Minds Connected in Song:

Music Performance as a Setting for EEG Hyperscanning

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Course: Interpersonal Perception

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25 March, 2019

Abstract

The progress of social neuroscience depends on the development of experimental paradigms wherein the brains of socially interacting individuals can be observed in real-time. By capturing data from two or more subjects simultaneously, EEG 'hyperscanning' offers an opportunity to investigate the neural activity of social interaction with high temporal resolution, low cost and high ecological validity. Musical performance offers an excellent setting for the application of this experimental paradigm as it involves two or more individuals interacting within a temporal framework and communicating in a coded behavioral manner that can be effectively captured and analyzed alongside EEG recording. This paper will elucidate the social interaction constructs pursued in EEG musical hyperscanning, the methodology employed and review existing literature on the topic, including paradigmatic limitations and directions for future research.

Human beings are social animals. Though capable of great feats of individual creativity and comprehension, it is through collaboration that humans have achieved their technological and cultural heights. Social interaction has made possible a multiplication of the capabilities of the individual and one may consider each human mind as a node in a greater network whose capacities far outstrip those of any one person. South African theologian and human rights activist Desmond Tutu describes the Zulu concept of *ubuntu,* which in the Nguni Bantu language, suggests, "A person is a person through other people." Tutu continues, "It is not 'I think therefore I am'. It says rather: 'I am human because I belong.' I participate, I share." (Tutu, 1999, pg. 35). It is through our interaction that we become human.

Among the products of the human social brain is creative expression. Story telling, visual artistry and music making have sprung from the minds of ancient people as a means of communication, entertainment and the maintenance of social cohesion. Music making in particular is a unique expression of the human social self as it is a collaborative endeavor using a coded system of sounds to communicate experience and feeling for which verbal language may not suffice. As a professional musician for over two decades, I have had the great privilege of experiencing the power of music to transcend language, geography and time to communicate something that, even today, defies clean academic explication.

In the realm of modern neuroscience, researchers seek the physiological substrate of human experience and behavior through powerful reductive techniques. The astounding intricacy of the human brain requires researchers to push ever deeper into the micro scale while the guiding principals of the scientific method call for the isolation of variables in order to make sound judgments. However, recent thinking brings to light the necessity for neuroscience to look not only down into the neuron, but also up, into society. Just as a neuron isolated *in vitro* may yield some insights into its activities and yet withhold its function as a component of the brain as a whole, a human being, taken on their own, isolated out of methodological necessity, will not reveal their true nature as an actor within society. Given the wisdom of *ubuntu*, clearly modern neuroscience needs methods that allow investigation of emergent phenomena on the supra-individual level if it hopes to capture the whole of the human.

Social neuroscience seeks to elucidate the neural mechanism of human social interaction (Acquadro, Congedo, & De Riddeer, 2016). This is an ambitious goal, given the complexity of social behavior, as well as the methodological difficulties present in isolating for study constructs

which, by definition, do not exist in isolation. However, recent technological and methodological advances have opened a door that allows neuroscience researchers to peer into the minute activities of a living human brain while simultaneously widening this view to include that brain's interaction with another. Rather poetically, this duality is reflected in the fact that these hyper-modern techniques may be most successfully brought to bear via one of humanity's oldest activities: music making.

Constructs and Concepts

'Social cognition' is a broad term meant to encompass all of the processes and capabilities employed by the human brain to understand and successfully interact with other humans. This includes the storage of semantic information about individuals' names, background, etc., as well as procedural knowledge about how to behave politely in conversation and also less explicit processes such as biases and affect (F. Babiloni & Astolfi, 2014).

One of the most fundamental phenomena enabled by social cognition is that of social interaction. While the concept of social interaction constitutes a 'dark matter of social neuroscience' in which philosophers, psychologists and neuroscientists approach the construct from a variety of perspectives (Przyrembel, Smallwood, Pauen, & Singer, 2012), for the purposes of this paper social interaction may be construed as a real-time exchange of information, via action or verbal communication, between two or more people, in which the exchange influences the behavior or mental states of the interactants.

Acquadro et al. (2016) categorize social interaction into three types: observation, turn-based interaction and continuous interaction. In the observation condition, an individual is a passive receiver of unidirectional stimuli. In a turn-based interaction, two or more individuals alternate receiving and transmitting according to rules of a task. In continuous interaction, two or more individuals exchange with one another in a low-constraint, fast-paced, dynamic fashion in which they may switch roles or act at the same time. These 3 types of interaction have been put to use in various social neuroscience experimental paradigms but it is continuous interaction which most closely resembles the natural behavior of humans in free social interaction.

Sänger, Lindenberger, & Müller, (2011) identify several types of activity which are possible through social interaction. Joint action is described as coordinated activity by interactants that brings about a change in the environment, occurring within the constraints of a

structured setting that dictates roles, turn-taking sequences and means of communication. The authors define coordination as a non-random correlation in the behaviors of interactants; those behaviors being coupled to one another or to another common system. The combination of joint action and coordination yield interpersonal action coordination, which the authors point out is purposeful and directed and does not include such behavior as two people simultaneously orienting to an unexpected sound stimulus.

Current literature suggests that social cognition may be subserved by two cerebral systems, termed Theory of Mind (ToM) and the Mirror Neuron System (MNS; Acquadro et al., 2016). Theory of Mind is the ability of individuals to infer the mental states of others, including their beliefs, desires, intentions and emotions, relative to and distinct from the individual's own mental state (Baron-Cohen, 2000). This ability is essential for the successful navigation of social interaction which requires an understanding of the motivations and perspective of the other. Functional imaging studies indicate that ToM is supported by a variety of neuroanatomical structures including the right supramarginal gyrus (SMG) and the temporo-parietal junction (TPJ; Steinbeis & Singer, 2014). Related to ToM is the concept of 'mentalizing' which is a conscious process allowing the inference of other people's goals and intentions. Mentalizing is proposed to rely also on the TPJ in concert with the medial pre-frontal cortex (mPFC; F. Babiloni & Astolfi, 2014) as well as the superior temporal sulcus, anterior cingulate cortex, temporo-occipital junction, temporal pole and the amygdala (Acquadro et al., 2016).

Proposed to interact with the mentalizing process and ToM is a less conscious system in which the physical actions of others are represented and internally simulated, termed the mirror neuron system (MNS). In this system, sensorimotor neurons involved in the performance of an action fire when an individual observes a conspecific performing the same action (Gallese, Keysers, & Rizzolatti, 2004). The neural substrate of this system is proposed to involve the inferior parietal lobe, the ventral premotor cortex, inferior frontal gyrus, dorsal premotor cortex and superior parietal lobe (Acquadro et al., 2016). Due to methodological constraints, dispute remains regarding the extent of the MNS (Lingnau, Gesierich, & Caramazza, 2009) however a body of literature suggests that the low-level perceptual, representational processes of the MNS may, in certain conditions, work in concert with the higher-level, deliberative processes of ToM and mentalizing to facilitate the decoding and understanding of the mental states of others

(Acquadro et al., 2016; F. Babiloni & Astolfi, 2014; Keysers, Renken, Schippers, Nanetti, & Roebroeck, 2010).

Interestingly, debate on the neurobiological mechanisms by which structures of the MNS and mentalizing system interact hinges on a concept which reappears when social neuroscience considers the interaction of two people: resonance. Buzsáki & Draghun (2004) state that "single neurons are endowed with complex dynamics, including their intrinsic abilities to resonate and oscillate at multiple frequencies" and that this activity within a network of neurons may represent the information the network is communicating. They continue, "The synchronous activity of oscillating networks is now viewed as the critical 'middle ground' linking single-neuron activity to behavior."

In the domain of social interaction, resonance is an idea used more metaphorically, to refer to variation in one interactant's behavior which leads to similar variations in the behavior of the other (Keysers et al., 2010). However, social neuroscience endeavors to delve more deeply into the concept of resonance than the externally observable back and forth of easy conversation or the coordinated actions of two people washing the dishes.

Sänger and colleagues (2011) hypothesize that, given the speed and precision of neuronal oscillatory activity in binding information as it moves across cerebral circuits and the functional role of oscillatory coherence in perception and action within an individual brain, coherent brain oscillation may represent a neural code through which the joint action of human behavior is coordinated. The synchronization of oscillatory neural activity across brains is proposed to facilitate social interaction (Müller, Sänger, & Lindenberger, 2018). Further, Sänger (2011) states, "coherent activity between brains should be observed when interacting individuals adjust their activity patterns in the pursuit of a joint action whose successful execution requires synchronization of behavioral patterns," (p. 659).

Methodology

Until recently, the experimental paradigms of social cognitive neuroscience were limited to the observation of a single individual at a time. However, in recognizing the value of recording neural activity from simultaneously interacting subjects, researchers have faced the limitations of various data capture modalities. Imaging techniques such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) are limited by coarse

temporal resolution as well as the complexity of the apparatus, which more than doubles if applied to two subjects simultaneously. Techniques measuring neuroelectric activity such as magnetoencephalography (MEG) and electroencephalography (EEG) offer high temporal resolution which is essential in measuring the millisecond scale of neuronal dynamics in social interaction, though MEG suffers from cost and complexity restraints (Sänger et al., 2011).

In terms of temporal resolution, cost of operation and ecological validity, EEG has emerged as a desirable technique for hyperscanning. Subjects can be seated facing each other, without obstruction or the need for a device to mediate their interaction. As some range of motion is tolerable, subjects may communicate and participate in more real-to-life behavioral tasks (Astolfi et al., 2011). Recent advents in data analytic tools make possible detailed comparisons of neural waveform time series from multiple subjects (Burgess, 2013). However, this is not to say that the idea of recording electrical brain activity simultaneously from two or more interacting subjects, known as 'hyperscanning', is entirely new.

In 1965, T.D. Duane and Thomas Behrendt, ophthalmologists at Jefferson Medical College in Pennsylvania, observed that 'photic driving', wherein the frequency of light flashed in the eyes of subjects under EEG produced alterations of the neuroelectric alpha rhythm and occasionally made subjects ill. Based on accounts in the 'non-scientific literature' Duane and Behrend became interested in the idea that identical twins might share a connection such that if one twin were to become ill, the other might become similarly affected despite geographical separation. To investigate the possibility that one twin exposed to photic driving (with or without feeling ill) would result in the other twin showing the same alpha activity, the researchers unwittingly conceived the world's first hyperscanning study.

Fifteen pairs of twins were recruited. According to the paper published in *Science*, "No specific criteria other than close similarity in appearance and a history of identity confusion were used to establish monozygosity," (Duane & Behrendt, 1965, p. 367). The twins were seated in identical lighted rooms 6m apart, told to keep their eyes closed until instructed and "electrodes were inserted subcutaneously over occipital protuberances," (Duane & Behrendt, 1965, p. 367). The researchers sought evidence of 'extrasensory induction' which they described as the elicitation of alpha rhythm in one twin through photic driving and also in the other twin, who was not exposed to the same stimulus. The publication states that of the 15 pairs of twins, 2 showed extrasensory induction based on visual inspection of the EEG waveform traces (on

paper, if one can imagine). These 2 pairs were "Intelligent, educated, serene Caucasian males 23 and 27 years of age," (Duane & Behrendt, 1965, p.367). The publication was not well received due a variety of methodological weaknesses and the experimental paradigm was forgotten to science for 40 years (F. Babiloni & Astolfi, 2014; G. Dumas, Lachat, Martinerie, Nadel, & George, 2011). Nonetheless, the paper serves not only as the birth of hyperscanning, but a valuable source of perspective for neuroscientists, lest we become too enamored with our modern sophistication, it is worthwhile to consider that neuroscience students 40 years in the future may scoff at the primitive nature of our work.

In recent years, hyperscanning has been revisited, with expanded technological capabilities in terms of data capture and analysis, as a means for social neuroscience to explore the activity of human brains as they interact with each other. In 2002, Montague and colleagues conducted a study using subjects in two fMRI scanners, linked via computer server over an Ethernet connection. The central server coordinated the behavioral task presentation to both subjects (a competition game in which winners were rewarded with a squirt of juice in their mouths) as well as provided a clock source for the synchronization of scanning and behavioral measures. At this early stage, limitations to the fMRI paradigm were identified including inter-scanner variability, temporal latencies introduced by computer server linkage as well as the complexity of the paradigm and the obvious lack of ecological validity resulting from subjects' occupancy of a large, mechanical device (Montague et al., 2002).

These methodological obstacles, in addition to the limited temporal resolution of fMRI, are avoided in the use of EEG for hyperscanning studies. However, there are a number of methodological concerns to be contended with in this modality. Primary among the considerations in the technical aspects of EEG hyperscanning is the of synchronizing of devices (Acquadro et al., 2016). In order to make secure conclusions about captured data, researchers must ensure that the time series recordings are made in perfect synchronization. Sampling rates of separate EEG devices must be exactly matched, typically between 200 and 500 Hz. An external trigger device may be employed to transmit a time code to all EEG devices and recorded alongside electrode channels for the purpose of synchronizing data for analysis. Attention must be paid to the introduction of clock jitter resulting from time code passed along local area networks. Alternately, data capture for both subjects may be performed by the same EEG device, depending on the paradigm and device capacities. However, synchronizing all EEG

devices to an external trigger is desirable when analyzing data at high sampling rates (up to 5 kHz) and because it sends a signal of fixed amplitude to all capture devices allowing calibration of different EEG devices with different sensitivities (F. Babiloni & Astolfi, 2014).

Because one of the desirable features of EEG hyperscanning is increased ecological validity, experimental behavioral tasks may be conceived that introduce artifacting to the EEG recording due to muscle and eye movement. In this case, post-collection analytic techniques have been developed to mathematically filter out these artifacts. Additionally, electrooculogram (EOG) and electromyogram (EMG) may be recorded from a hyperscanning subject alongside EEG and these recordings can be used to subtract artifacts from the EEG data (F. Babiloni & Astolfi, 2014).

In terms of the neurophysiological phenomena hyperscanning seeks to investigate as the substrate of social interaction, new concepts emerge with each published study. Hyperscanning is a very young paradigm, and as such, different ideas exist about how to quantify and describe the neural activity of social interaction. The primary concept is that a covariance of neural activity exists between socially interacting individuals and that a phase-locked neural coupling across brains facilitates this interaction. Though a deep investigation of the complex mathematical components of these techniques is beyond the scope of this paper, what follows is a broad survey of basic analytic techniques. (For more detailed information on EEG hyperscanning analytic methods see Burgess, 2013, and Toppi et al., 2015.)

In early EEG hyperscanning a common method for investigating neural coupling across brains was to examine covariance in waveform amplitude or power. Demonstrating contiguous changes in EEG amplitude or power is weakly associative and though suggestive of neural coupling, more conclusive measures are required. Partially directed coherence (PDC) offers a more powerful means which can establish the directionality of synchronization based on Granger Causality. This method is designed to predict the activity of one signal based on the past activity of another and can be applied to indicate the direction of information flow between two brains. However, this method assumes an unchanging signal over time, which is unsuited to EEG and some results obtained through this method have suffered from poor reproducibility (Burgess, 2013).

Measures of phase synchrony are a widely used means of estimating neural coupling. Phase locking value (PLV) and its relative, the phase locking index (PLI) are indices of this type

which provide a measure of the phase alignment between two waveforms on short timescales (Burgess, 2013). The PLI provides a measure of the phase invariance over time at a single electrode on one brain, whereas the PLV indicates change in oscillatory phase between different electrodes over a given time (Sänger et al., 2011). In these cases, synchrony is characterized, rather than interaction or causality. Other measures include interbrain phase coherence (IPC) which represents the stability of phase differences across trials between two electrodes measured from two brains simultaneously (Lindenberger, Li, Gruber, & Müller, 2009).

In recent years, graph theory has been applied to the investigation of neural coupling across brains in social interaction. Graph theory regards activity within or between brains as a mathematical network of connecting hubs or nodes, which are bridged by linkages called edges (Toppi et al., 2015). Various quantitative measures are applied to the graphs, describing the number of connections per node, path lengths (the number of edges traversed for information to move from one node to another), modules of strong interconnection within the network, the degree of 'clustering' of those modules (random networks have low clustering, while complex networks are highly clustered, creating efficiency) and various other means of describing the strength and efficiency of connections within the network. A network can be said to have 'small world' properties when it has high levels of local clustering and short path lengths globally linking all nodes within the network. Small-worldness is an efficient organization and can be observed in many natural and technological systems (Bullmore & Sporns, 2009).

Given the complexity of the analytical methods employed to determine neural coupling between two interacting brains, it is worthwhile to consider the basic constructs that underlie the concept of synchronicity. The phenomena which is of interest to hyperscanning researchers is a 'true' synchronization wherein the neural oscillators influence each other, constituting a communication of information between them (Burgess, 2013). According to Burgess, "Two oscillators can be said to be synchronized if deviations from the regular oscillatory cycle of one oscillator provides information about deviations in the oscillatory cycle of the other," (p. 3).

Social interaction is a dynamic process and thus the neural activity purported to underlie it should be investigated for similar dynamism. Given this, a simple index of phase coupling over short time scales may be insufficient to describe the relationship between two neural oscillators. Measures of phase covariance or correlation between oscillators over longer time

windows may be useful, in addition to comparisons of the degree of coupling across experimental conditions (Burgess, 2013).

Burgess identifies four types of synchrony and the differences between them point to the necessity of employing the proper statistical control and experimental design to ensure sound conclusions in hyperscanning. First, it is important to identify that two oscillators may be in perfect phase and yet have no reciprocal or causal relationship. This 'coincidental synchronization', where two unrelated oscillators happen to be in sync is a serious hazard to hyperscanning research given that some analytic measures will correctly identify this condition as phase locked, despite the fact that there is no communication or directed relationship between them. For this reason, care must be taken in choosing analytic measures and in making conclusions based on those measures.

In a 'reciprocal synchronization', both neural oscillators participate in a bi-directional exchange of feedback which maintains their phase synchronicity over time and frequency. Also possible is an 'induced synchronization' wherein two oscillators entrain to an external stimulus. Consideration of this phenomenon is of value to researchers whose experimental paradigm creates conditions in which both subjects are exposed to the same perceptual stimuli. Finally, 'driven synchronicity' is a condition in which one oscillator influences, or 'drives' the second, while the second oscillator has no influence on the first. This type of synchronicity may be of interest to researchers investigating leader/follower social behavior (Sänger, Müller, & Lindenberger, 2013) and may be investigated with PDC, as it is designed to detect directionality of information flow (Burgess, 2013).

Given these varieties of synchronicity and the importance of distinguishing between them in hyperscanning research, not only is careful choice of analytic methods important, but the type of social interaction to be engaged in by subjects becomes crucial. Many experimental settings have been devised including competitive/cooperative paradigms, turn-based games, gestural imitation, finger tapping, and more unique settings such as romantic kissing and pilots interacting in an aircraft simulator (for a review, see Acquadro et al., 2016). Among the most promising of paradigms for investigating neural coupling during interpersonal interaction is that of music making.

Music as a setting for Hyperscanning

Music making offers many desirable characteristics as an interactive setting for hyperscanning. It is a continuous interaction, which is more common in everyday human interaction as compared to observation and turn-based interaction. Further among music's ecological validity advantages are the familiar and recognizable nature of the setting: performing music together is a common activity. Additionally, the acoustic and visual stimuli produced by music making are coherent to the setting and familiar to participants. Lastly, the response required of the participant, the act music making itself, is one that is obviously natural to the context. By combining these dimensions, music making creates a holistic and familiar social setting which serves to counteract the unnatural reductivism encountered by subjects in a laboratory setting (Acquadro et al., 2016).

The growing field of music neuroscience provides a base of literature upon which methods and results of musical hyperscanning can be evaluated (Acquadro et al., 2016). Research has emerged elucidating the neural bases of auditory perception, musical motor planning and execution (Levitin & Tirovolas, 2009; Zatorre, Chen, & Penhune, 2007), and the cognitive processes involved in musical comprehension and production (Janata, 2015; Koelsch & Siebel, 2005) particularly with regard to rhythm (Grahn, 2012; Overy & Turner, 2009) which is very relevant to the oscillatory constructs pursued in hyperscanning.

The fact that music is temporally organized, consisting of hierarchical layers of metrical structure, make it not only an attractive phenomenon for the logistical methodology of hyperscanning, but also fascinating from a conceptual standpoint as activity in the brain is similarly organized temporally in a rhythmic way (Overy & Turner, 2009). The foundational pulses which comprise musical tempo occur isochronously, or in units of fixed and equal time, and their periodicity creates a framework of expectancy to guide both musicians and listeners (Vuust, Gebauer, & Witek, 2014).

This shared framework of expectancy in music may consist of neural coupling, both within and between the brains of performers and listeners. Within an individual musician's brain, sensorimotor coupling occurs as the pulse of musical auditory stimulus guides both the comprehension of the musical piece and the subsequent motor activity required to participate in it (Janata & Grafton, 2003). Recent research indicates that neural coupling between the brains of

interacting musicians facilitates the social coordination necessary for successful music making (Lindenberger et al., 2009; Müller, Sänger, & Lindenberger, 2013; Müller et al., 2018).

Another example of social processes at work in the musical context is that of behavioral sequencing, wherein an individual must perform sensori-motoric behaviors in the correct spatio-temporal pattern for successful music performance, just as one must in other social interaction (Janata & Grafton, 2003). Further, music involves rhythmic repetition on a variety of levels and this is complementary to EEG studies which require many repeated trials to average out noise from the signal (Acquadro et al., 2016). The value of coordination during transitions within musical performance is put forth by Acquadro et al., "Human interaction lies in coordination breakdowns and recoveries, the oscillation between these two states and the joint sense-making where the actions and intentions are co-constructed can be typically observed during musical performance, especially in improvisation" (p. 9). In the following pages, we will see that work by Sänger, Müller, & Lindenberger (2012) demonstrates the importance of these transitional moments in music making.

An additional advantage for hyperscanning researchers is that music production offers a behavioral measure which can be readily compared to EEG time series. The musical output of interacting subjects can be recorded and rendered as an audio waveform which can be laid alongside EEG waveforms. In this fashion, changes in tempo, pitch, note onset/offset as well as changes in leader/follower roles can be identified in the musical performance and then compared to the EEG activity at that point (Lindenberger et al., 2009; Müller et al., 2018; Sänger et al., 2012). Music making provides a uniquely rich context, from concept to logistics, for the application of EEG hyperscanning to the investigation of neural coupling between interacting individuals.

Existing Research in Music EEG Hyperscanning

Over the past decade a number of noteworthy studies have been conducted which combine EEG hyperscanning and interactive musical performance by subjects. In 2011, Babiloni and colleagues carried out a pair of studies wherein EEG was recorded from ensembles of saxophonists. The first (C. Babiloni et al., 2011) established a methodological paradigm wherein each member of a saxophone quartet wore a 30 electrode EEG cap, each converging on the same computer workstation additionally recording audio, digital synchronization trigger,

EOG and EMG. In the second study (C. Babiloni et al., 2012) the same equipment was employed to capture data from 3 different quartets as they performed music and, in a separate condition, listened passively to their performance. The recorded EEG data was then compared against subjects' scores on a questionnaire assessing emotional empathy. Results of these studies were not conclusive but the establishment of the complex technical paradigm is laudable.

The most significant body of work in musical EEG hyperscanning has been conducted by a team from the Max Planck Institute for Human Development in Berlin, Germany led by Ulman Lindenberger, Johanna Sänger and Viktor Müller. In 2009, the team conducted a study wherein 8 pairs of guitarists played a short musical segment in unison. A metronome set at a tempo chosen by the players (between 80 and 120 beats per minute, or 1.3 to 2 Hz) announced at least 4 beats of 'lead-in' after which one of the guitarists (pre-designated as the leader) tapped the guitar to signal performance onset. The musical segment was repeated over approximately 60 trials. Captured EEG data was analyzed with PLI to assess within-brain phase invariance across trials at single electrodes and IPC to evaluate phase differences across trials at two electrodes across brains (Lindenberger et al., 2009).

The results of the study showed a significant increase in phase synchronization both within- and between-brains at fronto-temporal sites during metronome count-off. Averaged PLI showed within-brain synchrony between 2 and 10 Hz with a maximum in the theta band (3 – 7 Hz). Between-brain synchrony measured by averaged IPC was strongest between 3 and 8 Hz with a maximum around 5 Hz. Also significant was synchronization within- and between-brains shortly after play onset. Again at fronto-temporal sites, both within- and between-brain synchronization was found between .5 and 7.5 Hz with a maximum around 3.3 Hz. Synchronization decreased considerably after the first two seconds of play (Lindenberger et al., 2009).

In interpreting their results, the authors note that synchronizations observed may be related to the frequency of auditory stimulus of the metronome (at various multiples, or harmonics of that frequency), asynchrony in play onset between the two players as well as the fact that both players performing the same music were exposed to the same perceptual stimuli. Thus, a causal relationship in interpersonal action coordination based on observed coupled neural oscillation could not be drawn (Lindenberger et al., 2009).

In an effort to dissociate the effects of similar sensory input and motor output for both subjects during musical performance from the neural coupling of interactive action coordination, Sänger, Müller and Lindenberger conducted a similar experiment, published in 2012. In this case, 16 duos of guitarists performed a Rondo in two voices (a musical form specifying different parts for each player). Additionally, the musical material called for a *ritardando* (decrease in tempo), followed by a *fermata* (a brief pause) with resumption of the piece occurring with *accelerando* (increase in tempo). The two parts of the Rondo were modified from their traditional leading/accompanying roles so that the two voices were relatively equal, however leader/follower roles were retained in that one player signaled the onset of performance both at the beginning of the piece and after the *fermata* pause.   Players were given the sheet music to study and asked to perform from memory during experimental sessions. The musical material was performed 60 times, with each trial preceded by 4 metronome beats at 1.33 Hz or 80 beats per minute (Sänger et al., 2012).

In terms of analysis, the same measures of phase synchronization used by Lindenberger et al. (2009), PLI and IPC, were employed. Based on the results of the previous research, only delta (1- 4 Hz) and theta (4 – 8 Hz) frequency bands were examined. Additionally, graph theory analysis was conducted to investigate node strength, small-world properties and community structures indicative of network activity both within- and between-brains (Sänger et al., 2012).

Results supported Lindenberger et al. (2009) in that within- and between-brain oscillatory phase locking and phase coherence at fronto-temporal sites were increased during sections of musical performance which required high levels of coordination between musicians, such as during preparatory tempo setting prior to play onset and after the onsets created by the *fermata* pause in the middle of the composition. Additionally, phase locking was found to be modulated by leader/follower roles, with leaders showing higher phase locking than followers (Sänger et al., 2012).

Only during the second play onset, following the *fermata*, did phase locking extend into higher, theta frequencies, which was speculated to relate to the higher tempo performed during this section of the composition. Results of graph theory analysis represent first steps into new statistical methodology and are thus not strongly conclusive, however they suggest 'hyperbrain modules' composed of network structures existing across brains as well as network nodes, within-brain and between-brain, whose strength increased during periods requiring high musical

coordination (Sänger et al., 2012). As discussed in more conceptual terms by Acquadro et al. (2016), moments of musical transition (preparing to start, slowing, stopping, restarting) revealed specialized neural activity at work.

In 2013, the same team of researchers conducted a further study reanalyzing the data collected for Sänger et al. (2012) to more deeply investigate the effects of leader/follower roles via measures of directed synchronicity. Based on the previous study's observation of different patterns of phase locking for different musical roles, the researchers conducted analysis via the integrative coupling index (ICI), a single-trial measure of time-lagged phase coupling. Advantages of this measure include its ability to indicate the direction of functional connectivity between brains and describe phase coupling across time as opposed to phase locking across trials (Sänger et al., 2013).

Results of the investigation showed directed connectivity, from leader to follower, in both alpha and beta frequency bands. Frontal sites were generally more active than other cortical regions in both bands, though increased between-brain alpha band activity at parietal sites was consistent with the previous study's symmetric coherence measures which indicated that parietal nodes are important to inter-brain connectivity networks. Regarding directionality of synchronization, the researchers found coupling to increase significantly at 12 Hz going from the leader's frontal nodes to the follower's brain following play onsets (Sänger et al., 2013). Again, due to the exploratory nature of these measures, conclusibility is limited. However, given alignment with work by Dumas, Nadel, Soussignan, Martinerie, & Garnero (2010) indicating asymmetrical functional activity of across-brain parietal sites during turn-based interaction, the results beg further investigation with variations of the musical paradigm and refined statistical measures.

Also in 2013, this busy team of researchers published yet another study of neural synchronization within and between performing musicians, this time bringing improvisation into the paradigm. Given that natural social interactions are not scripted word-for-word in the way that the Rondo in Sänger et al. (2013) was composed note-for-note, the inclusion of improvisation is another increase in ecological validity and another opportunity to investigate the social brain in action. Musical improvisation calls for high levels of mentalizing, as each performer must imagine the other performers' possible next action, while also guiding their own actions in such a way as to maximize creativity and expression while remaining within the

bounds of the musical setting (Acquadro et al., 2016). Such an activity requires a unique form of interpersonal action coordination and is thus fertile grounds for the exploring hyperscanning neuroscientist.

In Müller, Sänger, and Lindenberger (2013), 8 pairs of guitarists were recorded via EEG as they performed together in 3 sessions of 5 to 7 minutes each. In the first session, guitarist A improvised freely while guitarist B listened passively. In the second session, guitarist B improvised while guitarist A listened. In the third session, both guitarists played together, jointly improvising, typically with one guitarist inventing a melody while the other played supporting chords. These roles would then switch based on the musicians' impulse. No metronome was employed and musicians were free to choose their own tempo.

In analyzing the captured data, the researchers employed ICI as a measure of directed and undirected synchrony within- and between-brains and tailored this measure for continuous or single-trial application as opposed to previous measures which were applied across trials. Results showed synchronization patterns during musical improvisation that were complex: with increasing frequency, coupling strengths increased for within-brain networks, but decreased in between-brain networks. The authors posit that this reflects a higher operating frequency (beta band) for within-brain networks and a lower operating frequency (delta and theta) for between-brain networks. Joint improvisation showed higher connection strengths in the beta frequency band, whereas solo performance showed higher alpha frequency strengths (Müller et al., 2013).

A range of graph theory analyses were applied to the data and showed that some network properties were dependent on musical role (listening vs. playing vs. joint play). An increase in network nodes with high connectivity, both within- and between-hyperbrain modules in the delta and theta frequency bands, was observed during joint improvisation. Authors argue that the increase of connector hubs in these low frequency bands may subserve the interpersonal action coordination necessary for joint musical improvisation (Müller et al., 2013). Taken together, these results support the body of literature indicating that between-brain neural synchronization is functionally related to musical interaction and that networks of activity comprised of sites both within- and between-brains are active in this process. Furthermore, the introduction of improvisation to music-based experimental paradigms improves ecological validity and provides a new type of social interaction for investigation.

In a further pursuit, Müller, Sänger, and Lindenberger (2018) expanded their paradigm to record EEG from all members of a guitar quartet as they performed two complex pieces of music chosen for changes in tempo, varying harmonic consonance, alternation of leader/follower roles and other compositional dynamics. Audio and video of the performance were recorded along with EEG and then judged by an expert musician to identify key moments of change in the composition, as well as moments of musical interaction among the musicians. The complexity of this paradigm is notable as examining the interacting neural dynamics of 4 performing musicians is a significant analytical task, as is the interpretation of the relationship between changes in the musical piece and their relationship to recorded EEG data. The data were investigated for within- and between-brain synchronization dynamics, hyperbrain network properties and their changes over the course of the performance (Müller et al., 2018).

Analysis of the collected data showed that that the hyperbrain networks across the quartet were dynamic, shifting as the musical piece went through changes of tempo, harmonics and leader/follower roles. Given the temporal and behavioral framework provided by the musical composition, the researchers were able to examine the hyperbrain network dynamics and compare them to the musical activity of each performer at each point in time. The publication provides a detailed account of different moments in the arc of the composition and how neural network architecture changed at those moments (Müller et al., 2018).

Key findings include that the hyperbrain networks observed in this guitar quartet show the characteristics of small worldness (short path-length between highly connected hubs) and that this network was composed of overlapping modules which varied over frequency and time. This change was observed to be modulated by the momentary requirements of the musical situation. Further, hyperbrain modules with nodes among two, three or four brains showed strong connections within modules and weaker connections between them. The authors posit that this type of network organization reflects efficient flow of information within- and between-brains, allowing both functional specialization of the module and sufficient interconnection among modules for interpersonal action coordination (Müller et al., 2018).

The preceding body of work provides a fascinating opportunity to consider the interactive behavior of a highly coordinated social activity on many levels. Given the audio and video recording of a performance, along with the musical score allows the behavioral activity of the subjects to be examined from a cognitive, sensorimotoric and socially interactive perspective.

This information may then be compared directly to a very detailed recording of performers' individual neural activity as well as the flow of information between them. That the network activity of musicians' interacting brains should vary over time, as the musical situation dictates, is fascinating to see through empirical data and simultaneously very familiar from the phenomenological perspective of an ensemble-playing musician.

New Paradigms, Directions for Future Research

Among other adventurous paradigmatic explorations conducted by researchers at the Max Planck Institute for Human Development in Berlin is a 2017 study by Szymanski, Müller, Brick, von Oertzen and Lindenberger in which transcranial alternating current stimulation was applied to two individuals simultaneously (hyper-tACS) as they performed a synchronized dyad drumming task. It was hypothesized that same-phase same-frequency stimulation applied to the right hemispheres of the drummers would increase inter-brain neural coupling and thus improve interpersonal action coordination as measured by performance on the synchronized drumming task (Szymanski et al., 2017). Though results were inconclusive, the paradigm is inventive and the proposal combined hyper-tACS and EEG hyperscanning in the future is worth watching.

Similarly inspiring as a platform for further research in musical EEG hyperscanning is a facility at McMaster University in Ontario, Canada, operated by the McMaster Institute for Music and the Mind, called the LIVELab. The Large Interactive Virtual Environment Lab is a 106 seat performance hall built to create neuroscientific research capabilities in a performing arts space. The facility has the capacity to capture 64 channels of EEG plus 8 physiological measures (EMG, heart rate, body temperature, galvanic skin response or respiratory rate) from each of 4 performers on stage, while simultaneously capturing EEG or physiological data on up to 256 channels from the audience in flexible configurations ("McMaster LIVELab," n.d.).

The facility also includes capabilities for digital motion-capture of performers via 28 infrared cameras. There are 9 large flat-panel video monitors behind the stage capable of displaying EEG waveforms captured from performers as well as multi-channel sound and video recording equipment and 'active acoustics' which employ a series of microphones, speakers and digital signal processing to change the perceived acoustics of the performance space. All of these data capture capabilities are available simultaneously and synchronized ("McMaster LIVELab," n.d.).

The LIVELab has produced notable research including a 2018 publication by Chang, and colleagues in which digital motion capture of performing string quartets was analyzed with Granger Causality methods to determine directionality of information flow (leader to follower relationships) during music-making. Performers' ability to see one another was experimentally varied and results indicate that both visual and auditory information are involved in musical interpersonal action coordination (Chang, Livingstone, Bosnyak, & Trainor, 2017).

The progress of future research in the domain of musical EEG hyperscanning will be driven in large part by the development of new statistical data analytic methods for identifying different types of synchrony within and between the brains of interacting musicians. Graph theory approaches to investigating dynamic networks of neural information flow across and within musicians' brains are an important and promising avenue. Additionally, refinements of neuroelectric recording modalities will be impactful, such as the combination of EEG and functional near-infrared spectroscopy (fNIRS), possibly improving the spatial resolution.

Alongside refinements of analytic measures and experimental paradigm, conceptual matters pertaining to the experience of playing music are of equal importance. In modern music the many different settings of musical style and ensemble type create a wide variety of synchronicities and leader/follower roles. Two musicians following a conductor or a metronome are engaged in a type of induced synchronization. Two musicians who are freely interacting, mutually deciding a tempo without a conductor or metronome, are engaged in a reciprocal synchronization. In some settings, the behavior of the audience influences tempo, adding another element to the reciprocity of synchronization. In various types of jazz settings, one instrumentalist may be responsible for maintaining and delineating the tempo while another freely improvises, only to switch roles on a whim. Various types of synchrony may coexist and leader/follower roles may not be exactly binary.

In my decades as a professional drummer, much of my work dealt with synchronization and I performed in a wide variety of ensemble types, many including electronic devices such as drum machines and sequencers. When performing in an ensemble composed entirely of human beings, typically the job of setting and maintaining tempo falls to the drummer. However, it is important for the drummer to listen to other members of the ensemble, particularly vocalists and improvising soloists whose emotional expression might manifest in rhythmic phrasings that could push or pull the tempo. In this setting, a successful ensemble allows tempos to fluctuate

expressively and for leader/follower roles to shift. In this way, a number of types of synchrony (driven, induced and reciprocal) can coexist within the same musical moment.

In the setting of electronic music, often times a computer or other machine is producing musical sounds that repeat without variation in rhythm or tempo. As a drummer in such settings, it is paramount to precisely synchronize one's playing to that of the machine. I have found the act of entraining my own tempo construct to an external and mechanical pulse is a unique opportunity to compare human timekeeping to that of a digitally precise oscillator.

In live performance, on occasions where I am excited by a boisterous crowd, I might feel that the machines are dragging the tempo down. At the end of a long performance, when I am physically tired, it might feel to me that the machines are pushing the tempo faster. Clearly, the machines are maintaining their precise clocks, but my phenomenological experience of time is deeply embodied in my dynamic flesh and blood. Furthermore, I often experience the quality or strength of synchronicity between myself and a machine not so much with my ears but rather with the way my body feels as it moves rhythmically. This embodiment is an important concept for music hyperscanning researchers to bear in mind, as the act of playing an instrument and playing in an ensemble is not performed simply by a brain, rather it is performed by a brain connected to a body and only through the interaction of the two does music emerge.

That these different sync scenarios are available within one ecologically valid paradigm is a boon to hyperscanning researchers, but it is important to bear in mind that these types of synchronization may shift over the course of a music making and that different musicians approach their roles differently. Some musicians are fastidious time-keepers, some are excellent listeners, others single-mindedly follow their creative impulses and must be dutifully followed. Additionally, it is important to bear in mind that the existing body of music-related EEG hyperscanning research has been conducted in a Western musical context. In cultures across the globe, collaborative music making is practiced in myriad ways and it is crucial that research expand beyond the laboratories of Europe and the United States so that the full range of human musical expression, social interaction and the neural coupling that underlies it may be investigated.

Music making as a setting for EEG hyperscanning research offers many advantages and opportunities for the investigation of the neural substrate of social interaction. There are distinct logistical advantages created in the temporal framework of music and the ability to compare, in

great detail, a non-verbal coded behavioral expression alongside its underlying neural activity. In addition, the ecological validity created by music making as a task for EEG hyperscanning is extremely valuable in a scientific realm where necessary reductivism threatens the generalizability of conclusions.

For me as a life-long musician however, the most exciting aspect of musical EEG hyperscanning is its extraordinary window into the neural mechanics of a uniquely human expressive phenomenon allowing us to communicate through time, across geography and culture feelings for which there are no words. Music has the power to access ineffable, even spiritual emotions or motivate groups of strangers to commune in the act of joyous dance. The opportunity to peer into this phenomenon and reveal some of its secrets is truly thrilling.

References

Acquadro, M. A. S., Congedo, M., & De Riddeer, D. (2016). Music Performance As an Experimental Approach to Hyperscanning Studies. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/fnhum.2016.00242

Astolfi, L., Toppi, J., De Vico Fallani, F., Vecchiato, G., Cincotti, F., Wilke, C. T., … Babiloni, F. (2011). Imaging the social brain by simultaneous hyperscanning during subject interaction. *IEEE Intelligent Systems*. https://doi.org/10.1109/MIS.2011.61

Babiloni, C., Buffo, P., Vecchio, F., Marzano, N., Del Percio, C., Spada, D., … Perani, D. (2012). Brains "in concert": Frontal oscillatory alpha rhythms and empathy in professional musicians. *NeuroImage*. https://doi.org/10.1016/j.neuroimage.2011.12.008

Babiloni, C., Vecchio, F., Infarinato, F., Buffo, P., Marzano, N., Spada, D., … Perani, D. (2011). Simultaneous recording of electroencephalographic data in musicians playing in ensemble. *Cortex*. https://doi.org/10.1016/j.cortex.2011.05.006

Babiloni, F., & Astolfi, L. (2014). Social neuroscience and hyperscanning techniques: Past, present and future. *Neuroscience and Biobehavioral Reviews*. https://doi.org/10.1016/j.neubiorev.2012.07.006

Baron-Cohen, S. (2000). Theory of mind and autism: A fifteen year review. In S. Baron-Cohen, H. Tager-Flusberg, & D. J. Cohen (Eds.), *Understanding other minds: Perspectives from developmental cognitive neuroscience* (pp. 3–20). New York, NY, US: Oxford University Press.

Brick, T. R., Lindenberger, U., Müller, V., von Oertzen, T., & Szymanski, C. (2017). Hyper-Transcranial Alternating Current Stimulation: Experimental Manipulation of Inter-Brain Synchrony. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/fnhum.2017.00539

Bullmore, E., & Sporns, O. (2009). Complex brain networks: Graph theoretical analysis of structural and functional systems. *Nature Reviews Neuroscience*. https://doi.org/10.1038/nrn2575

Burgess, A. P. (2013). On the interpretation of synchronization in EEG hyperscanning studies: a cautionary note. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/fnhum.2013.00881

Buzsáki, G., & Draguhn, A. (2004). Neuronal olscillations in cortical networks. *Science*. https://doi.org/10.1126/science.1099745

Chang, A., Livingstone, S. R., Bosnyak, D. J., & Trainor, L. J. (2017). Body sway reflects leadership in joint music performance. *Proceedings of the National Academy of Sciences*. https://doi.org/10.1073/pnas.1617657114

Duane, T. D., & Behrendt, T. (1965). Extrasensory electroencephalographic induction between identical twins. *Science*. https://doi.org/10.1126/science.150.3694.367

Dumas, G., Lachat, F., Martinerie, J., Nadel, J., & George, N. (2011). From social behaviour to brain synchronization: Review and perspectives in hyperscanning. *IRBM*. https://doi.org/10.1016/j.irbm.2011.01.002

Dumas, G., Nadel, J., Soussignan, R., Martinerie, J., & Garnero, L. (2010). Inter-brain synchronization during social interaction. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0012166

Gallese, V., Keysers, C., & Rizzolatti, G. (2004). A unifying view of the basis of social cognition. *Trends in Cognitive Sciences*. https://doi.org/10.1016/j.tics.2004.07.002

Grahn, J. A. (2012). Neural Mechanisms of Rhythm Perception: Current Findings and Future Perspectives. *Topics in Cognitive Science*, *4*(4), 585–606. https://doi.org/10.1111/j.1756-8765.2012.01213.x

Janata, P. (2015). *Neural basis of music perception. Handbook of Clinical Neurology* (1st ed., Vol. 129). Elsevier B.V. https://doi.org/10.1016/B978-0-444-62630-1.00011-1

Janata, P., & Grafton, S. T. (2003). Swinging in the brain: Shared neural substrates for behaviors related to sequencing and music. *Nature Neuroscience*, *6*(7), 682–687. https://doi.org/10.1038/nn1081

Keysers, C., Renken, R., Schippers, M. B., Nanetti, L., & Roebroeck, A. (2010). Mapping the information flow from one brain to another during gestural communication. *Proceedings of the National Academy of Sciences*. https://doi.org/10.1073/pnas.1001791107

Koelsch, S., & Siebel, W. A. (2005). Towards a neural basis of music perception. *Trends in Cognitive Sciences*, *9*(12), 578–584. https://doi.org/10.1016/j.tics.2005.10.001

Levitin, D. J., & Tirovolas, A. K. (2009). Current advances in the cognitive neuroscience of music. *Annals of the New York Academy of Sciences*, *1156*, 211–231. https://doi.org/10.1111/j.1749-6632.2009.04417.x

Lindenberger, U., Li, S. C., Gruber, W., & Müller, V. (2009). Brains swinging in concert: Cortical phase synchronization while playing guitar. *BMC Neuroscience*.

https://doi.org/10.1186/1471-2202-10-22

Lingnau, A., Gesierich, B., & Caramazza, A. (2009). Asymmetric fMRI adaptation reveals no evidence for mirror neurons in humans. *Proceedings of the National Academy of Sciences*. https://doi.org/10.1073/pnas.0902262106

McMaster LIVELab. (n.d.). Retrieved from https://livelab.mcmaster.ca/lab-technology/

Montague, P. R., Berns, G. S., Cohen, J. D., McClure, S. M., Pagnoni, G., Dhamala, M., … Fisher, R. E. (2002). Hyperscanning: Simultaneous fMRI during linked social interactions. *NeuroImage*. https://doi.org/10.1006/nimg.2002.1150

Müller, V., Sänger, J., & Lindenberger, U. (2013). Intra- and Inter-Brain Synchronization during Musical Improvisation on the Guitar. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0073852

Müller, V., Sänger, J., & Lindenberger, U. (2018). Hyperbrain network properties of guitarists playing in quartet. *Annals of the New York Academy of Sciences*. https://doi.org/10.1111/nyas.13656

Overy, K., & Turner, R. (2009). The rhythmic brain. *Cortex*, *45*(1), 1–3. https://doi.org/10.1016/j.cortex.2008.11.002

Przyrembel, M., Smallwood, J., Pauen, M., & Singer, T. (2012). Illuminating the dark matter of social neuroscience: Considering the problem of social interaction from philosophical, psychological, and neuroscientific perspectives. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/fnhum.2012.00190

Sänger, J., Lindenberger, U., & Müller, V. (2011). Interactive brains, social minds. *Communicative and Integrative Biology*. https://doi.org/10.4161/cib.17934

Sänger, J., Müller, V., & Lindenberger, U. (2012). Intra- and interbrain synchronization and network properties when playing guitar in duets. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/fnhum.2012.00312

Sänger, J., Müller, V., & Lindenberger, U. (2013). Directionality in hyperbrain networks discriminates between leaders and followers in guitar duets. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/fnhum.2013.00234

Steinbeis, N., & Singer, T. (2014). Projecting my envy onto you: Neurocognitive mechanisms of an offline emotional egocentricity bias. *NeuroImage*, *102*(P2), 370–380. https://doi.org/10.1016/j.neuroimage.2014.08.007

Toppi, J., Ciaramidaro, A., Vogel, P., Mattia, D., Babiloni, F., Siniatchkin, M., & Astolfi, L.
(2015). Graph theory in brain-to-brain connectivity: A simulation study and an application
to an EEG hyperscanning experiment. In *Proceedings of the Annual International
Conference of the IEEE Engineering in Medicine and Biology Society, EMBS* (Vol. 2015–
Novem, pp. 2211–2214). https://doi.org/10.1109/EMBC.2015.7318830

Tutu, D. M. (1999). *No Future Without Forgiveness*. New York, NY: Doubleday.

Vuust, P., Gebauer, L. K., & Witek, M. A. G. (2014). Neurobiology of Interval Timing, *829*.
https://doi.org/10.1007/978-1-4939-1782-2

Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: Auditory-
motor interactions in music perception and production. *Nature Reviews Neuroscience*, *8*(7),
547–558. https://doi.org/10.1038/nrn2152