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The Science-Music Borderlands

Reckoning with the Past and Imagining the Future

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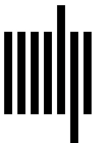
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11 Combating Reductionism in Music Neuroscience with Ecologically Valid Paradigms: What Can (and Cannot) Be Gained?

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Introduction

Why, across cultures and history, do we consistently find music to be an integral part of every human society? One reason must be because of its temporal and structural complexity, its ability to at times surprise us and at times reassure us, to connect us with our past as well as bring us into the present moment, to teach us about ourselves as well as others. When we listen to or perform music in our daily lives, we rarely pay attention to only one aspect of sound. Rather, music is experienced as a collective whole embedded within our own psychodynamic context. It develops and changes over time, and we develop and change over time as we listen. Yet in the field of cognitive science, music is often studied in isolated contexts, with the sounds themselves broken down into controlled or confined components (e.g., beats vs. tones). It has been argued that studying any complex processes in such a componential manner may lead to artificially constrained or inaccurate theories of the mind (Friston et al., 1996). Neural populations may very well behave differently when processing highly controlled stimuli in the lab versus multimodal stimuli in the natural world (Hasson et al., 2004). This all begs a very important question: what can studying individual components of music in the lab really tell us about how the mind works and how music interacts with it in our daily lives?

Part of the reason neuroscientific explorations have focused on individual components of music, rather than the collective whole, pertains to the technological limitations of the tools available for imaging the brain. The earliest studies of the human brain's physiological responses to music used electroencephalography (EEG), a noninvasive technique that involves placing electrodes on the scalp to record the electrical signal produced by a collection of neurons in the brain. EEG has high temporal resolution, meaning that a reliable signal can be recorded every 0.5 to 5 msec (200–200 Hz). With EEG, scientists can directly measure neural activity that is time-locked to a single

change in the environment or stimulus, termed an event-related potential (Biasiucci et al., 2019). Because a response to a single event tends to be small and noisy, EEG studies typically require repeated trials of the same stimulus. Consequently, the first EEG studies with music used highly repetitive and rhythmically standardized musical sounds with a very clear moment of change, such as monophonic musical phrases that ended with either a harmonically “correct” or “incorrect” note (Besson & Macar, 1987).

As new imaging techniques developed, research on music adapted to the new technological limitations. With functional magnetic resonance imaging (fMRI), for example, researchers can use the electromagnetic properties of molecules in the brain to measure changes in blood flow (technically, deoxygenated hemoglobin) in spatially precise cubes, or voxels, within the brain (typically 1–3 mm³). This fine spatial resolution comes at the cost of temporal resolution, wherein a measure of blood-flow change (referred to as fMRI signal) is recorded on the order of seconds rather than milliseconds (typically 0.8–2 sec). Because of this limitation, fMRI analyses typically involve temporal averaging of the brain signal recording during a task (generally about 15–200 sec in duration) and subtracting this average from the average brain signal recorded during a control condition that does not involve the cognitive process being studied (the *subtraction method*). The univariate methods and highly constrained stimuli required for certain EEG and fMRI analyses afford a high degree of experimenter control, which is useful for testing certain hypotheses. Findings with such paradigms have therefore yielded useful and informative insights into aspects of certain cognitive processes that are likely involved in the musical experience.

That being said, more recent schools of thought argue that focusing on mean activation across time in a particular area of the brain may be misrepresenting how the brain functions in the natural world (Nastase et al., 2020; Poldrack, 2012). Mapping a single component of a stimulus onto a single area of the brain—a practice referred to as *localization of function* or, more colloquially, *blobology* (Poldrack, 2012)—has not proved fruitful, leading many to contend that cognition is likely the result of multiple brain regions functioning in tandem. Given these considerations, there has been a push in neuroscience to adapt more naturalistic paradigms and stimuli into the study of the brain and mind (Sonkusare et al., 2019; Zaki & Ochsner, 2009). While there is no single definition of what makes research studies naturalistic, they typically involve (1) stimuli that are dynamic, complex, and as unconstrained as possible, conveying situations, actions, and behaviors that mirror how we might encounter them outside the lab (e.g., film clips, spoken narratives, full musical pieces); and/or (2) unintrusive tasks that require participants to do little more than engage with the stimulus as they would in everyday life (e.g., free-viewing, free-listening paradigms).

Listening to or playing music while inside an MRI scanner or while wearing EEG electrodes on the scalp is certainly not the most natural way to experience music.¹ The process of collecting fMRI data is particularly abnormal. The participant needs to restrict movements while inside a narrow tube. Plus, the noise emanating from the scanner while collecting images (continuous beeps ranging from 85 to 105 dB, depending on the magnetic strength and sequence parameters) can be particularly problematic in auditory studies (Gaab et al., 2007). Typically, researchers have addressed these challenges by including rest conditions (scanner noise alone without a stimulus) and contrasting the signal between a music condition and the rest condition. Other techniques include using sparse temporal sampling² or headphones with active noise-canceling abilities (Dewey et al., 2021). Because EEG does not require the magnetic pulses that cause scanner noise and is less susceptible to movement artifacts, it can be used in situations that more closely mirror how we experience music outside the lab. That being said, the spatial advantages provided by fMRI may justify its use, despite these constraints.

In this chapter, we juxtapose the findings from research taking a reductionist approach (optimizing for more experimenter control) with those taking a more naturalistic approach (optimizing for ecological validity) to the study of music and the brain. Rather than draw a clear line between research that is naturalistic and that which is not, we take the stance that it is more instructive and more accurate to consider the methodologies, tasks, and stimuli as separate components that lie somewhere along a continuum of ecological validity and experimenter control. The technology used to measure some component of neurophysiology is a third consideration when assessing the overall naturalistic nature of study. For the sake of clarity, this chapter is organized into sections covering a single cognitive process, even though these cognitive processes have some degree of overlap in terms of neural correlates and subjective experience and likely influence one another. We conclude with a discussion of how more ecologically valid paradigms allow researchers to integrate findings across cognitive domains and then consider how future studies can avoid the common pitfalls associated with designing more ecologically valid studies to enhance our collective understanding of musical experience and its neural underpinnings.

A Note on Methodology and Statistical Approaches

As neuroscientists move away from the constrained, univariate designs traditionally used with neuroimaging, they are embracing computational analytical approaches that do not require making hard assumptions about the structure and timing of the expected signal. These methods allow increased flexibility and generalizability and

are therefore more suited for assessing neural activation patterns associated with less-controlled stimuli in which the timing of modeled events or changes are rarely defined a priori or even known. Furthermore, some of these methods can determine changes within and across brain regions, as well as across time, within a single model. These models seek to relate patterns of multivariate brain activity measurements with cognitive processes, based on the assumption that aspects of a stimulus are “represented” by a collection of brain voxels (presumably, populations of neurons) whose activity can overlap in time and location (Nili et al., 2014).

No matter what model is used to analyze fMRI data (hypothesis driven or data driven), the question is always how best to determine what information is shared across people’s brains. Most processing pipelines involve some sort of spatial normalizing, or warping each individual person’s anatomical data into a standard space. This process, however, can wash away potentially important microanatomical and topographical differences across people. Some researchers therefore opt to use a functional localizer, an additional imaging task used to locate a spatially contiguous set of voxels that are functionally selective to a particular stimulus or cognitive demand, such as looking at faces (Kanwisher & Barton, 2011) or sentences (Scott et al., 2017). The voxels significantly activated by this localizer task are then used to test specific hypotheses about their role in a subsequent task of interest. Importantly, the voxels used can vary across participants. In this way, individual differences in anatomy can be preserved, while ensuring that the function of these voxels is shared across people (Saxe et al., 2006). That being said, depending on how it is employed, a functional localizer approach assumes that brain function can be clearly mapped onto a set of discrete spatial clusters, which goes against the evidence that multiple structures in the brain can perform the same function (i.e., degeneracy; Friston & Henson, 2010). For that reason, this approach is not commonly employed with more complex, naturalistic stimuli.

Researchers have recently started to incorporate algorithms that can project subject-specific functional data in response to a naturalistic task into a common “informational” space.³ The naturalistic task for alignment is kept separate from the task of interest, although it should be similar enough that it can presumably trigger brain states that are likely shared across people (Haxby et al., 2020). Hyperalignment and shared response modeling (Chen et al., 2015) are two such algorithms that have been employed with relative success and have certain advantages over functional localizers, in that they involve fMRI tasks that are more engaging and suitable for specific populations (movies versus flashing images with localizers) and are designed to activate multiple brain areas that respond to many ecologically valid examples and categories (Jiahui et al., 2020).

It is not necessary for readers to fully comprehend these analytical techniques; rather, it is important to understand that while these methods provide new ways to assess the functioning of the brain, they involve a number of drawbacks that can hinder or obfuscate the discovery process if they are not employed carefully. For interested readers, a more thorough discussion of the advantages and disadvantages of various methods used to analyze naturalistic neuroimaging data can be found in Nastase et al. (2020) and Poldrack (2012).

Long-Timescale Processing of Musical Structure

Some of the earliest neuroscience studies of music were dedicated to understanding the sensory systems of the brain that allow the processing of tonality, rhythm, timbre, and harmony. Although these studies provided fundamental insights into functional specialization of the human brain, their ecological validity is questionable, given their use of highly controlled musical stimuli, such as short, isolated melodic sequences (Milner, 1962; Shankweiler, 1966; Zatorre et al., 1998) and simple rhythmic patterns (Kester et al., 1991; Penhune et al., 1998). In addition to quick sensory changes, music contains information at longer timescales, such as the reintroduction of a theme or chorus or the transition from one segment to the next. Somehow, our brains are able to process and maintain information that is changing over the course of minutes (Sridharan et al., 2007; Williams et al., 2022). This type of music processing can be assessed only with stimuli that convey these structural changes over time.

In light of this, researchers have used longer, more dynamic musical pieces to understand aspects of music perception that evolve over longer timescales. In one study, participants listened to four 9.5-minute symphonic excerpts during fMRI, as well as scrambled versions that preserved the pitch, loudness, and spectral information but disrupted the temporal structure. This study showed that activity patterns in the inferior frontal cortex and superior and medial portions of the auditory cortex were most correlated across participants in response to temporally coherent music rather than scrambled music (Abrams et al., 2013). To further assess how the brain processes the different timescales embedded in music's inherently hierarchical structure (musical notes make phrases, which make measures, which make movements), Farbood et al. (2015) played approximately four minutes of a Brahms piano concerto to expert pianists undergoing fMRI. The excerpt was presented to each participant in its intact form as well as in versions scrambled at different levels: one at the section level, the phrase level, and the measure level and a completely time-reversed version. They found that anatomically distinct areas of the cortex were involved in processing the hierarchical structure of

music. The early auditory cortical areas responded to all conditions, whereas the neighboring superior temporal gyrus (STG), as well as parts of the parietal and frontal gyri, became engaged only in the more coherent, higher-level temporal conditions (phrase and measure scrambles, as well as the intact version). Although research with less ecologically valid music has also demonstrated the involvement of these brain areas in at least some aspects of music processing (Zatorre et al., 1994; Janata et al., 2002; Menon et al., 2002), studies that incorporate extended, polyphonic music have been able to dissociate the brain regions involved in processing rapid, low-level temporal information from those that process longer timescale information.

That being said, these studies still relied on a contrast condition with very unnatural-sounding music—that is, music played in reverse and temporally scrambled music. A recent investigation applied data-driven analytical techniques to show that it is possible to use intact musical recordings to investigate the brain regions that represent the high-level temporal structure of music. Williams et al. (2022) had fMRI participants listen to jazz and classical excerpts ranging from one to four minutes and then had a separate group of behavioral participants mark when they felt that a meaningful transition had occurred within each piece. The authors subsequently applied a data-driven statistical approach (hidden Markov models, or HMM⁴) to participants' fMRI data and found that in addition to the auditory cortex, the angular gyrus, medial prefrontal cortex (MPFC), and posterior medial cortex (PMC)⁵ showed HMM-defined transition points that aligned with the transition points provided by the behavioral participants. These HMM-identified events were significantly longer in the MPFC than in the lower-order auditory cortex, PMC, and angular gyrus.⁶ Taken together, the results suggest a hierarchical neural representation of musical event structure, with the auditory cortex, PMC, and angular gyrus processing shorter-term transitions and the MPFC processing longer-term transitions.

To summarize, when we encounter music in everyday life, we likely experience it as a collective whole, recognizing that events are unfolding over the course of minutes. Evidence from more ecologically valid music-listening paradigms indicates that higher-order areas of the brain, in addition to the sensory processing auditory cortex, together represent the hierarchical structure of music, stitching together information occurring at various timescales (e.g., from short to long). Earlier studies using simple musical sequences to investigate the neural basis of music perception have proved limited in their ability to tell us how the brain constructs these holistic musical representations.

Memory

We've all encountered a piece of music that has instantaneously transported us back to the past, stirring up vivid and evocative memories of who we once were. Despite music's powerful ability to connect us to our past, many studies investigating music's influence on memory focus on recalling simplistic things, such as images of faces (Proverbio et al., 2015) or lists of words (Wallace, 1994; Balch & Lewis, 1996; Cournoyer Lemaire, 2019). Even if some of these studies incorporate more complex and dynamic musical examples, they still pair the music with these less naturalistic stimuli (Ferrerri et al., 2013, 2014). In our everyday lives, however, we typically experience music alongside continuous, multimodal, and dynamic sensory information. Therefore, the results from these studies cannot address how the brain uses music to encode and bind events from an individual's life.

In an attempt to measure this binding effect under more ecologically valid conditions, Janata (2009) selected thirty songs from the *Billboard* Top 100 Pop and R&B charts for the years the participants were between the ages of seven and nineteen years. Participants rated how autobiographically salient these excerpts were and then listened to truncated (30-second) versions of the songs during fMRI. The author found that activity in the dorsal medial prefrontal cortex (DMPFC) was positively correlated with the mnemonic salience of the different pieces, suggesting that this region is a key mediator for the retrieval of music-evoked autobiographical memories. The DMPFC was significantly involved in tracking the tonality of the pieces as well, suggesting that this region provides a mechanism by which structural features of the music are used as retrieval cues for personal memories. Follow-up neuroimaging studies with similar musical stimuli confirmed the DMPFC's critical role in connecting musical cues with autobiographical memories and in accessing the full sensory context during event retrieval (Belfi et al., 2018; Ford et al., 2016).

Although these studies incorporated popular music from participants' past, their ecological validity is still limited because the content of the music-evoked memories was unobserved. Moving forward, laboratory studies that are capable of probing music-related episodic events from everyday life will be necessary to better understand the brain changes that enable the formation of memories. Recent investigations not focused on music have tried to address this issue by having participants navigate real-world environments outside the lab using life-logging devices (e.g., video recorders, portable microphones) and subsequently cueing these recorded memories during fMRI (Nielson et al., 2015; Rissman et al., 2016; Chow & Rissman, 2017). These studies have already provided evidence that the prefrontal cortex (including the DMPFC),

the hippocampus, and the parietal cortex play important roles in episodic memory retrieval for real-world events. Employing such designs and using musical moments from a person's life may be a promising avenue for better understanding how complex brain networks integrate music with our subjective experience.

Reward

Music is often cited as one of life's most enjoyable activities (Zatorre & Salimpoor, 2013), and neuroimaging tools have allowed us to uncover the brain activation patterns involved in the rewarding aspects of musical engagement. At the same time, music can be a useful tool for uncovering how our brains learn to seek and obtain stimuli that make us feel good. Brain recordings from animals learning to perform an action that results in getting a treat have led to the theory that reward processing actually contains two separable mechanisms: wanting versus liking. *Wanting*, sometimes referred to as incentive salience, refers to the motivational process or desire to obtain or pursue an attractive stimulus, whereas *liking* refers to the positive, hedonic feelings upon consumption of a rewarding stimulus.⁷ When we refer to human feelings of pleasure or enjoyment, we are typically referring to the liking mechanism; in contrast, the wanting mechanism would apply to cravings or yearnings or the pursuit of pleasure (Berridge & Kringelbach, 2015). We know that both mechanisms involve several areas located deep within the brain (subcortical brain regions such as the nucleus accumbens [NAc], ventral pallidum, and parts of the insula), as well as other areas closer to the surface (cortical brain regions such as the orbitofrontal cortex [OFC] and parts of the anterior cingulate cortex [ACC]). Reward also involves a third component, *learning*, which is the process of associating a stimulus with a positive (or negative) valence over time. The learning phase appears to involve mainly dopaminergic neurons in subcortical regions, such as the ventral striatum (which includes the NAc), amygdala, ventral putamen, and pallidum (Garrison et al., 2013).

One empirically sound hypothesis for why music is such a rewarding experience is that its temporal, rhythmic, and harmonic structure motivates the listener or performer to naturally form expectations and predictions that can then be violated or confirmed (Vuust & Frith, 2008). An fMRI study that used highly controlled musical stimuli (four-part Bach chorales played on a musical instrument digital interface [MIDI] piano at 75 beats per minute [bpm]) showed that musical violations can induce activity related to reinforcement prediction errors (RPEs) in the NAc during a reinforcement-learning paradigm in which the chorales ended as written (consonantly) or with a manipulated, unexpected dissonant chord (Gold et al., 2019). Furthermore, RPE-related activity in

the NAc was correlated with a self-reported measure of music reward sensitivity—that is, the degree to which one finds various forms of musical engagement enjoyable. By experimentally controlling tempo, timbre, and form, the authors of this study were able to show that listening to music can motivate reinforcement learning by setting up and subsequently subverting expectations. It is therefore plausible that reinforcement learning is one mechanism by which music is experienced pleurably.

Several limitations of this study weaken the conclusions that can be drawn about how the brain imbues music with reward value. First, participants were not asked to report how pleasurable they found the musical stimuli. Second, because of the highly controlled nature of the stimuli (MIDI versions of manipulated Bach chorales), it is unlikely that repeatedly listening to these musical excerpts could result in feelings of enjoyment comparable to hearing one's favorite song on the radio. Addressing the neural systems involved in the conscious experience of pleasure likely requires using less controlled, more familiar music. This poses a challenge because, with more complex stimuli, it becomes difficult to isolate the neural components that are specific to reward and not conflated with other processes that are likely co-occurring, such as memory.

Another fMRI study attempted to balance these concerns by using chord progressions extracted from recorded pop songs featured on the *Billboard* charts (Cheung et al., 2019). To create the stimuli, the melody and rhythm were removed, transposed to a common key, played on a single MIDI instrument, and elongated so that each chord lasted for the duration of the temporal resolution of fMRI. With these controlled stimuli, the authors were able to disentangle the interrelated components of musical expectations: *surprise*—how predictable or unpredictable a particular chord is within the musical environment—and *uncertainty*—how predictable or unpredictable an upcoming chord is, based on the established musical environment. They found that the interaction between the amount of surprise and uncertainty of a chord predicted subjective ratings of pleasure. This interaction effect was reflected in fMRI signal changes recorded from the amygdala, hippocampus, and auditory cortex. Surprisingly, striatal activation (NAc and caudate) was involved in coding only for uncertainty, not for surprise, suggesting that this system plays a role in something akin to the wanting mechanism, by which we are motivated to gain subsequent information that resolves the musical uncertainty. The involvement of the NAc, as well as the rest of the striatum, has also been shown in response to rhythmic violations in piano chords (Matthews et al., 2019, 2020).

By breaking down musical stimuli into these basic components, researchers were able to show how two temporal aspects of musical processing relate to rewarding experience. But once again, it is unlikely that the enjoyment experienced while listening

to decontextualized chord sequences equates to the enjoyment of listening to one's favorite music (Laeng et al., 2016). Moments of peak enjoyment in music, often co-occurring with chills (Mori & Iwanaga, 2017), are associated with changes in the music that unfold over periods longer than a few seconds, such as crescendos, builds, and the entrance of singers and the human voice (Bannister, 2020). It would be difficult to study this fascinating phenomenon using stimuli in which the vocals, dynamics, and instrumentation had been regularized, manipulated, or edited in such noticeable ways. Studies using more familiar musical clips have shown that the NAc (in particular, dopamine released in the NAc) is linked with the experience of peak enjoyment of music, whereas other areas of the striatum (e.g., the caudate) are likely involved in the anticipation of reward (Salimpoor et al., 2011, 2013). Furthermore, the more rewarding the listening experience, the more likely it was that activity in the NAc was correlated with activity in higher-order brain regions such as the ventromedial prefrontal cortex (VMPFC) and OFC.

More recent studies have attempted to address the higher-level experience of pleasure by playing pieces of music in full, with no cuts or edits and requiring no explicit tasks other than listening. Although it is always somewhat unnatural to listen to music in an unfamiliar setting while being monitored in some way, the hope is that such paradigms move closer to how we experience music outside the lab so that the multiple complex processes involved in musical enjoyment can be assessed. The neural findings from such studies vary somewhat from those using less ecologically valid paradigms, showing that coactivation patterns in large-scale brain networks, both within an individual (Lehne et al., 2014; Singer et al., 2016) and across individuals (Sachs et al., 2020), track changes in subjective feelings in response to the music. Specifically, such studies have shown that the default mode network (DMN; a large-scale brain network consisting of regions in the parietal, temporal, and frontal cortices that tend to function together) is involved in the subjective experience of enjoyment in response to music.

At this point, we can only speculate about the DMN's role in musical enjoyment, but existing theories argue that it is actively involved in integrating external information from the stimulus with internal information from the body. EEG findings provide evidence for this active role of the DMN in reward processing: in participants with heightened reward sensitivity to music, there was less of a match between the temporal complexity of the brain signals recorded in DMN areas (ACC and inferior parietal lobule) and the temporal complexity of the musical stimuli. When these same participants were explicitly told to attend to perceptual features of the music, however, the match between neural and musical signal was higher, suggesting that the DMN might be involved in shifting focus away from the external information coming from the stimuli

and toward the internal process of generating expectations and emotions related to the piece as a whole (Carpentier et al., 2020). Such insights into the significance of this clearly intrinsic yet poorly understood brain network can result only from studies involving more complex, more ecologically valid musical stimuli.

In sum, studies that have isolated and manipulated specific components of music (e.g., harmony, rhythm) have laid the groundwork for our understanding of the process by which music can become preferred and liked and the role of subcortical regions in this learning process. Studies with polyphonic, unmanipulated music indicate the involvement of higher-order brain regions, particularly the OFC and DMN, during the subjective experience of music-evoked pleasure. The extent to which subcortical and cortical brain systems interact with each other during pleasurable experiences with music requires further exploration with techniques that allow the use of self-selected music.

Emotions and Feeling

Enjoyment and pleasure can be viewed as one of many possible affective responses to music. But music can evoke many feelings.⁸ Indeed, music's ability to both convey and induce a range of emotions makes it a useful tool for studying the neural systems involved in emotional responses (Juslin, 2013). However, despite decades of neuroscience research, the definition of emotions and the appropriate way to measure them are still fiercely debated (Barrett & Satpute, 2019). While there is evidence that the emotions evoked by music across genres and cultures cluster into categories that mirror those evoked by faces and video clips (Cowen et al., 2020), there is also evidence that what music evokes can be accurately captured by dimensional models corresponding to how pleasant or unpleasant, arousing or unarousing the music feels, rather than basic emotional categories such as happy or sad (Cespedes-Guevara & Eerola, 2018).

Part of this discrepancy stems from the issue of how to establish a "ground truth" when studying emotions and feelings: that is, how do we define an agreed-upon, ideal outcome with which we can compare the actual findings. There is not one method of assigning an emotional label to a stimulus. One way of dealing with this empirical uncertainty is to focus on the individual, not on what is common across people but on what is different, and try to relate these differences to some aspect of that individual's unique experience. Another way is to obtain multiple measures that describe the stimulus (e.g., acoustic and musical analysis, subjective ratings, composers' intentions) and use models that combine these features in different ways to predict a particular response. Although a purely objective ground truth may never be realized when it comes to emotions, certain methodological approaches can afford a higher degree of

certainty with regard to how an observed response relates to some aspect of a stimulus or cognitive process. For now, since there is no clear definition of *emotion*, we consider the concept broadly, including studies that operationalize emotions as discrete categories as well as continuous dimensions.

Despite these limitations, dozens of studies have used musical stimuli to assess the neural systems involved in music-evoked emotions—that is, how we feel when listening to a piece, as opposed to what emotion we perceive in the music. One meta-analysis reported that across these studies—some of which used emotional stimuli that were highly controlled (computer-generated music or chord sequences) and some of which used unmanipulated excerpts—music listening was consistently associated with activation patterns across the entire brain, including subcortical areas (amygdala, hippocampus, ventral striatum–NAc, dorsal striatum–caudate nucleus, inferior colliculus), auditory areas extending into the parietal operculum and secondary somatosensory cortex, and medial cortical areas (OFC, ACC, middle posterior cingulate cortex; Koelsch, 2020). Many of these regions overlap with those found to be associated with aspects of emotions outside the realm of music (Adolfi et al., 2017). Given that the studies included in the meta-analysis varied with regard to the behavioral measures used to determine the emotional response and included mostly musical examples from the European classical world, the investigation of music-evoked emotions appears to be plagued by some of the same methodological issues and ethnocentrism as other non-musical neuroscience investigations of emotions. There is thus little indication that using musical stimuli helped resolve outstanding issues in terms of the conceptualization of emotions.

Naturalistic listening paradigms might provide new insights into the neuroscientific understanding of emotions by exploring the brain systems sensitive to emotion dynamics. Despite the fact that our feelings and moods are constantly in flux, the temporal component of emotions in the brain is relatively unexplored. Full-length pieces of music that traverse different themes, motifs, rhythms, and melodies might allow researchers to determine whether and how regions of the brain that respond to music-evoked emotions in isolation track emotional dynamics. Recent studies using naturalistic listening paradigms have been able to extend these findings to show brain regions and networks in which time-varying patterns of activation and connectivity reflect changes in emotional responses to music. Continuous ratings of felt emotions outside the scanner in response to music were associated with time-varying coactivation patterns in the amygdala, caudate, hippocampus, thalamus, insula, and cingulate (Sachs et al., 2020; Singer et al., 2016). Brain activation in many of these regions was associated with nondynamic, less naturalistic emotional stimuli as well, but by assessing temporal

patterns, these results clarify the role of these regions in integrating emotionally relevant information over time.

Another way that naturalistic musical paradigms could lead to new discoveries in the neuroscience of emotions is to focus on complex emotional experiences that occur infrequently in everyday life and typically only in the realm of aesthetics (Juslin, 2013; Mori & Iwanaga, 2017). These could include chills or frisson (as previously discussed), as well as feelings of being moved (Menninghaus et al., 2015) or *kama muta* (Fiske, 2019), awe, nostalgia, entrancement or transcendence, wonder (Juslin, 2013; Mori & Iwanaga, 2017), pleasurable sadness (Sachs et al., 2015), and general aesthetic appreciation. Music is not the only art form that can induce these emotions, but it is certainly more easily accessible to most people on a daily basis than fine arts, movies, or nature.

Finally, the issue of ground truth with emotional stimuli could be minimized by incorporating non-Western musical systems with a clearer mapping between musicality and feeling. North Indian classical music, for example, uses a musical system, in which specific tonal relationships, rhythms, and tempos are capable of eliciting distinct, predictable emotions (Valla et al., 2017). The expansion of music cognition research to include musical stimuli from a broad range of cultures could be used to validate, or potentially establish, a more robust relationship between brain function and the phenomenological experience of emotions. Moving forward, neuroscientific investigation of emotions might benefit from embracing these deeply meaningful and deeply human affective experiences that tend to occur uniquely within the realm of music.

Incorporating the Social Context

Listening to or performing music is rarely a solo experience. Until recent technological innovations changed the way music can be distributed and consumed, people almost exclusively experienced music in the company of others. Throughout this chapter, we have circled around this fundamental question of whether breaking down the experience of engaging with music into testable components is a viable strategy for understanding the associated bodily and neural reactions. Perhaps the strongest criticism against this reductionist approach is that with such an empirical design, it is difficult or impossible to assess how other people might influence the cognitive and behavioral processes involved in the experience.

Listening to music can range from the less naturalistic (sine tones) to the more naturalistic (full-length recorded music), and studies designed to probe the social component of the musical experience range along this same axis. Some use very simple tasks that probe one particular element of shared music making, such as joint tapping (Cui

et al., 2012), whereas others try to capture the holistic experience, such as recording brain activity while professional musicians are performing together (Müller et al., 2018). With recent technological advances (e.g., mobile systems for recording EEG, movement, and physiological responses), it has become easier to obtain rich, multisensory data from multiple music performers and listeners simultaneously (see McMaster University's LIVE Lab concert hall founded by Dr. Laurel Trainor; Chang et al., 2019). Incorporating these technologies into real-world spaces has the potential to provide an ecologically valid understanding of how our brains and bodies change as a function of engaging with music in group settings.

Because relatively few studies have used joint music paradigms, it is difficult to draw any strong conclusions about how the naturalistic nature of the task influences neural processing. Furthermore, the issue of naturalism in tasks that require group dynamics presents an additional methodological challenge associated with the cost and portability of the various neuroimaging techniques. The sheer size of MRI scanners makes it quite challenging to image the brains of two or more people engaged simultaneously in an interactive task. Typically, these so-called hyperscanning studies involve two separate scanners and virtual interactions conducted via screens and headsets (but see Renvall et al., 2020, for the future possibility of dual-coil scanning). Because of the high cost and low mobility, hyperscanning studies are more commonly performed with EEG (Lindenberger et al., 2009; Osaka et al., 2015) or functional near-infrared spectroscopy (fNIRS; Duan et al., 2015), both of which are more portable, more mobile, and less susceptible to movement artifacts than MRI. These studies have focused on the implications of correlated neuroimaging signals across musicians' brains for performance quality (Greco et al., 2018), as well as prosocial behaviors such as cooperation (Balconi & Vanutelli, 2017) and empathy (Babiloni et al., 2012). However, they reveal very little about which brain regions and networks vary as a function of the social context. Given evidence that real-time nonmusical social interactions involve coordination between subcortical regions (Krill & Platek, 2012; Špiláková et al., 2019), a more complete understanding of the social impact of the neural processing of music may require complementary neuroimaging techniques that can assess spatial components of the brain and body.

One potentially fruitful avenue for studying the brain networks modulated by social components is to use music tasks that compare solo listening experiences to listening with others. No study to date has used hyperscanning techniques to assess co-listening, even though such a task would evade the movement artifacts associated with playing music that currently make fMRI hyperscanning studies less tenable.⁹ Studies without neuroimaging have shown that listening to music alone versus with another person

has implications for self-reported emotions and enjoyment (Egermann et al., 2011; Liljeström et al., 2013; Sutherland et al., 2009). Therefore, research that involves music listening tasks with other people seems like a plausible means of furthering our understanding of sensory processing, reward, and emotions in a more naturalistic context. Such studies could provide an innovative perspective on the social bonding that occurs as a result of emotional sharing or emotion matching, an idea very much at the heart of the argument for music's cultural importance and ubiquity (Savage et al., 2020).

Conclusions and Future Directions

Throughout this chapter, we have discussed the advantages and disadvantages of incorporating more ecologically valid paradigms into music cognition research, highlighting the key insights garnered from taking a more holistic, rather than reductionist, approach. We have also suggested some areas for future research that can push forward our collective understanding of the functioning of the human brain and its relationship to musical experiences.

Given music's ability to touch on so many aspects of cognition, one additional direction for future research with naturalistic musical paradigms is to test existing theories of the structure and function of the brain as a *complex system* made up of networks and nodes that integrate information from functionally distinct neural populations (Honey et al., 2007). Evidence suggests that these networks are dynamic and adaptive; they form and dissolve in real time to meet specific computational demands (Pessoa, 2018). How an integrated conscious experience emerges from the interaction of these multiple brain systems remains an open question. Incorporating polyphonic music with analyses designed to assess connectivity and network changes over time may therefore lead to a clearer understanding of the dynamic quality of the brain.

Several studies have already been conducted along this line of inquiry. Carpentier et al. (2020) showed that the temporal complexity of the EEG signal across the entire brain matched the temporal complexity of the musical stimuli, particularly when participants were attending to perceptual aspects of the music. With naturalistic fMRI paradigms, several functional brain networks appear to be consistently and reliably involved when engaging with a variety of stimuli, yet the nature of the interactions between them varies as a function of the demands of the stimulus, such as movies versus music (Bottenhorn et al., 2019), joyful versus fearful music (Koelsch & Skouras, 2014), or changing rhythmic complexity in music (Toiviainen et al., 2020). Together, these findings provide evidence for segregated brain networks that become functionally integrated with one another as internal and external information changes while

engaging with dynamic, complex stimuli. Future studies could incorporate analytical approaches that consider multiple events occurring on multiple timescales to better capture how brain networks form and dissolve over time during musical engagement.

Another promising method of evaluating the neurobiological basis of music perception is to employ more advanced computational models. Artificial neural networks, for example, learn in a data-driven manner how information is transmitted through a series of transformations (via hidden layers), similar to hierarchical information processing in the mammalian brain (Kriegeskorte, 2015). As discussed, music has a unique temporal structure, whereby representations become more abstract and complex as they travel along a cortical processing hierarchy (Farbood et al., 2015; Williams et al., 2022). Therefore, it is likely that using neural networks to construct rich music-based representations will help us more accurately model how our brains represent complex musical information. Some studies have already taken promising steps in this direction (Güçlü et al., 2016; Kell et al., 2018). However, it is important to keep in mind that although the inputs (e.g., musical stimuli) and outputs (e.g., musical behaviors) of these networks may resemble the types of representations and behaviors observed in humans, the series of input-output transformations in these networks (particularly in the case of deep neural networks) are typically intractable, which limits our ability to make claims about whether these transformations resemble the way musical information is processed throughout the human brain. As we become better at quantifying and mapping the relevant aspects of our stimuli and participants, we will become better at using advanced computational models to quantify and map brain functioning.

Another important area for future endeavors is to incorporate non-Western populations and stimuli into neuroscientific investigations to expand the generalizability of existing findings. The majority of research discussed in this chapter used stimuli and study populations within the Eurocentric framework, which, among other biases, limits the conclusions we can draw about the perceptual, social, and emotional impacts of music (Baker et al., 2020). Furthermore, the structure and cultural function of certain musical traditions might be uniquely suited to study certain aspects of cognition (Valla et al., 2017). The expansion of music cognition research to include stimuli from around the world will therefore not only result in more ecologically valid theories but also lead to a more inclusive path of inquiry.

Notes

1. It is important to note that the term *natural*, used in this context, is not meant to indicate that there is an unnatural way in which people listen to, perform, or experience music in everyday life. Rather, it is a comment on and response to the types of tasks and stimuli that have traditionally been used in lab-based scientific studies. It is also worth mentioning that despite the recent

push to use more ecologically valid musical stimuli in the lab, this largely involves using recorded music in studies, which is a relatively modern way of engaging with music and may not reflect how certain cultures or communities around the world commonly engage with music (Walther-Hansen, 2020). That being said, we use the term *naturalistic* throughout this chapter to align with other fields of neuroscience that continue to use it.

2. In sparse temporal sampling, sounds are presented while the MRI scanner is turned off (to prevent sound interference from the scanner), and brain volumes are acquired following the silence when the hemodynamic response function is at its peak (Hall et al., 1999). This approach has clear advantages when it comes to studying auditory stimuli like music, although there are severe drawbacks as well, such as lower statistical power with fewer data points.

3. *Information* in this context refers to the relationships among functional pattern vectors, typically quantified as the similarity (or dissimilarity or distance) between each pair of vectors.

4. HMM is a statistical method that learns the temporal structure of data and identifies latent state transitions within a brain region without requiring any timing information about the stimulus.

5. The PMC includes the precuneus, dorsal posterior cingulate, ventral posterior cingulate, and retrosplenial cortex (Bzdok et al., 2015).

6. Higher-order cortical areas refer to a set of brain regions that support more complex (i.e., high-level) cognitive functions such as planning, executive functions (Miller & Wallis, 2009), and integrating information across sensory inputs (Chen et al., 2017), as opposed to more automatic, less integrative neural processes such as sensory perception (i.e., low-level cognition).

7. Throughout this chapter, we use the term *pleasure* to refer to the “liking” mechanism.

8. For the sake of clarity, we do not distinguish between emotions and feelings, as others have suggested (see Damasio, 1999). Here, we use the term *emotion* to refer to any bodily state changes that accompany a change in the environment, as well as the subjective experience of those bodily state changes.

9. Given the logistical and economic constraints of hyperscanning, for any future endeavor, it is important to consider whether obtaining *simultaneous* measures of brain activation is absolutely necessary to answer the proposed research question. To aid in the design of future social neuroscience studies, we suggest following the framework proposed by Misaki et al. (2021) and Redcay and Schilbach (2019). They argue that fMRI hyperscanning is necessary only if the task involves a reciprocal interaction that is evolving, unpredictable, and difficult to reproduce. Sharing a new piece of music with someone may very well fall into this category if one is interested in both the giver’s and the receiver’s neural responses, although it may be possible to study this type of social interaction with music sequentially, scanning only one person at a time.

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