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Title: Toward a standard model of musical improvisation

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Abstract

Musical improvisation is a sophisticated cognitive process that combines creativity, goal-directed action, sensory monitoring, and social interaction. With a renewed interest in quantifying creative processes facilitated by recent advances in neuroimaging technology, musical improvisation has emerged as an ideal paradigm to study creativity. However, many studies isolate the top-down processes related to creativity from those related to production and auditory perception, leaving the question of how creative behaviours integrate sensory information with higher cognitive processes unanswered. The bottom-up neural correlates of music perception have been extensively quantified, comprising networks for auditory processing and parsing semantic and syntactic content. In studies of spontaneously generated music and domain-general creativity, executive control and goal-directed movement networks are added to the perceptual foundation. This review summarizes previous work on music perception and improvisation, and presents a conceptual model of musical improvisation with known neural correlates. We make recommendations on future directions for the study of improvisation and discuss the challenges posed by this endeavour.

Introduction

Musical improvisation is a complex cognitive task that employs numerous brain networks to devise, produce, and monitor novel musical output. Writing in 1988, Pressing proposed a model of musical improvisation that incorporates its cognitive tasks or states, which was updated to include relevant neuroimaging findings by Beaty (2015) with particular focus on the neural correlates of creativity. While improvisation is undoubtedly a creative enterprise, it also incorporates sensory information. Creating music implicates a network of higher-order brain

regions involved in decision-making and executive functioning. This network formulates a plan and interacts with regions involved in production. Where the plan is generated, it can be considered a top-down process however, monitoring the output and affirming or altering the plan relies on bottom-up sensory information from low-level auditory processing networks. These bottom-up perceptual networks are a vital part of improvisation and in this review, we propose a conceptual model of musical improvisation that incorporates the neural correlates of music listening.

The neural correlates of music perception have been examined in detail (for a comprehensive review, see Koelsch, 2011), and several recent studies have begun quantifying the neural correlates of individual pieces of the musical improvisation model proposed by Pressing (1988). The advent of network neuroscience and its utility in describing large-scale functional connectivity provides an opportunity to establish frameworks that describe complex, whole-brain processes. McPherson and Limb (2013) provide a detailed overview of the challenges of studying improvisation, calling for a combination of methods to understand both creativity as a holistic entity, and the quantification of its sub-processes. Biasutti and Frezza (2009) describe improvisation as an interconnected series of cognitive states (see Biasutti, 2015), whereas Loui (2018) presents a tiered model of improvisation containing computational, algorithmic, and implementation (neural) levels.

The components described by Pressing (1988), Beaty (2015), Biasutti and Frezza (2009), and Loui (2018) can be conceptualized as a collection of sub-processes operating at variable time scales nested under the umbrella behaviour of improvisation. This review will describe the neural correlates of these sub-processes and will review findings on the neural correlates of musical improvisation, music listening, domain-general creativity, and computational music analysis;

presenting a conceptual model of music improvisation. This conceptual model is flexible enough to accommodate the heterogeneous nature of improvisation while providing a structure for future study of improvisation as a whole-brain process.

A conceptual model of improvisation

This conceptual model (Figure 1) is a four-tier representation of musical improvisation. Though it is presented as a serial, hierarchical structure, the networks may overlap in space and time, as detailed in subsequent sections. We do not wish to suggest that these networks exist solely to oversee the sub-processes of improvisations described in this review, rather, that they form on an ad-hoc basis and disband when the behaviour is resolved. The first tier is the input network and includes areas related to auditory processing. The second tier describes the network for musical output monitoring and evaluation, including syntactic and semantic processing. The third tier describes the networks responsible for the physical and creative production of spontaneous music, and the final tier describes social music-making. The model primarily includes cortical regions. Though sub-cortical structures, particularly those in the limbic system, has been shown are activated during listening to familiar, pleasurable music (see Salimpoor, 2011), how these structures contribute to novel music in improvisation is unclear currently. Each tier will be discussed in detail below.

[Figure 1 goes here]

Bottom-up Networks

Tier 1: Auditory Processing

When sound is present, an auditory network engages. Here, the auditory signal is registered and projected to higher-order areas for parsing. Brown (2000) presents this stage of signal detection as *musilanguage*: an identical network of brain areas shared between language

and music. Though music and language rely on different auditory information (Zatorre, 2013), shared cortical networks oversee both, including Broca's and Wernicke's areas (Koelsch et al., 2002). Functionally, this root network extracts salient features from auditory signals (Koelsch, 2012) and includes the bilateral auditory cortex (Brodmann Areas (BAs) 41 and 42; Alluri et al., 2012; Koelsch, 2012; Toivainen et al., 2014), the ventral thalamus, the bilateral anterior insulae (Brown et al., 2006), precuneus, basal ganglia, and cingulate gyrus (Alluri et al., 2012; Alluri et al., 2013).

Tier 2: Output Monitoring

Following stimulus detection, a right-lateralized network for musical syntactic processing is engaged (Brown et al., 2006), including music with lyrics (Alluri et al., 2013). Broca's area and its right-hemisphere homologue are active in processing syntactic features in music (Koelsch et al., 2002), with activity in Broca's and Wernicke's area (BAs 44 and 22 respectively) right-lateralized for melody (Brown et al., 2006). There is a seemingly analogous relationship between this network and a left-lateralized network for linguistic syntax, though these networks may share resources. In a 2018 study, Fiveash and colleagues found syntactic interference effects of music listening on sentence recall, indicating a shared syntactic processing system rather than parallel error detection systems. The ventral premotor cortex is also implicated in parsing musical and linguistic syntax (Friederici, 2004; Parsons, 2001), monitoring input for violations of expectations (Koelsch, 2011).

Syntactic rules are also present in music production. Musicians show shorter reaction times and fewer errors in playing tasks where harmonic sequences are resolved congruently compared to incongruently (Novembre & Keller, 2011, Sammler et al., 2013). Sammler and colleagues (2013) found an early right anterior negativity (ERAN) response in trained pianists

imitating chord sequences at earlier latencies than previous perceptual studies. They attributed this finding to skilled musicians' ability to anticipate harmonic progressions, and detect incongruencies through subtle discrepancies in hand and finger trajectories.

Music also has semantic meaning, however, defining musical semantics and their corresponding neural correlates is not straightforward (Koelsch et al., 2002). What is *meant* by music can be vastly different between composer, performer, and listener; and this *floating intentionality* (Cross, 1999) allows music to communicate a diverse array of meanings to a likewise diverse audience (Cross & Morely, 2009). Mithen (2005) proposes music as a primarily emotional medium, and its dynamic elements convey semantically-relevant emotion through various culturally-specific features, including timing, harmony, tonality, and tension-resolution (Steinbeis & Koelsch, 2008; Thompson, 2009). This sensitivity to emotion conveyed by tonal elements is analogous to speech prosody; however, speech comprehension may rely on a two-factor hierarchical model with lexical elements and prosody factored together (Friederici, 2011). Sammler and colleagues (2015) propose a dual-pathway model in the right hemisphere for prosody with dorsal regions in the pre-motor cortex and inferior frontal gyrus (IFG) related to processing and parsing auditory signals; and ventral regions in the temporal lobe related to assigning meaning to these signals. Binding lexical and prosodic information occurs shortly after the onset of a speech signal, and employs the posterior third of the corpus callosum (Sammler et al., 2010).

In music, melody has been shown to supersede lyrics in parsing emotional content from unfamiliar excerpts (Ali & Peynircioğlu, 2006), though an excerpt's emotional valence can affect accuracy in attending to lyrical content (Fiveash & Luck, 2016). Emotional accuracy is preserved when lexical information is ambiguous or absent (Hellbernd & Sammler, 2016), but variance in

accuracy is more extreme for language, supporting the above-mentioned lexical/prosodic comprehension model in determining emotional content (Faber & Fiveash, 2014).

Brown and colleagues (2006) studying improvised linguistic and musical phrase completion propose bilateral regions in the temporal pole playing a central role for processing musical semantics, particularly BAs 22 and 38, and Koelsch (2011) has identified the N5 event-related potential (ERP) as sensitive to parsing meaning in music; but more work is needed to further understand music's semantic dimension.

Top-down networks

Tier 3: spontaneous creativity

The next tier includes a network governing the production of spontaneous musical output and implicates brain areas responsible for motor activity and goal-directed action. Generating novel output requires the assembly of musical elements into a novel and coherent phrase that obeys syntactic conventions and makes sense in its context. In 2006, Brown and colleagues compared brain activity in music students improvising novel musical and linguistic phrase endings for presented phrase beginnings. They found many identical and analogous activations between the modalities, but noted a divergence in semantics with a more wide-reaching left-lateralized collection of brain areas for sentence generation compared to melody generation.

De Manzano and Ullén (2012) specifically examined the role of the pre-supplementary motor area (pre-SMA) and the dorsal pre-motor cortex (PMD) in improvising pianists. They described activation in both the pre-SMA and PMD during melodic and rhythmic improvisation (thought to correspond to temporal and spatial sequence production/perception respectively), and a unique pattern of functional connectivity between the pre-SMA and cerebellum during rhythm-focused improvisation. They also found greater activity in the left dorsolateral prefrontal cortex

(dlPFC). Berkowitz and Ansari (2008) studied pianists improvising freely in the rhythmic or melodic domains, finding activations in the premotor cortex, cerebellum, frontal and temporal gyri, and the cingulate cortex. Bengtsson and colleagues reported similar findings in 2007, also detailing higher activity in the dlPFC during improvisation based on a novel melody. They proposed that the dlPFC may function as a supervisor during improvisation, holding recently-played notes in working memory and selecting subsequent notes from a limited pool of notes in the participant's music plan.

In a 2008 study, Limb and Braun used fMRI to monitor jazz pianists' brain activity during improvisation and the playing of over-learned passages. In improvisation, they found a broad pattern of dissociations from the lateral orbito-frontal cortex to the superior medial area of the prefrontal cortex, accompanied by activation in the frontal polar medial prefrontal cortex (mPFC). These findings were partially replicated in a 2012 study by Liu et al. on freestyle rappers alternately reproducing over-learned pieces and generating novel improvised pieces over a pre-recorded backing track. They found a production-related network that included the right inferior frontal gyrus (IFG) and the bilateral anterior insula, basal ganglia, and inferior parietal lobule. However, while Bengtsson and others (2007) and De Manzano and Ullén (2012) found activations in the dlPFC during improvisations based on a given melody, Limb and Braun (2008) identified deactivations in the dlPFC.

Both vocal and instrumental improvisation featured a dissociation between the mPFC (increased activity) and other regions in the prefrontal cortex (decreased activity) with deactivations for vocalists in the dlPFC (Liu et al., 2012), and broad deactivations in the prefrontal cortex, including the dlPFC, for pianists (Limb & Braun, 2008). Limb and Braun (2008) cited this dissociation as evidence of an extra-volitional flow state (Kouneiher et al.,

2009) that is both shaped by form and rules, and unconstrained by volition, but it could also be a measure of familiarity and/or expertise. In piano studies (Limb & Braun, 2008; Bengtsson et al., 2007; De Manzano and Ullén, 2012), professional pianists were employed, however, Limb and Braun's study specifically recruited jazz pianists, who receive extensive training in improvisation, and had them improvise based on memorized passages. In Bengtsson and colleagues' study (2007) pianists were presented with novel melodies to use as a framework for improvisation. Though they were professional pianists, the novelty of the melodies used may have required a degree of attention and monitoring not seen in improvisation using familiar melodies (referential improvisation) or improvisation without conditions (non-referential improvisation).

De Manzano and Ullén (2012) attributed their participants' dlPFC activation to their classical training, proposing that jazz musicians are more familiar with improvisation which is directly related to their dlPFC activity. Pinho and colleagues (2014) specifically examined the role of the dlPFC in improvisation with both jazz and classical pianists, finding condition-based differences in the dlPFC with greater activation during tasks with more regimented rules, and deactivations during freer tasks. Rosen and colleagues (2016) studied changes in improvisatory behaviour using transcranial direct current stimulation (tDCS) to interrupt the right dlPFC. They found the quality of improvisation improved for novice improvisers, but decreased for experts indicating a different creative process based on expertise.

A study by Dhakal and colleagues (2019) studied jazz musicians of variable instrumental expertise improvising vocally with a pre-learned singing task as a contrast. Here, the authors described a network of brain areas including the left IFG, bilateral superior temporal gyrus (STG), left dlPFC, left SMA, left lateral PMD, and right cerebellum. The dlPFC was connected

to other regions during pre-learned and improvised conditions, however, participants were expert instrumentalists improvising vocally, likely attenuating their expertise.

An additional feature of the dlPFC is its connections with brain areas related to motor activity including the supplementary and pre-supplementary motor areas (Miller & Cohen, 2001). In light of Novembre and Keller's (2011) and Sammler and colleagues' (2012) findings on response time discrepancies and error-related ERP responses to videos of hands playing harmonically incongruent chord progressions and Rosen and colleagues' use of tDCS on the right side dlPFC, deactivations of the dlPFC may reflect an embodied understanding of music that emerges with advanced training in improvisation.

Domain-General Creativity

Much recent work has been done on the neural correlates of creativity which may help specify the role and organization of regions in the frontal cortex in music improvisation. Beaty and colleagues (2018) found a combined network of regions affiliated with the default, salience, and executive control networks engaged during a general test of creativity. Interestingly, they identified sub-groups of participants who exhibited low or high creative ability. Low-creative individuals showed weaker functional connections between the prefrontal cortex and other regions, and higher connections between the temporal lobes and other regions compared to high-creative individuals. The authors theorized that low-creative individuals rely on procedural memory rather than generate completely novel material however, how these connections change with instrumental improvisation, a necessarily procedural memory-driven behaviour, is a relevant avenue for future research. Hippocampus involvement in improvisation was described by McPherson and colleagues (2016) who found that emotionally-cued improvisation for positive, ambiguous, and negative emotions was related to deactivation in the left, right, and

bilateral hippocampus, respectively. Whether these deactivations are part of a general improvisation network or specifically related to emotional tasks is unclear.

Lopata and colleagues (2017) reviewed two modes of creative thinking (as proposed by Evans, 2008; Evans, 2009; and Dietrich, 2004): an automatic/spontaneous mode, and a deliberate/effortful mode. These modes may factor into the coupling of default and executive control networks in domain-general creativity described by Beaty et al. (2016; 2018). This coupling is also seen in musical improvisation, which requires deliberate planning of musical material with automatic execution of that plan using the target instrument. In the Rosen and colleagues study (2016) detailed above, tDCS disruption to the right dlPFC helped performance for deliberate-dominant novice improvisers, but had a detrimental effect on the improvisations of automatic-dominant experts. Lopata and colleagues (2017) further explored this two-mode system finding more frontal alpha synchronization in creatively complex improvisation task conditions, particularly in the right electrodes of musicians trained in improvisation.

Beaty et al. (2016) also highlighted the relationship between the executive control and default mode networks, reviewing findings that show the networks cooperating with creative tasks rather than in opposition as seen in other cognitive tasks. With creativity in general, Saggar and colleagues (2017) identified six widely-distributed clusters of brain areas in a drawing task. Individuals participating in a creative capacity training program showed less activity across clusters, possibly indicating a more streamlined process from decision-making to action (namely spending less time deciding and more time acting). The authors acknowledge that different cognitive resources may be recruited for different types of creative processes, and many of the clusters identified key regions in the music perception and production network (specifically, the cingulate gyrus, precuneus, thalamus, cerebellum, and frontal gyrus).

Creativity training also alters temporal brain dynamics. Przysinda et al. (2017) found higher ERAN responses to unexpected stimuli and higher attention and engagement to an unexpected stimulus followed by a faster return to baseline activity for trained jazz musicians. The authors proposed this heightened sensitivity and processing efficiency to unexpected stimuli is related to the nature of creativity training where unexpected stimuli occur frequently and must be acknowledged and rapidly consolidated to maintain the flow of behaviour. Kleinmuntz and colleagues (2014) tested jazz musicians with improvisation training, non-improvising musicians, and non-musicians on divergent thinking tasks. They found jazz musicians scored highest on measures of fluency and originality, and attributed this to jazz musicians evaluating ideas more leniently than non-improvising musicians and non-musicians. However, the authors include a caveat that divergent thinking tasks are an individual process and improvisation is often a social enterprise.

Tier 4: social improvisation

Improvisation relies on complex, self-directed neural processes, but is also a social behaviour and should be studied with respect to its social dimension, a feat only recently made possible by advances in neuroimaging technology. Amodio and Frith (2006) describe several functions of the medial prefrontal cortex in social cognition, but while improvisation undeniably employs social cognition, the general elements of social interaction are beyond the scope of this review and music studies will be reviewed exclusively in this section.

In an EEG experiment featuring guitar-playing dyads engaging in simultaneous play of identical pre-learned passages, Lindenberger and colleagues (2009) observed synchronized neural oscillations in the low-frequency delta and theta bands within and between participants' brains during preparatory tempo setting and play onset. These patterns were also found in a

follow-up study on the pairs' brain activity while playing pre-learned duet excerpts (Sänger et al., 2012). They found additional synchronized neural oscillations during more musically complex passages requiring enhanced coordination, a finding that was later replicated by Müller and colleagues (2013) studying the same guitarists engaging in dyadic improvisation.

Lindenberger et al. (2009), later replicated by Sänger et al. (2012), also identified hyper-brain networks during musical playing, with correlated nodes between frontal and central sites. Müller and colleagues (2013) extended these findings, observing that improvising guitarists showed more within-brain high frequency synchronization and more low-frequency between-brain synchronization during improvisation. One notable exception was a prevalence of beta oscillations in the dyadic playing condition, which the authors suggest may be necessary for behaviours requiring a high degree of coordination.

Donnay and colleagues, meanwhile, studied jazz pianists “trading fours”, a technique where groups of musicians trade four-bar passages, with one of the pair in an fMRI scanner (2014). They found differences in the rostral portion of the dlPFC, with the dlPFC activated during dyadic play, and deactivated during solo play. This finding adds support to Limb and Braun's (2008) and Liu and colleagues' (2012) findings on extra-volitional control in spontaneous play, indicating a freer, more self-directed pattern of behaviour in individual improvisation that is constrained when a second player is introduced.

Music production and network engagement: the temporal dimension

Creativity-focused studies illustrate expertise-modulated networks for the conceptualization and execution of musical improvisation. While these networks shape the musical output by sending information to the production network, they undoubtedly rely on feedback from the music listening network and must be constantly evaluating and consolidating

that information. The temporal dynamics of these interactions, however, are unclear. It may be helpful to divide the networks into time scales with areas contributing to the listening network operating at the quickest scale followed closely by regions in the parsing/evaluation network. Regions contributing to the production network rely on feedback from the planning network and will operate on a slower scale accompanied by regions in the planning network; monitoring the musical plan and relying on a critical threshold of information or error from the bottom-up networks to deviate from the plan.

Here, it is useful to analyze the output. Low-level features extracted from recorded music (see Lartillot et al., 2008) can be applied to brain data to map the activity of the listening network in tracking low-level acoustic information (eg. amplitude, spectral information) over time (see Alluri et al., 2013). Alluri and colleagues (2012) described neural correlates related to specific musical features, dividing features into short- and long-term categories corresponding to acoustic and syntactic information respectively.

In the monitoring network, music shows syntactically-driven ERPs in frontal electrodes sensitive to syntactic errors described as ERAN with peak latency occurring between 150 and 250 milliseconds (ms) in music, thought to originate in the inferior fronto-lateral cortex (Koelsch, 2009), though this can be confounded by timbrally variable music (Fiveash et al., 2018a). This monitoring system for violations of expectations contributes to the monitoring mechanism detailed in Pressing's model (1988). Music also features a late positivity in centro-parietal electrodes (P600) associated with content analysis and feature integration occurring between 600 and 900 ms (Fedorenko et al., 2009; Patel et al., 1998). Koelsch (2011) characterizes shifts in musical content as occurring gradually (compared to language, which

exhibits a P600 at 500 ms; Angrilli et al., 2002), accounting for the rather broad ERP latency window.

For high-level features that may link the parsing and planning networks in improvisation, we can take cues from work on statistical learning in music. Hansen and Pearce (2014) and Daikoku (2018) both detail the utility of Markov models in predicting uncertainty over time in musical output. Hansen and Pearce (2014) found training-based differences in expectations from musicians and non-musicians with musicians displaying lower degrees of uncertainty for pieces of varying complexity during music listening. Daikoku (2018) expanded this further applying two-process statistical learning proposed by Thiessen et al. (2013) to music. In this framework, local statistics (transitional probabilities) are integrated into summary statistics to generate predictions for novel sequences. This echoes the two-stage creative processes detailed by Beaty and colleagues (2016) where bottom-up local information and high-level summary information combine. Norgaard (2014), meanwhile, used computational analysis to analyze solos by eminent jazz improviser, Charlie Parker, searching for patterns between improvisations. This study contrasted two theories: pre-existing patterns are recalled and assembled into groups before being inserted into an improvisation (Pressing, 1988); and patterns emerge as the improviser applies well-learned rules of tonal jazz without a library of motifs (Johnson-Laird, 2002). The patterns present in the corpus indicated pre-formed pattern units are assembled and inserted into the music however, whether this arises incidentally or from a library of motifs remains unclear (Norgaard, 2014).

Another dimension of the planning network is social interaction. Within a group or dyad, there are social roles that shift rapidly requiring the consideration of social dynamics. As Lindenberger and colleagues (2009) note, EEG synchronization may occur as a result of physical

cueing during play onset, raising an interesting point on the merits of analyzing kinematic movements that could signal heightened connection or salient communication during play (Himberg et al., 2013). Musicians physically communicate intentionality and emotion during performance (Dahl & Friberg, 2007), and it is possible to capture and quantify such movement in fine detail using motion capture technology (Thompson & Luck, 2011). Additionally, while social music-making and language both have actor and listener roles, a musician playing in a dyad is able to fulfill a polyphonic mode where both dyad members are producing novel melodic information simultaneously while listening and reacting to their partner.

Future Directions

This conceptual model represents a very early foray into the holistic study of musical improvisation and is not without limitations. Capturing temporally and spatially resolved data from improvising participants will affect the ecological validity of the improvisation, whether by scaling down musical instruments for scanner compatibility, or limiting participants' range of motion to minimize head movements. Following a paradigm similar to Donnay and colleagues (2014) where only one member of a dyad is scanned could allow for motion data to be collected from the individual not in the scanner and applied to the partner's brain data for comparison. Dyadic scanning parameters can also be taken from Baess et al. (2015) where participants are digitally connected while in separate scanners, though this limits physical cueing. Participants could be instructed to use eye cueing, which could be captured using a combined fMRI and eye tracking approach (see Kanowski et al., 2007).

Another limitation is the heterogeneity of the stimuli. A right-handed amateur ukulele player will present a different pattern of brain activity than a left-handed piano virtuoso or a non-musician instructed to tap on a drum, both in the motor activity required to play their

instruments, and in the organization of their musical network (Oechslin et al., 2012; Acer et al., 2017). Developing a normative contrast condition is essential to identify differences related to instrument and expertise, which will help to strengthen the model's applicability.

Finally, the timing and directionality of these behaviours is very complicated. Improvisation may rely on a standard functional network, but each recording will be different. McPherson and Limb (2013) detail the challenges of researching musical improvisation while preserving its creative integrity and call for a greater understanding of the sub-processes and brain states that generate creative behaviours. One possible solution is captured in the structured flows on manifolds framework as described by McIntosh and Jirsa (2019); a paradigm that conceptualizes the behaviour of a complex system (like the brain) as dynamic flows rather than a series of static states. These flows are coordinated on a low-dimensional manifold that constrains the potential behaviour(s) a system can employ. Quantifying an improvisation manifold would address many of McPherson and Limb's concerns by providing a baseline specific enough to differentiate musical improvisation from domain-general creativity, and flexible enough to accommodate improvisation's behavioural heterogeneity.

Music with amateurs and clinical populations

Music is an undeniably universal behaviour, however, the majority of the studies detailed in this review examined highly trained musicians. While this presents a useful first look at the neural correlates of improvisation, it is unclear how these findings will translate to amateurs or non-musicians. This is important as an often-overlooked aspect of music is its robustness in the face of injury or disease. Improvisation can be used therapeutically as a communicative tool with individuals with absent or underdeveloped speech (Wigram, 2004), and individuals with language loss due to neurodegeneration or trauma (Svansdottir & Snaedal, 2006). Music therapy

has been extensively qualitatively described, but its underlying mechanisms are not easily or reliably quantified with the behavioural tools currently available (McDermott et al., 2013). Establishing a reliable baseline network of musical improvisation in healthy musicians will provide a starting point for research into musical behaviour with healthy amateurs and clinical populations, a rich area of investigation that combines neuroscience, clinical practice, social interaction, and creativity.

Conclusion

Music is a medium we can use to describe our experiences, express our deepest emotional states, and engage in social bonding. Advances in neuroimaging technology have enabled the study of this unique behaviour, building our understanding from ERP responses of tones and clicks to fMRI recordings of dyadic jazz improvisation. Music relies on elaborate brain networks blending auditory processing, goal-directed action, executive control, and creativity; and understanding how these networks interact in a naturalistic way is fast becoming possible. Examining the neural correlates of music from perceptual response to goal-directed production can teach us much about how we interact with our experiences and each other, and how these patterns change with age, illness, and injury. It is our hope that these initial studies will lead to investigations of social music-making so that we may further understand what it is that we have to express, and how it is that we express it.

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Competing Interests

The authors declare no conflicts of interest.

Author Contributions

S. Faber drafted the manuscript and A.R. McIntosh edited the manuscript.

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Figure 1: A conceptual model of improvisation. Abbreviations are described below:

Output Monitoring:

Semantics: STG, superior temporal gyrus; IFG, inferior frontal gyrus

Spontaneous Creativity:

Motor Activity: SMA, supplementary motor area; PMD, dorsal pre-motor cortex; MTG, medial temporal gyrus; STG, superior temporal gyrus; IFG (R), right inferior frontal gyrus; IPL, inferior parietal lobule

Planning: FTG, frontal temporal gyrus; dlPFC, dorsolateral prefrontal cortex

Flow State: mPFC, medial prefrontal cortex; dlPFC, dorsolateral prefrontal cortex; oPFC, orbitofrontal prefrontal cortex

Social improvisation: rostral dlPFC, rostral dorsolateral prefrontal cortex