The Visceral Experience: Embodiment in Music Cognition

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Abstract

As perspectives in cognitive science have shifted over time, the perceived role of the body in cognition has likewise shifted. Current ideas of embodied cognition hold that the body is a constitutive component of the cognitive apparatus, in concert with the brain. The human endeavor of making and consuming music is a deeply embodied process. In music performance, dance, or even stationary listening, motor systems are active and essential to understanding and participating in music. Entrainment is a key concept in the embodied cognition of music, observable on both the neural and behavioral level and providing a means of synchronization to musical pulse. Sensorimotor coupling is also central to music perception and is evident in the contribution of vestibular and mirror neuron systems to an embodied process of music cognition. Awareness of the influence of history, culture and technology on the practice of music cognition research is essential for comprehensive and unbiased investigation into embodiment.

Keywords: embodied cognition, music cognition, entrainment, mirror neurons

“It is understood that to perceive rhythm is to imagine movement.”

-Vijay Iyer, 2016

For those who seek to understand the cognitive processes underlying human behavior and experience, there is perhaps no better window than the investigation of music. The simple perception of musical sound requires complex neural computation, while the decoding of emotion from airborne vibrations involves a process bordering on the mystical. The creation and consumption of music are universal across human history and culture (Peretz, 2006). In modern society there are seldom settings in which music is not included, and the emotional arc of a human life is often transcribed by the songs that transport us vividly back to a moment of joy, romance or loss. Music is an expression and a practice which seems to spring from a deep place within us, and while it may attain heights of great sophistication, music’s value to us remains elemental, enigmatic, visceral.

It is of interest then, that the inclination to describe the experience of music as ‘visceral’ is a common one. Through the history of human self-understanding, it has been believed that various cognitive processes were located throughout the body. The humours, the heart and indeed, the gut were seen as the loci of various characters and emotions. However, as modernity arrived, science began to focus its attention on the brain as the locus of cognition (M. Gaebler, personal communication: class lecture, 17 April, 2019). To describe a feeling as ‘visceral’ became a charmingly anachronistic turn of phrase. Yet, much in life is cyclical and the advent of theories on embodiment have restored the body to its seat at the table of cognition. To refer to music as ‘visceral’ is perhaps no longer an anachronism.

A brain without a body faces a host of challenges, many of them rather urgent. But among deprivations, the disembodied brain exists without the capacity to make or hear music. The following pages will investigate ideas on embodiment in musical cognition, describing the synchronizing influence of entrainment, the contributions of the vestibular senses and the implications of the mirror neuron system. Additionally, in discussing directions for future investigation in embodied music cognition, the need for an increased awareness of historical and cultural perspectives will be addressed. Finally, questions will be posed related to the significance of electronic music in ideas on musical embodiment. As more of our music culture is created through digital means, the prospect of disembodiment in music-making stands to cast light on embodiment.

Embodiment

In the historical arc of cognitive science, a number of paradigmatic shifts have occurred as ideas have gained or lost traction and new empirical methods have arisen. In the epic task of using the mind to understand the mind, researchers have approached the daunting complexity of the endeavor by employing one of the most successful and reliable devices in the human intellectual arsenal, that of reduction. In the beginnings of the modern era of cognitive science, behaviorism appeared as a way to tame the complexity of the mind by reducing the variables under consideration to those externally observable actions which could be reliably measured. In the mid-1950's, the focus shifted to cognition as a computational process, applying a mechanistic framework to the processes of the brain. In recent neuroscientific pursuits, a localizationist approach, wherein the discrete cerebro-anatomical loci of cognitive and affective processes have been sought, has suited both the technical means of discovery (imaging modalities that 'zoom in') as well as the innate way the human mind disassembles complex processes into subcomponents which are presumed to ultimately sum into the whole (M. Gaebler, personal communication: class lecture, 17 April, 2019).

However, recent perspectives in disciplines from philosophy to mathematical non-linear dynamics show that elucidation of mechanisms is essential, but no less so than understanding how those mechanisms interrelate, or recognition of the emergent properties created by that interrelation. There is necessity for cognitive science to peer not only reductively downward into ever smaller and smaller windows, but also upward and outward, more broadly and expansively. (Bechtel, 2009). The idea of embodied cognition is such an upward and outward view.

Whereas previous eras have employed a narrow view of cognition as a process occurring solely within the brain, the embodied approach acknowledges the contribution of sensory, motor and other non-cerebral bodily systems. This perspective views the entirety of the body as an essential component of the human cognitive apparatus; that perceptual and motor systems are not merely modular input/output devices peripheral to the thinking mind as held by Fodor (1983), but rather, constitutive of it (Clark, 1999; Wilson, 2002).

In the embodied approach, cognition becomes decentralized, arising from an ongoing interaction between brain, body and environment. While the cognitivist approach focused on the activity of the brain, it likewise encouraged a dichotomy between the inner state of the mind and the outer state of the physical environment (Schiavo and Altenmüller, 2015). In addressing the dissolution of lingering dualism in cognitive theory, Di Paolo and colleagues propose, "the body is not a puppet controlled by the brain but a whole animate system with many autonomous layers…that create its sense-making activity. Indeed, to say that cognition is embodied is to express a tautology — it simply cannot but be embodied if we understand the core of cognition as sense-making" (Di Paolo, Rohde & De Jaegher, 2010, p. 42).

Key to the embodied view is the idea of sensorimotor coupling, wherein the processes of sensing and acting can be seen as aspects of the same process. Corness (2008) illustrates the inseparability of perception and action by pointing out that as one surveys a visual scene, proprioceptive awareness of the turning of one's head is essential for the brain's ability to interpret the resulting visual input. Corness goes further to relate this phenomenon to Merleau-Ponty's idea of *reversibility* which, in the case of music, holds that a musician is both one who hears and who is heard. "Merleau-Ponty uses the concept of reversibility to explain our existence as a reciprocal interaction with the world" (Corness, 2008, p. 21).

In a practical sense, examples of the coupling of perception and action include the immediate orienting that happens when we are startled by a sound. Nearly instantaneously and without conscious volition, we turn our heads in the direction of alarming noises or our names being shouted. Froese and González-Grandón (2019) point out that because of the direction-finding function of the shape of the external ear, humans are constantly in the unconscious practice of turning their heads as they localize sound sources. For this to be effective, the brain must accurately track head position, using information from the vestibular senses to aid in the computation of sound source localization (Froese & González-Grandón, 2019). Given the millisecond timescales in which these calculations are performed, the tightness of integration of perception and action are clear. Leman, Maes, Nijs & Van Dyck (2018) state that the embodied view of music cognition widens previous ideas focused on the role of 'perception in cognition' to a broader perspective of 'cognition in interaction'.

In application to the practice of music, embodiment approaches yield many perspectives.

At its most basic, an embodied approach to music cognition points to the essential role of the bodies of the musician and the listener for the understanding of music (Leman, 2008). From this starting point, many lines of academic pursuit diverge. Perlovsky (2015) suggests that music exists to embody abstract thought and to reduce cognitive dissonance through its soothing qualities. McGuiness & Overy (2011) state that while music may be communicative, what distinguishes it from language is *communion*; that "music provides an intimately shared, embodied experience rather than communicating a specific message" (p. 245).

A lovely example of the role of embodiment in music cognition can be seen in the development of neurologic music therapy (NMT; Schiavo & Altenmüller, 2015). Pioneered by Michael Thaut and colleagues in the early 1990's, NMT employs musical rhythm as stimulus and temporal framework for rehabilitation exercises in clinical populations suffering movement disorders resulting from Parkinson's disease, stroke, traumatic brain injury, cerebral palsy and other neurological conditions. The natural inclination for people to synchronize their movement to musical rhythm creates a therapeutic mechanism in which bodily motion can be prompted through musical cues when endogenous, verbal or visual cuing is ineffective (for a review, see Thaut, 2010; 2015).

Neural Motor Systems Process Musical Rhythm

The entrainment mechanisms through which NMT operates offer a view of a neurobiological substrate of musical embodiment. Prior to its discussion however, a brief survey of the anatomical architecture of music processing in the brain, specifically with regards to rhythm, will provide insight into the extent of sensorimotor coupling at work in music cognition.

Perception of tonal information, such as musical pitch, is processed in the primary auditory cortex, which is ‘tonotopically’ organized, such that pitches adjacent in terms of frequency are processed in regions equivalently adjacent in terms of anatomy (Janata, 2015). The adjoining structures of the superior temporal gyrus and planum temporale are believed to process harmonic interval, melody and contour (Koelsch & Siebel, 2005; Levitin & Tirovolas, 2009). This is in keeping with a cursory view that music cognition is an affair primarily conducted by auditory resources. However, double-dissociation evidence from neuropsychological studies strongly suggest that pitch and rhythm are processed through separate pathways (Levitin & Tirovolas, 2009). In fact, a meta-analysis of neuroimaging studies on musical processing found that, other than regions TE1 and TE3 of the auditory cortex, which are activated by all dimensions of music, no other temporal lobe foci were activated by rhythm (Janata, 2015). It is in the cortical and sub-cortical structures related to motor control of bodily movement that the processing of musical rhythm occurs (Grahn, 2012; Janata, 2015; Thaut, 2009)

Shared cerebral processing architecture indicates how profoundly rhythm, perhaps the most foundational element of music, is related to bodily movement. Among the motoric cerebral structures involved in the processing of rhythm are the cerebellum, basal ganglia, supplementary motor area (SMA) and premotor cortex (PMC; Zatorre, Chen, & Penhune, 2007). The basal ganglia is associated with motor control and action selection while the cerebellum is involved in maintaining coordination and error-correction during movement. Acting as intermediaries between these structures, the PMC and SMA have roles in planning and execution of motor action (Grahn, 2012).

In addition to motor control, the cerebellum, basal ganglia, PMC and SMA have a role in motor learning and organization (Levitin, Grahn & London, 2017). In conjunction with the frontal cortex, the basal ganglia is implicated in the learning of movement sequences, while the cerebellum is considered important for integrating those learned sequences into unified actions (Thaut et al., 2009). Further, the pre-SMA and SMA are implicated in the process of chunking, wherein complex motor sequences are divided into simpler action components for the purpose of organizing those complex behaviors (Zatorre et al., 2007).

Taken together, the fact that motor areas of the brain are involved in rhythm perception, even when the listener is immobile, lends support to the embodied view of music cognition and provides a specific example of the linkage of perception and action. In the case of neurologic music therapy, a key mechanism for creating motoric activation in patients whose neurological conditions erode the ability to endogenously initiate motion, is that of entrainment (Thaut, 2009). Musical rhythm provides a temporal framework to which patients' neural and thus, motoric activity can become synchronized. Given the steady, repeating musical cue, patients are able to initiate motoric action. Music provides a continuous metric for anticipatory timing and a temporal guide for conducting motor actions through their spatiotemporal trajectories (Thaut, 2015). But what is entrainment, exactly and how does it manifest in music cognition?

Entrainment in Music and Beyond

At its most specific, entrainment refers to period or phase synchronization achieved by otherwise independent, self-sustaining oscillating systems (Clayton, 2012). Examples abound in the natural world, as seen when fireflies synchronize their flashing during mating, when neurons fire in sync to communicate across the cortex or as astronomical bodies spin through space in coupled orbits (Buzaki, 2006; Strogatz, 2012). More expansively, entrainment is used to describe the interpersonal alignment necessary for two people to hold a conversation (Phillips-Silver, Aktipis & Bryant, 2010) or for a room full of dancers and musicians to perform a Bavarian *Schuhplattler*. In an example of the serendipity that seems to pervade scientific discovery, entrainment was first described by a bed-ridden physicist who found himself staring at a clock.

In the late 17th century, Dutch scientist Christiaan Huygens built state-of-the-art clocks of superior accuracy by employing the periodic motion of a pendulum. During an illness, Huygens was confined to his bed and spent hours observing two of his newest pendulum-driven clocks mounted on his bedroom wall. He noticed the tendency for the pendula of the clocks to align their swings over time, exactly out of phase, regardless of the position in which they were started. Huygens sought the physical origins of this “odd kind of sympathy”, hypothesizing the influence of “imperceptible agitations of the air” (Strogatz, 2012; p. 106). Though he was ultimately able to discern that the clocks were influencing each other through vibrations transmitted across the beam on which they were both mounted, it would be another 300 years before non-linear dynamic systems theory would arrive to quantify the reciprocal negative feedback at work (Thaut, 2015; Montague, 2018). Nonetheless, a period of involuntary convalescence had led to the identification of what we now call entrainment.

At its most mathematical, entrainment describes the tendency of two or more oscillating systems to achieve and maintain period or phase-locked synchronicity over time and despite transient perturbations to the cycle of those oscillators (Large, Herrera & Velasco, 2015). While simple synchrony may result from the chance alignment of two cycling systems, entrainment involves forces which nudge oscillators towards each other, achieving the same period and phase, maintaining that relationship and reestablishing it in the event of disruption (Clayton, 2012). In the case of entrainment in music, the oscillators in question may be neurons, musical rhythms or the bodies of musicians or dancers. As such, entrainment constitutes sensorimotor synchronization which has its roots in neuronal dynamics and its broadest expression in coordinated social behavior.

When one hears a single sound, neurons in the auditory pathway fire in response to the sonic stimulus, producing what practitioners of electroencephalography (EEG) refer to as an auditory evoked potential (AEP). This single waveform represents the brain's response to the single stimulus (Buzsaki, 2006). If one is listening to music with a steady beat, the brain responds in a similarly steady way, with AEPs corresponding to each beat of the music. In electrophysiology, this train of regular AEP waveforms, stable in amplitude and phase, are referred to as a steady state evoked potential (SS-EP; Nozaradan, 2014). The SS-EP is the physiological manifestation of neural entrainment to music. In this case, the brain is no longer reacting to a single stimulus, one after the other, but is in fact, tapping its metaphorical foot to the beat.

When neurons in the auditory pathway synchronize their firing so that the period of their oscillation matches that of the ongoing rhythmic stimulus, reaction gives way to prediction. An organism that can entrain its neural firing to the period of stimuli in its environment is able to use that endogenous oscillation as a predictor for the future behavior of the exogenous stimulus (Henry & Herrmann, 2014). As such, by creating an internal version of the musical pulse, a dancer is not in a constant process of reacting to each beat as if surprised, rather each beat is anticipated and predicted to occur, allowing the dancer to plan her movements and execute them in synchrony with the music (Phillips-Silver, Aktipis & Bryant, 2010).

In the context of music perception, one of the more fascinating abilities that entrainment provides the listener is the ability to extract beat and meter from a musical sensory stream which may not physically include that information (Large, Herrera & Velasco, 2015). In Western music, the fundamental pulse of music is referred to as the *tactus*, or more colloquially, the beat. The beat may be considered the baseline from which hierarchical divisions of musical time are made above and beneath the beat level, creating divisions both broader and finer than the tactus but all based on its pulse. The hierarchical level of temporal organization above the beat is referred to as *meter.* Meter implies a grouping of tactus beats which will regularly occur throughout a piece of music. In modern popular music, 4/4 is the most widely heard meter, or *time signature*, in which 4 tactus beats define one group, known as a *bar* or *measure* (Levitin, Grahn & London, 2017).

However, frequently in music, the beat or meter are not explicitly sounded. Many music styles create rhythmic tension through *syncopation,* when strongly stressed rhythmic accents occur unexpectedly between tactus beats, or when sound is completely absent on the tactus beat (Levitin, Grahn & London, 2017). One needs only to listen to James Brown's "I Got the Feelin'" to appreciate the fact that although the rhythms performed by the band seem to occur everywhere *except* the tactus, a listener is not only able to feel the underlying pulse, but is in fact motivated to move (Brown, 1968, single).

Examination of the sonic envelope of "I Got the Feelin'" shows that the tactus is not explicitly sounded. It is our cognitive construction of the beat as a temporal framework against which we interpret the syncopated rhythm that grounds our understanding of the rhythmic narrative (Large, Herrera & Velasco, 2015). That grounding is provided by neural entrainment to the tactus pulse, creating an internal metronome which guides our comprehension of the music and our motor responses to it, should be choose to dance, which clearly we should.

Neural entrainment to musical rhythm has been investigated empirically in a number of ways. Of note is the EEG 'frequency tagging' approach employed by Nozaradan and colleagues (2014). In this paradigm, EEG is recorded from subjects as they hear auditory rhythmic stimuli while sitting motionless. The resulting EEG time series are transformed into the frequency space such that frequency is plotted against amplitude. In this representation, entrained neural oscillations appear as spikes in the frequency spectra. Thus, if a subject hears a repeating sound that occurs twice every second, or at a rate of 2 Hz, neural entrainment to that rhythm will be visible as an amplitude spike in the frequency spectra at 2 Hz (Nozaradan, 2014).

Whereas early frequency tagging studies of neural entrainment to auditory rhythm employed series of isochronous clicks as the sonic stimulus, the paradigm has also been applied to the perception of complex rhythms. Stupacher, Wood and Witte (2017) employed the technique to investigate neural entrainment to polyrhythm. Polyrhythms occur in many Latin and African music styles and can be defined musicologically as the simultaneous presence of two or more non-factorial rhythms occurring over the same tactus (Vuust, Gebauer & Witek, 2014). Put more simply, if a rhythm that is made of a group of 3 evenly spaced notes repeats while a rhythm of the same duration but made of 2 evenly spaced notes repeats at the same time, both at the same tactus pace, they will cycle over each other in a complex and often engaging way.

Fascinatingly, the perceptual mechanisms involved in tracking the complexity of a polyrhythm are similar to those at work when we view the 'Rubin's vase' image, in which one sees either two white faces in profile against a black background, or a single black vase against a white background. Both are conditions known as 'bistable percepts' in which the brain vacillates between two ways of interpreting the stimuli and have been examined through the EEG frequency tagging paradigm (Nozaradan, 2014). Just as the image of Rubin's vase alternates between percepts of faces vs. vase as figure vs. ground, so too does one experience a polyrhythm. If one hears a repeating rhythm in 3 at the same time as a repeating rhythm in 2, the inclination is to choose one as the base and the other as the variant against that base rhythm. That perception may shift over time or as a result of musical training (Vuust, Gebauer, & Witek, 2014).

Just as the brain infers information about spatial relationships between figure and background from a visual image which may not contain that specific information, the brain infers musical beat and meter from auditory stimuli, despite an incomplete presence of those characteristics (Large, Herrera and Velasco, 2015). Thus, musical meter may not a property of the stimulus, though it is induced by the stimulus. Rather, it is a cognitive construct born of a perceptual process. In this way, different listeners may extract many different rhythmic percepts from the music they hear, a process strongly guided by the listener's culture and music education (Nozaradan, 2014).

Further noteworthy research on entrainment in musical settings 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. Beginning in 2009, the team employed a methodology known as EEG 'hyperscanning' in which EEG is recorded from multiple individuals simultaneously as they interact in real time. The team applied this framework to ensembles of musicians as they performed in a variety of settings. In a musical ensemble, the necessity to synchronize with one's fellow players (and the conductor if one is present) is essential. A number of types of synchrony can be observed: induced (a conductor dictating a tempo to all), reciprocal (the members of a string quartet collaboratively creating a tempo by listening to each other) or driven (a jazz soloist improvising freely while the bass player holds a steady rhythm; Burgess, 2013). These phenomena all require an alignment of neural processes among the members of the ensemble and by recording EEG during these musical moments, the MPI team was able to examine neural activity against the temporal framework provided by the musical score (Lindenberger, Li, Gruber & Müller, 2009; Müller, Sänger, & Lindenberger, 2013, 2018; Sänger, Müller, & Lindenberger, 2012, 2013).

The hyperscanning paradigm creates a substantial amount of complex data. The researchers employed a variety of analytical techniques to identify coupling effects across the brains of musicians. A variety of algorithmic coupling indices were applied in the effort to identify entrained neural oscillations and to determine the directionality of sync. Of note was the application of graph theory analysis to evaluate ‘hyperbrain modules’, networks of information processing whose nodes exist in the brains of different ensemble members (Sänger et al., 2013; Müller et al., 2013, 2018). The studies suggest that such between-brain networks are highly dynamic, shifting as different movements in the musical score require different types of coordination among the musicians.

In the discussion of human entrainment to music, if one broadens the consideration from the level of neural dynamics, we encounter autonomic physiological entrainment. The possibility that aspects of music may influence the function of sympathetic and parasympathetic nervous systems seems familiar at face value, given the common use of slow, legato music to soothe babies to sleep or to accompany a massage in a spa. A review by Trost, Labbé and Grandjean (2017) points to a number of studies which indicate that respiratory and cardiac rates may adapt toward the tempo of stimulus music. Slow, dynamically flat music has been suggested to bring about a reduction in heart rate, respiratory rate and blood pressure (Ellis and Thayer, 2010). However, such relationships are more difficult to quantify than the tight temporal coupling of neural oscillation to musical rhythm, as they change slowly and without explicit phase or period locking (Trost, Labbé and Grandjean, 2017).

When considering entrainment at the level of musical behavior, there are conceptual and methodological adjustments that must be made. On the scale of neural firing, musical tempo and rhythm, researchers may examine easily quantifiable phenomena such as neural oscillation or the moment when a stick hits a drum. However, in behaviors including dance, expressive physical gestures in instrumental performance or affective experiences in music listening or performing, there may not be obvious ways to identify phase or period in oscillation. Musicologist Martin Clayton (2012) points to the necessity for abstraction when evaluating phase and period in such cases and to consider entrainment as hierarchical and domain general.

Clayton (2012) identifies three levels at which musical entrainment may be seen to operate. Intra-individual entrainment includes neural oscillation but also motor actions such as the coordinated but independent trajectories of a drummer’s limbs. Inter-individual entrainment may be observed as the affective, physical, and expressive interactions between performer and audience, or within members of an ensemble (although the work of Lindenberger et al. (2009), Sänger et al. (2012), and Müller et al. (2018) demonstrate that neural activity may be investigated on this level as well). Clayton (2012) also points to inter-group entrainment, wherein independent groups of people influence each other’s behavior in conscious or unconscious ways.

Inter-group entrainment is a difficult concept to conjure in the case of Western music, but Clayton points to ethnographic observation of Brazilian musical religious ritual in which groups of musicians parade through their village and as they pass each other, their tempos tend to converge (Lucas, Clayton and Leante, 2011). The phenomenon is also described slightly more empirically in a pilot study performed by musicologist Marc Lehman (2012) involving two groups of marching percussionists. The percussion groups began in different locations, playing the same rhythmic pattern but at different tempos. The groups then approached each other and as they did so, audio recordings showed their tempos converging. When the groups crossed each other, their tempos came into close alignment and as they marched away from each other, their tempos diverged. According to the authors, this observation is suggestive of the mechanisms through which disparate groups of humans agglomerate to form larger organizations (Lehman, 2012).

Given the difficulty of identifying period and phase with empirical accuracy in expressions such as dance or the performative gestures of instrumentalists, motion capture technology has been employed in several settings. Leman calls for a spatiotemporal dimension to the quantifying of entrainment, and to that end, applied motion capture to dancers performing a Samba and the Charleston. By tracking the spatiotemporal trajectories of the dancers limbs, the researchers were able to precisely identify periodicities in the movements and relate them to periodicities in the accompanying music (Naveda and Leman, 2010).

Further use of motion capture technology was carried out by Chang and colleagues who recorded the performance of string quartets. Tracking postures, motion and gaze, the team analyzed performers' physical gestures 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 indicated that in addition to the obvious auditory component of coordinated ensemble playing, musicians visually track the physical gestures of one another in order to coordinate their performance (Chang, Livingstone, Bosnyak, & Trainor, 2017). Motion capture technology represents a significant opportunity for musicologists seeking to add empirical precision to their observations, as well as a chance for neuroscientists to evaluate the cognitive processes embodied in musical performance.

Vestibular Contributions to Music Cognition

While it's easy to assume that our ears are the perceptual entry point for our experience of music, anyone who has stood near a parade as a marching drum corps passed by or ventured into a Berlin dance club has experienced the bodily sensation of sound. Rock concerts, movie theaters and discotheques are engineered to create powerful vibrations in the air which register perceptually as music, but whose low frequency and high amplitude energies in fact activate both vibrotactile and vestibular sensory modalities. In a body of work which includes the tantalizingly titled "Vestibular responses to loud dance music: A physiological basis of the 'rock and roll threshold'?" British researcher Neil P. McAngus Todd examines the contribution of these sensory pathways to our experience of music (Todd & Cody, 2000).

In the aforementioned study, the researchers considered the sternocleidomastoid muscle, which runs from the collarbone to just beneath the ear, as resonant body whose sympathetic vibration during exposure to low frequency, high amplitude sound may activate vestibular receptors and contribute to the perception of sound. At the time of the study, Todd was on the faculty of the University of Manchester and it is thus unsurprising that he employed as an experimental stimulus the sound of a bass drum taken from a techno record and amplification profiles gathered from local dance clubs. By measuring the electromyographic (EMG) activity of the muscle in response to the sonic stimulus at varying amplitudes, Todd and colleagues found that beneath 100 dB of sound pressure, few subjects showed EMG activity, while at 120 dB, 90% of subjects showed what they called acoustically evoked vestibularly mediated response (Todd & Cody, 2000).

The researchers posit that ‘self-motion’ is a pleasurable activity for humans, as evidenced by the popularity of rocking chairs, porch swings and roller coasters. They go on to propose that, given their results showing loud music stimulating vestibular receptors which code a sensation of bodily movement, some of the pleasure of loud music may manifest in an induced sensation of self-movement. Interestingly, the authors point out that the amplitude and frequency thresholds observed for the induction of acoustically evoked vestibular response are very similar to levels known to live sound engineers for the fact that rock concert and dance club audiences prefer to hear music with similar profiles for low frequency and high amplitude (Todd & Cody, 2000).

While the idea of an intersection of academia and rock & roll may provoke mirth, the implications of Todd’s work are noteworthy in the discussion of embodiment in music cognition. In consolidating a sensory-motor theory of rhythm and beat induction, Todd, O’Boyle and Lee (1999) put forth a model which holds that the vestibular system contributes significantly to the sense of hearing broadly, and to musical rhythm perception specifically, in concert with cortical and sub-cortical motoric circuits. The theory points to a hedonic quality of acoustic vestibular sensations, particularly in the low frequency bands, and describes the perception of musical rhythm as a sensorimotor manifestation of the sensation of bodily movement (Todd, O’Boyle & Lee, 1999).

In an update to their sensory-motor theory of rhythm and beat induction, Todd and Lee (2015) point to recent neuroimaging evidence of extensive interconnections between the vestibular system and auditory, proprioceptive, somatosensory and motor pathways as the substrate of sensorimotor coupling. Connections between the vestibular system and the limbic system are pointed to as a pathway for the hedonic quality of bobbing one's head to music, and, in conjunction with proprioceptive and motoric activation, the hedonic quality of what they unromantically term 'vestibular self-stimulation' or dancing. Taken together, the theory suggests that musical rhythm, processed by auditory, motor, limbic, proprioceptive and somatosensory regions, is experienced as an abstraction of bodily motion and informed by internalized awareness of the shape of one's own body as it moves through space (Todd and Lee, 2015).

In the investigation of embodiment in music cognition, it seems reasonable that the value of empirical work should not be confirmed until laboratory efforts have been replicated with proper ecological validity in a discotheque. While the technical restraints of current neuroimaging modalities prevent its investigation in the context of the dance club, another line of research dealing with sensorimotor coupling, and relevant to ideas of embodiment in music cognition, is that of the 'mirror' neuron.

Mirror Neurons and Musical Embodiment:

One of the most widely reported neuroscientific discoveries in recent decades was first observed in the early 1990's in a modern example of the scientific serendipity that led Huygens to identify entrainment 300 years ago. Giacomo Rizzolatti, Vittorio Gallese and colleagues were investigating 'canonical' neurons in the brains of rhesus macaques, which activate both when a monkey performs a motor act, and when it observes an object that can be manipulated by that same act. The team recorded single-cell activity in the macaques' ventral premotor cortices as the monkeys held or observed food objects. To provide it with a stimulus food object, a researcher stepped in front the monkey to extend to it the food in his hand. To the team's surprise, neurons in the monkey's premotor cortex fired not when the animal looked at the food, but rather in response to the experimenter's reach (Rizzolatti and Fabbri-Destro, 2010).

Further investigation yielded a type of neuron that fired when the monkey reached for a food object, but also when it observed another agent performing the same action (Rizzolatti and Craighero, 2004). Despite applying the appealing title of 'mirror neurons' to these newly discovered cells, the subsequent manuscript detailing the discovery was rejected by *Nature* for "lack of general interest" (Rizzolatti and Fabbri-Destro, 2010; p. 223). However, the researchers persisted, eventually finding receptive publishers and touching off a frenzy of research and public fascination.

The discovery of the mirror neuron was met with heated interest in both philosophical and neuroscientific realms. With tempting implications for the mechanisms which allow humans to understand the actions and goals of others, mirror neurons have been widely cited as the root of neurocognitive phenomena from self-recognition to autism (Overy and Molnar-Szakacs, 2009). A body of experimental evidence indicates that neural mirroring exists in human beings (Mukamel, Ekstrom, Kaplan, Iacoboni & Fried, 2010; Rizzolatti & Sinigaglia, 2016) though there is dispute and controversy regarding the extent and true functioning of such a system in the human brain (Lingnau, Gesierich, & Caramazza, 2009; Arévalo, Baldo, González-Perilli, & Ibáñez, 2015).

While mirror neurons respond to observed action, rather than coding a representation of motor motion, these cells encode the goal of the action (Rizzolatti and Fabbri-Destro, 2010). This is supported by a variety of experimental manipulations in both monkeys and humans wherein the action-goal and the action itself were systematically varied. Mirror neuron were shown to be active when the goal (grasping an apple) was held constant, while the action was performed by different means (the apple grasped by hand, mouth or pliers; Rizzolatti & Sinigaglia, 2016).

In the context of embodiment, mirror neurons represent a physiological mechanism in which action and perception are coupled so intimately as to be performed by the same system. Gallese (2003) suggests neural mirroring may represent a 'simulation mechanism' whereby engaging the same neural resources to act, and observe that same act, the observer can understand the intent and feelings behind another's action, a concept with bearing on the experience of emotion in music. Neural mirroring is also posited to subserve imitation behavior (Schiavio, Menin, & Matyja, 2014) which is key in learning to play an instrument (Overy & Molnar-Szacks, 2009).

Of particular relevance to music cognition, the mirror neuron system appears active across sensory modalities (Molnar-Szakacs & Overy, 2006). Audio-motor mirror neurons were discovered in the brains of rhesus macaques which fire when performing an action (tearing a sheet of paper), when visually observing the action performed by another agent (watching a researcher tear a sheet of paper) and when hearing only the sound of the action (hearing a sheet of paper torn by a researcher out of view; Kohler et al., 2002). A similar type of cell, referred to as an audio-vocal mirror neuron, has been found in a number of species of songbirds, firing when the bird sings and when it hears the same song sung by a conspecific. This is posited to play a role in song learning (Aglioti & Pazzaglia, 2010).

Mirror neuron activation appears directly related to the observer's experience with the action in question (D'Ausilio, 2009). Mirror activation occurs only for actions within the subject's motor repertoire and correlates with the observer's skill and familiarity with the observed action (Calvo-Merino, Jola, Glaser, & Haggard, 2008; Rizzolatti & Fabbri-Destro, 2010). Agliotti and Pazzaglia (2010) point to a variety of experimental literature indicating that sounds that are associated with a manual action, such as the sound of hand tools, produce activity in mirror motor networks, whereas sounds of non-manual tools, like a washing machine, do not. D'Ausilio, (2009) along with Agliotti and Pazzaglia, (2010) posit that in order for a mirror response to occur, the observer must posses the physical capacity and motor knowledge to engage in the observed action.

These lines of evidence are relevant for the application of mirror neuron theory to music cognition. They suggest that when hearing the sound of a violin, a listener is non-consciously simulating the motor action required to play that violin. The strength of this mirror simulation may be modulated by one's musical experience or training. This is raises questions when considering modern music, in which electronic production techniques yield sounds that cannot be created by human physical motion.

D'Ausilio (2009) states that, after learning to play a piece of music, hearing a recording of that piece of music activates the motor programs necessary to perform that music. The author reinforces the role of sensorimotor coupling in music performance by pointing out that in learning to play an instrument, a relationship between a musical sound and the specific physical gesture required to create that sound is reinforced through repetition. Additionally, Schiavo, Matyja and Menin (2014) point to a body of empirical work which indicates stronger activation in mirror-related fronto-parietal networks amongst musicians versus non-musicians when observing music-related actions, as well as stronger activation of musician's primary motor cortices when they are engaged in a passive listening task.

Among prominent theorists on the role of neural mirroring in music cognition are Katie Overy and Istvan Molnar-Szakacs. The authors begin with the idea that music making involves purposeful and organized motor action by a performer, and that mirror neurons create a shared representation of intention between actor and observer via action understanding. Given this, they suggest that the mirrored representation of musical motor actions and their intents in the brain of music listeners constitutes a mode of non-verbal communicative transmission (Molnar-Szakacs and Overy, 2006).

Neuroimaging evidence of neural resources shared by language, motor function and music cognition (Koelsch and Siebel, 2005) reinforces Molnar-Szakcs and Overy's conception of music as a communicative act supported by sensorimotor coupling. Further, in addressing music's power to evoke emotion in listeners, they refer to the idea that the substrate of empathy is an internal affect simulation based on perception of the other's face, body and voice (Gallese, 2003). Thus, a multi-modal mirror mechanism which allows for inference of emotion among visuo-motor and auditory percepts creates a 'sensorimotor-affective coupling' wherein the sound of music is understood as bodily motion which is understood as emotion (Molnar-Szakacs and Overy, 2006).

Carrying these ideas forward, Overy and Molnar-Szakacs (2009) introduced a consolidated model they call shared affective motion experience or, SAME. The authors begin with the idea that music is an *actively* experienced auditory stimulus. This is an idea furthered by Froese and González-Grandón (2019) who state that passive listening is in fact, not passive, given the motoric activation occurring through sensorimotor coupling, even when listening to music in an immobile state. The SAME model holds that musical sound, beyond a simple auditory percept, constitutes a hierarchical encoding of expressive motor acts which convey emotion (Overy and Molnar-Szakacs, 2009).

In their model, Overy and Molnar-Szakacs (2009) predict that a listener's musical training has a bearing on their experience of music. They suggest that behind a musical sound lies an expressive motor act containing information on four hierarchical levels: motorics, kinematics, goals, and intention. The layered depth of musical understanding is dependent on the listener's own personal experience with performing music.

In the case of deepest understanding, the authors suggest the example of a professional saxophonist who hears a composition for solo saxophone which they have themselves performed in the past. The saxophonist has a very detailed cognitive mapping for the fine motor actions and sequencing required to perform the piece, and they have a kinematic understanding of the spatiotemporal trajectories of their hands and arms during performance. On the goal level, the saxophonist understands the purpose of the motorics and kinematics in the performance of the larger composition, and on the level of intention, they have a deep, lived experience of the emotional content of the musical piece. At the other end of the spectrum, the authors point to a complete novice, who has no idea what a saxophone is, listening to the same composition. The novice lacks precise understanding at any level in the hierarchy, "but may feel the beat, sub-vocalize, and interpret emotional intention accordingly (e.g., fast, loud, and high in pitch might be considered emotionally charged)" (Overy and Molnar-Szakacs, 2009, p. 493).

While the idea that trained musicians have greater motoric understanding of a piece of music they have performed makes sense in light of evidence that mirror mechanism activation is greater when observing actions within the observer's skill set (Calvo-Merino et al., 2008; Rizzolatti and Fabbri-Destro, 2010), the SAME model loses traction in its assessment of untrained music listeners. The model fails to explain how or why an untrained ear equates high-tempo, high-volume or high-pitch with high-emotion. And given a lack of further explanation, one is left to wonder why the Philarmonie is attended by anyone other than trained virtuosi. The suggestion of an impoverished experience of music due to a lack of formal musical training would surely upset the multitudes of people who are musically untrained but whose experience of music is nonetheless complex, rich and deep.

Despite some weaknesses, the SAME model is noteworthy for its identification of the fact that music is able to create in the listener an awareness of a musical agent; a sense of another person and their ideas or affective state, transmitted through sound. Overy and Molnar-Szakacs (2009) link this to the pro-social aspects of music making, such as cooperative physical work coordinated by collective singing, or social group cohesion promoted by shared music. The idea of music's creation of a sense of the other, even when listening alone, begs the implication of theory of mind processes and 'mentalizing' which allow the inference of other people's intentions based on their actions and are proposed to share neural architecture with mirror mechanisms (Steinbeis and Singer, 2014).

Another strength of the SAME model is its acknowledgement that the shared (synchronized) affective experience of music listening is deeply gratifying or therapeutic. Overy and Molnar-Szakacs (2009) keenly point out that when listening to music, the individual feels that they are not alone, which is soothing or cathartic. The mechanism by which this sensation is created is worthy of investigation, but its effect is undeniable given the comfort humans derive from their favorite music.

Future Directions: Cultural, Historical and Technological Perspectives

Key to our understanding of music as a cognitive phenomenon is acknowledging it as an evolving and dynamic expression profoundly influenced by culture, history and technology.

That which we call ‘music’ is not only defined by our sociocultural perspectives but also by the lens of time.

Musical practices which today seem canon, are in fact significant departures from the way music has been practiced over long stretches of earlier human history. The practice of sitting quietly listening to an ensemble of professional musicians stretches back hundreds of years in European culture. Yet, this is but a fraction of the thousands of years humans have been making music, much of it in informal settings performed by ‘amateur’ musicians and incorporating movement and dance by all parties (Fitch, 2016). Thus, when considering embodiment in music making, it is crucial to consider that the means and meanings of music in its beginnings were quite different from what we see in current practice.

Much of the academic work on music cognition has taken place in the context of a narrow band of culture and history: tonal concert music of pre-20th century Western Europe. Musician and researcher Vijay Iyer identifies the cultural myopia inherent in this and points out that such an incomplete survey distorts any conclusions drawn (Iyer, 2002). Quite rightly, he implies that an exclusive study of English, no matter how exhaustive, allows few solid judgments about human language on the whole.

W. Tecumseh Fitch (2016) argues that the divorcing of music and movement is a recent phenomenon of Western art music. He suggests that contemporary settings in which movement to music is not socially acceptable obscure the fundamental nature of music as a participatory embodied process. Fitch points out that the tradition in Western European culture to make a distinction between ‘high art’ and ‘folk art’, the former being refined and courtly, the latter being for the entertainment of lowly urges, is one which unconsciously influences the types of stimulus employed in music perception research. Thus, though motor regions of the brain are engaged when a contemporary symphony attendee listens motionlessly to Mahler, Fitch argues that this is a situation very unlike that in which music was born. Latent bias against music forms which are not viewed as ‘high art’ risks missing out on opportunities to discover important embodied practices in music.

In addressing African-American music, Iyer (2002) identifies the insufficiency of Western European musical lexicon in describing its characteristics. The sensation of ‘groove’ is a powerful element of African-American music, and yet there is no Western European musical term for this rhythmic quality which ineffably captures attention and inspires bodily movement. Iyer, in a gracious gesture to dry academics, allows that this phenomenon may be termed rhythmic ‘expressive microtiming’.

Iyer points to the fact that very different expressions of groove are found in different cultural musics, such that Cuban Rumba and Nigerian Afrobeat are rhythmically distinct in important and subtle ways. Further, these different types of groove have different bodily manifestations in different cultures, appearing uniquely in dance, music and meaning. Means of quantifying these subtleties and they way they are grounded in culture and embodiment is a necessary effort for music neuroscientists and musicologists in a comprehensive study of human music.

Recent empirical work by Jacoby and McDermott (2017) shows that at the fundamental level of perception, culture has a profound impact on music cognition. The researchers visited indigenous people in the Amazon region and found that their expectations and perceptions of musical rhythm differ from those of American musicians and non-musicians. Work of this sort, which meets cultures on their own terms, is needed to elucidate the power of enculturation in shaping music perception and also to indicate to the research field where its own latent cultural biases lie.

Another thread to be attended to in the fabric of human music making is that of technology. While a modern oboe is vastly more sophisticated than a Paleolithic bird-bone flute, throughout the bulk of human history, the means of producing musical sound has remained acoustic and bodily. However, since the 1950s, the advent of electric amplification and electronic sound synthesis has dramatically changed both the means of creation of music and its consumption. Modern audiences are exposed to electronic sounds which have no basis in human physical gesture and enjoy those sounds at volumes, frequencies and clarities not only impossible 50 years ago, but beyond the imagining of composers, musicians and listeners of the time.

Technology has a significant bearing on theories of neural mirroring in music cognition. Ideas such as the SAME model of Overy and Molnar-Szakacs (2009) are based in the notion that emotional experience in music is derived from an understanding of the bodily action required to create that music. But how is emotion derived from a sound that has no origin in human bodily capabilities? Clearly, electronic music enthusiasts derive deep emotional meaning and inspiration for fervent bodily motion from the music, despite its being composed of sounds which originate from no physical acoustic instrument. The sound of electronic music is created and reproduced with technological capabilities beyond human physiology. Where does that leave the mirror neuron?

If we apply the SAME model to the example of electronic dance music, we find it lacking. No human has bodily motor knowledge of how to move electrons through a circuit to produce the sounds created by a synthesizer. If there are no physical gestures in our motoric awareness that we can call upon to explain the origins of the musical sounds we hear, how do we experience emotion through that music? Without an updated and expanded model, we are left to conclude that electronic music is simply empty of the richness of hierarchical layers of meaning the SAME model attributes to traditional acoustic music. Clearly, further modeling is called for.

But are we to consider electronic musics ‘disembodied’? They are widely produced through non-physical means; while a mouse-click is a physical action, it is not spatiotemporally coupled to the sound that results. Much electronic music is created in not-real-time and composed of digital information that has no airborne, vibrational presence until it reaches the speaker. And yet, the styles which predominate modern ‘dance music’ are created through these means and elicit no less motoric enthusiasm than the Lindy Hop or the Waltz ever did.

Is it possible that a rhythm produced with digital precision, amplified cleanly and powerfully, containing the intense low frequency energy conjured by modern technology, creates neural entrainment *stronger* than that to Clyde Stubblefield’s flesh-and-blood drumming on James Brown’s “I Got the Feelin’”? This is a question waiting for research funding. For mirror neuron theorists, the difficult questions posed by electronic music will get only thornier as artificially intelligent generative music systems, the ultimate in disembodied sound, appear more widely in our musical lives.

Despite the difficulties in unwinding the threads of music cognition, we are left with the obvious fact that music is powerful in our minds, our bodies and our culture. Regardless of the ebb and flow of theories on neural mirroring, lines of research like neurologic music therapy not only indicate that music is deeply woven into our physiology, but also show that we can activate that powerful filament to heal, soothe and bond us. Future work will elucidate the mechanisms of entrainment and use them for therapeutic purposes both psychological and corporeal. And certainly, when academic pursuits become too fraught, one need simply head to a good discotheque, where embodiment will take the reigns and allow a moment of bliss in motion and connection amongst those carried by the beat.

Just as the embodied approach to understanding cognition has encouraged researchers and theorists of the mind to pull back from their reductive perspectives which peer ever downwards, and to look around at interconnections and up at emergent phenomena, the pursuit of musical understanding requires that we similarly widen our view. As investigators of music in the body, brain, mind, psyche and society, we must look more broadly, across global cultures and up and down the social hierarchies. We must look backwards and forwards in time, to understand where music originates and how those origins inform its evolution. And most important is that we look at *now*, in order to grasp how dramatically technology has transformed our experience of music, for in that transformation are keys to a deeper understanding of how music lives in us: viscerally.

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