them at early stage careers (age range of 20–30 years) and one highly skilled professional (age of 45 years). They were presented with 20 classical musical excerpts (Fig. 1) and given a variety of instructions which included to *play* the excerpts exactly as presented and to *improvise* freely on some element of this excerpt. All musical excerpts were unfamiliar and varied in terms of tonality, rhythm and melodic contours so as to avoid the effect of memory and related bias; this was ensured by including classical excerpts that were not used in any

Fig. 1 **A** range of musical excerpts that were used as stimuli in the pilot study. Note the variety of time signatures, rhythms, tempi, tonalities, keys, dynamics and melodic contours

degree syllabus (after consultation with Richard Dickins, conductor of Imperial's Symphony Orchestra and member of the Royal College of Music and Associated Boards of Music).

We recorded continuous EEG from 64 electrodes and analysed the functional co-operation between different electrode regions by a measure of phase synchrony, PS (Varela et al. 1999). PS values between all possible electrode-pairs were calculated, and averaged across pairs. Subsequently, the mean PS values were thresholded to examine the periods of higher synchrony in the top quartile (25 %). These periods could be termed as 'perseverance', and their duration was measured for the improvisation and play conditions (Fig. 2). These specific higher synchronised events spanned two orders of magnitude in timescales suggesting a degree of scale invariance through a possible observed power-law. Note that due to the limited sampling frequency of 512 Hz (though it is a standard sampling rate for EEG recording), there were not enough sample points in smaller time periods to investigate over a broader range of time scale. Nevertheless this tendency towards scale invariance in pair-wise synchrony could be a putative characterisation for musical improvisation.

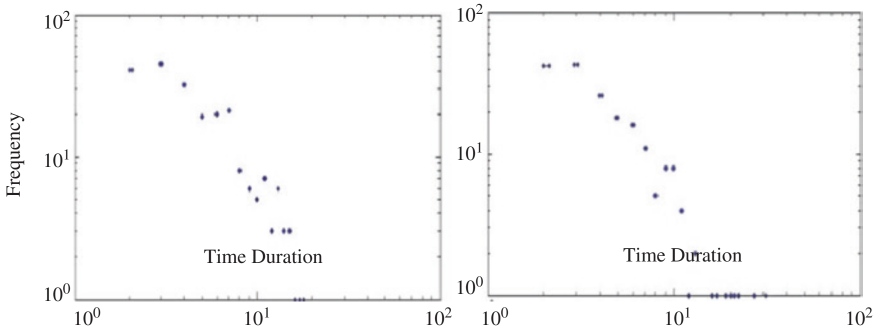

Fig. 2 Two log scaled plots with the *y*-axis signifying ‘frequency’ and the *x* axis the time duration ‘persevered’ above the threshold. *Left panel* This is the plot for the condition of ‘play’. *Right panel* For the condition of ‘Improvisation’ which shows a slight tendency toward a heavy tailed distribution

In our next study, we recruited 8 pianists (4 female) and presented them with 20 musical excerpts (10 classical and 10 jazz) and instructed them to *improvise* freely, *interpret* as per the composer’s markings and *play* just the notes written without any affect. Like earlier, all excerpts were unfamiliar and this was ensured by including classical excerpts that were not used in any degree syllabus and jazz excerpts that were freshly composed for this study. All excerpts were standardised to accommodate both jazz and classical backgrounds of which there was an equal split. Participants were given a fixed amount of time to mentally think about the instruction to either improvise or interpret the excerpt and their actual performance was not constrained by any time limit. Continuous EEG signals were recorded by 64 electrodes and analysed by the source localisation software, sLORETA (Pascual-Marqui et al. 1994) to identify the brain areas associated with improvisation or interpretation.

sLORETA allows an accurate linear inverse mapping of the electrical activity recorded at the scalp surface onto deeper cortical structures as the source of the recorded activity. It 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, Pascual-Marqui et al. (1994), sLORETA yields images of standardized current density with zero localization error.

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. However, further research suggests that extracranial measurements of EEG and MEG are generated by cortical pyramidal neurons undergoing post-synaptic potentials (PSPs) (Pfurtscheller and Lopes Da Silva 1999). 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.

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 $N_V \gg N_E$.

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 1994) 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.

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 et al. 1994).

Figure 3 shows the improvisation-interpretation contrast during thinking and displays an increased activation of left inferior parietal lobule, supramarginal gyrus (Brodmann area, BA40) which has previously been related to an insightful strategy in verbal creativity (Betchereva 2005). This area has been linked to phonological and semantic processing of words (Stoeckel et al. 2009), thus this finding may support the findings of Brown et al. (2006) who found an overlap of areas for melody and sentence generation.

One of these areas of overlap of music and language is BA6 and is found in our study for both improvisation-interpretation and improvisation-play contrasts during the actual performance (Fig. 4). Brown's study found a bilateral activation

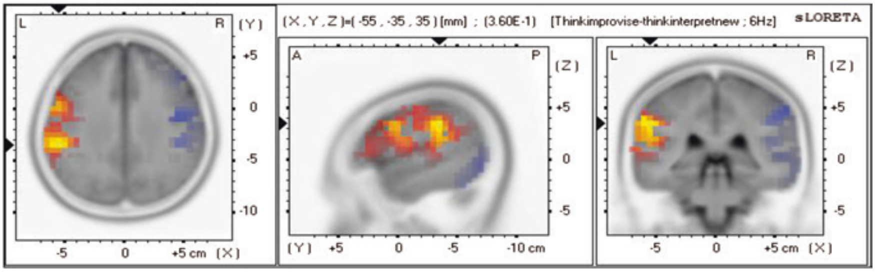

Fig. 3 Comparing the tasks of thinking about improvisation to thinking about interpretation shows a positive modulation in the left BA40. This may imply phonological and semantic processing for improvisation and point to a different mental imagery required, in the form of an 'insightful' strategy

which includes the left hemispheric language areas, whereas in our study, a hemisphere-specific positive/negative modulation activity pattern of BA6 and BA9 presents itself dependent on the time evolution of the task such that in the middle 4 s and last 7 s segments of the improvisation and interpretation tasks, there is a right hemispheric positive modulation concurrent to a left hemispheric negative modulation. This was also accompanied by a negative modulation of the left hemispheric BA42/45/46 in both the last 4 s and 7 s (see Fig. 4).

There is in fact a temporal evolution in improvisation (Sawyer 1992) and interpretation (Dean and Bailes 2010), and the particular global structure of the music that the performer may create or phrase (Cooper and Meyer 1960), which is thus reflected in these findings of large-scale brain activity.

Interestingly, the negative modulation in the left dorsolateral prefrontal cortex (BA9/45/46) for the improvisation-interpretation contrast was hemispherically opposite to that found by Liu et al. (2012) in their recent study of lyrical improvisation. This could be due to the non-verbal nature of our improvisation task and the fact that we were comparing this to a second creative task of interpretation. This latter task may be similar to their lyrical improvised task as they are both goal-oriented.

The positive modulation of BA 6 for the improvisation-interpretation contrast has further implications as this area, which corresponds to the preSMA and dorsal premotor cortex, was recently found in the positive association of improvisation training to functional connectivity during improvisation compared to rest (Limb et al. 2014). Limb corrected for classical training whereas our study involved both jazz and classical musicians performing both the improvisation and interpretation tasks. This implies the association of this brain area to the nature of the improvisation task itself despite other training, however the more experience the performer has of improvisation, the association is further strengthened. Additionally, our pilot study investigated the perseverance of higher global phase synchrony which underlies functional connectivity and this was found to be greater and more scale invariant within a range of timescales, for improvisation compared to play tasks, which is further supported by Limb's study.

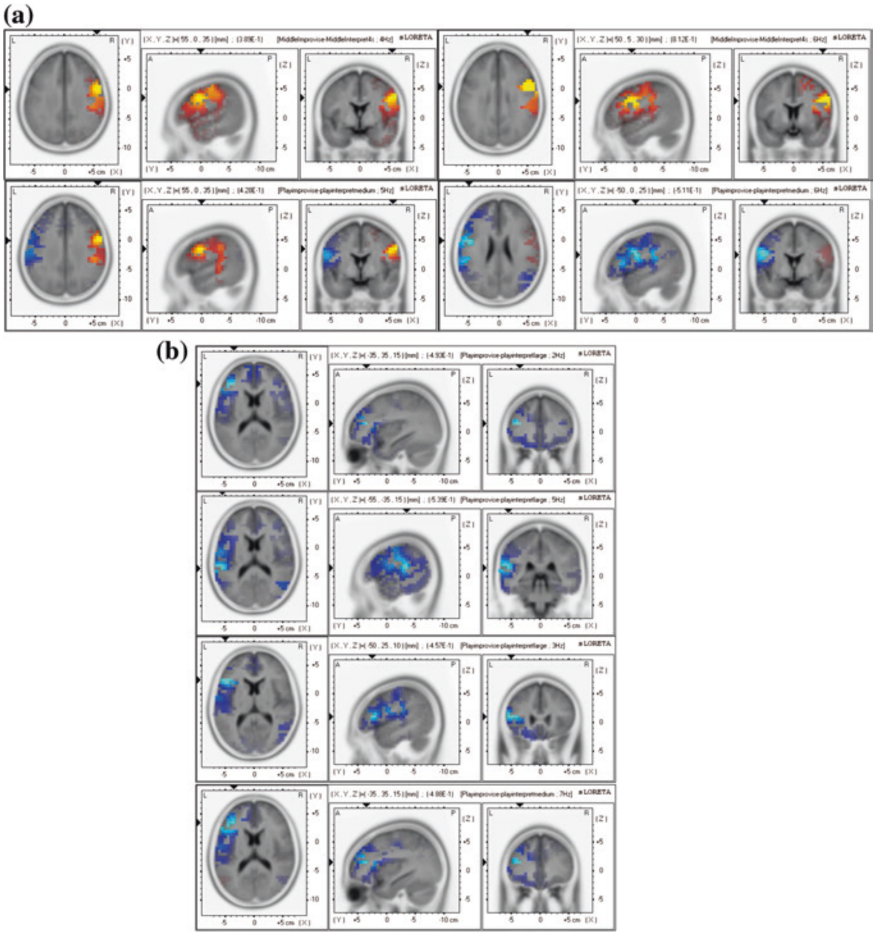

Fig. 4 Source profile for improvisation versus interpretation contrast. **a** The *first row* depicts the positive modulation of the right BA6 and BA9 during the middle 4 s segment. The *second row* depicts the last 7 s segment where the pattern of concurrent negative modulation in the left BA 6 and 9 start to emerge. **b** In order of rows are the negative modulation of BA42, 45 and 46 in the last 4 s segment and finally a maintenance of negative modulation in the BA46 in the last 7 s 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 recent study investigating the interactive improvisation of 'trading fours' in jazz (Ullen et al. 2014), also identified the bilateral activation of the SMA supporting Brown's study. The study also showed an activation of the Broca's and Wernicke's language processing areas in the left hemisphere as well as a comparative increase in their right homologues. This presented differently in our results, of a left hemispheric negative modulation in BA 42/45/46 (which corresponds to these language areas), though they also found a bilateral anti-correlated connectivity in these areas. The main focus of Ullen's study was the bilateral deactivation of the angular gyrus leading them to propose that there was no overlap in the semantic processing of music and language and only a syntactic one. If the word 'semantic' is examined closely, the role of the angular gyrus is linked to metaphor processing (Ramachandran and Hubbard 2003) and corresponds to BA 39 whereas our findings presented a positive modulation within BA 40 which is linked to the direct semantic relation between two simultaneously presented words (Stoeckel et al. 2009), though the implication of its involvement is thought to be due to an automatic phonological processing of a word even if the task does not require it. In fact, Ullen's study also reports a bilateral activation of the supramarginal gyrus (BA 40). Furthermore, our findings presented in participants during an improvisation-interpretation contrast rather than differing complexity of improvisation tasks and also during the mental imagery stage when participants were asked to 'think' about performing rather than actual performance. Our improvisation task was also more 'free' as there were no tempo constraints without a rhythmic accompaniment. This could have led to or allowed participants to create more of a stand-alone semantic structure, developed as a presentation within their improvisations that required no shared syntactic musical rules and even allowed individual rule-making. Importantly, Ullen's study examined *interactive* generative behaviour in the improvisation task through the 'trading fours' technique, giving it a more conversational and communicative framework with shared syntactic rules. Finally, their study looked at a pure jazz musician cohort whereas our participants were not only an equal mix of classical and jazz, but also of male and female; the gender differences in the neuroscientific basis of musical processing remains unexamined.

Subsequently in our analyses, participants were divided into two groups (4 in each group), Jazz or Classical, based on their academic training and performance experience and preferences.

For both the tasks of improvisation and interpretation, there was a negative modulation of BA 18 between the jazz—classical contrasts of participants (see Fig. 5). 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).

The activity pattern of concurrent right hemispheric positive modulation and left negative modulation in BA6/9 and 45/46 is found only during improvisation-interpretation contrasts in the middle and last 4 s in Jazz background participants. This suggests that other instances of this activity patterns are due to participants' Jazz pedagogical training which is in keeping with both the Limb and Ullen research.

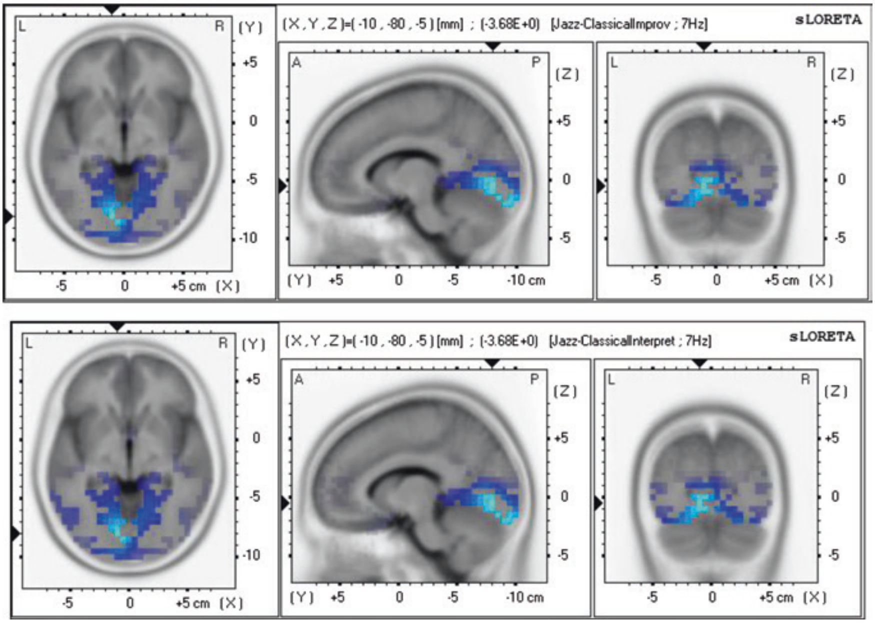

Fig. 5 Negative modulation patterns in BA18 for both tasks of improvisation and interpretation between participants of jazz and classical backgrounds. This indicates that musicians with a classical background adhere more to the visual musical score (visual saccades) and use a different form of mental imagery as compared to musicians with a jazz background

Conclusion

In this chapter we have provided a brief overview of our current understanding of the neurocognitive architecture of musical creativity with a special emphasis on musical improvisation. Music-making is predominantly human, at least at this level of complexity and aesthetical experience. So a proper understanding of musical creativity leads to a novel and critical insight of a core component of human cognition. Empirical neuroimaging research on musical creativity is at its infancy and the limited number of available findings does clearly suggest that musical creativity cannot be localised to a single brain region nor confined to a single cognitive process. This is not unexpected considering the omnipresence of brain networks across tasks and the multifaceted nature of musical creativity itself.

Although this chapter focusses mainly on the performative aspects of musical creativity such as improvisation, another aspect of creativity is planned musical composition which due to the limitations of neuroimaging techniques available, is not adequately researched in the neuroscientific field.

Future research and advances in technology will hopefully further reveal and refine the characteristics of the structure and dynamics of the network underlying both performed and planned musical creativity and also its possible modulations with training, personality, gender, musical style (e.g. non-Western repertoire), collaborative interaction and aesthetical experience.

Acknowledgment The research is partially supported by the Research Grant EP/H01294X funded by the EPSRC, UK and the CREAM project (Grant Agreement no. 612022) funded by the European Commission.

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