ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *The Year in Cognitive Neuroscience*
REVIEW

Musical anhedonia and rewards of music listening: current advances and a proposed model

Amy M. Belfi[1] and Psyche Loui[2]

[1]Department of Psychological Science, Missouri University of Science and Technology, Rolla, Missouri. [2]Department of Music and Department of Psychology, Northeastern University, Boston, Massachusetts

Addresses for correspondence: Amy M. Belfi, Department of Psychological Science, Missouri University of Science and Technology, 135 Humanities-Social Sciences, 500 W. 14th St., Rolla, MO 65409; Psyche Loui, Department of Music and Department of Psychology, Northeastern University, 360 Huntington Ave, Boston, MA 02115. amybelfi@mst.edu; p.loui@northeastern.edu

Music frequently elicits intense emotional responses, a phenomenon that has been scrutinized from multiple disciplines that span the sciences and arts. While most people enjoy music and find it rewarding, there is substantial individual variability in the experience and degree of music-induced reward. Here, we review current work on the neural substrates of hedonic responses to music. In particular, we focus the present review on specific musical anhedonia, a selective lack of pleasure from music. Based on evidence from neuroimaging, neuropsychology, and brain stimulation studies, we derive a neuroanatomical model of the experience of pleasure during music listening. Our model posits that hedonic responses to music are the result of connectivity between structures involved in auditory perception as a predictive process, and those involved in the brain's dopaminergic reward system. We conclude with open questions and implications of this model for future research on why humans appreciate music.

Keywords: music; reward; emotion; anhedonia; pleasure

Introduction

The capacity to perceive, produce, and appreciate music, together termed musicality,[1] has been a growing topic of interest in the past 20 years of cognitive neuroscience. While most cognitive neuroscience studies on musicality focus on music perception and production skills, there has been a recent explosion of interest in the appreciation of music.[2,3] Multiple research programs in the cognitive neuroscience of music have involved comparing participants with different types and levels of musical training.[4–7] However, to cognitive neuroscientists who are not particularly concerned with music, these studies may appear to be highly specialized and of limited interest as they seem to focus on a special population—highly trained musicians. In contrast, studies on the appreciation of music can be thought of as more general and inclusive, encompassing the vast majority of humans regardless of formal musical training.

Humans show knowledge of fundamental musical building blocks, such as rhythm and beat, from as early as 1 day old,[8] and as shown from the success of the multibillion-dollar music industry, humans around the world enjoy music. One of the most frequently reported reasons for listening to music is the overwhelming influence it has on feelings and emotions.[9] Music has been deemed an ultimate group bonding activity;[10,11] this is supported by structural features of melody, harmony, and scales that are observed across many cultures,[12] as well as the ubiquity of songs that serve social functions, such as lullabies, dance songs, healing songs, and love songs, across cultures.[13] Singing and making music together enhance social interactions and group bonding[14,15] and elicit physiological effects that are observable from infancy.[16] Even in the few cultures where music is not produced in groups, members of these cultures nevertheless enjoy singing for each other,[17] suggesting

doi: 10.1111/nyas.14241

that the capacity for music enjoyment, that is, the rewarding aspects of music, may be intrinsic to humans as a social species. Together, these lines of research suggest that understanding why humans love music may offer a window into how humans interact in a social environment.

The rapid growth of research on musical enjoyment, specifically in cognitive neuroscience, may also be facilitated in part by recent findings on the role of dopamine in coding for prediction and reward. Since the classic observations that stimulating dopaminergic neurons elicits motivated behavior,[18] and that dopaminergic neurons signal changes in the predictability of rewards,[19] thousands of studies have identified a set of regions within the human brain that are especially sensitive to reward. These regions center around the midbrain (the ventral tegmental area and substantia nigra (SN)), the dorsal and ventral striatum (VS) (the caudate, putamen, nucleus accumbens (NAcc), and globus pallidus), and the medial prefrontal cortex (mPFC).[20] These areas, which we refer to throughout this article as the reward system, are reliably activated during the experience of unconditionally rewarding, evolutionarily salient stimuli, such as food and sex, as well as stimuli that are strongly associated with such rewards, such as money. Findings from the monetary incentive delay task show that cues that predict monetary rewards reliably activate the striatum and mPFC,[21] core areas of the reward network. Interestingly, activity in the striatum is also observed when social stimuli (faces) are substituted for monetary rewards,[22,23] suggesting that social and monetary cues tap into "common neural currency" of the reward system.[22]

The findings that food and sex activate the same reward system can be readily explained as being evolutionarily adaptive: being motivated to seek out these stimuli improves our chances of survival. In contrast, the adaptive value of music—and aesthetic stimuli more generally—is less obvious. Nevertheless, much recent work has shown that music engages the reward system (as reviewed below; see also Ref. 24). While music ranks highly among the pleasures in life,[25,26] recent work has identified a unique condition of people with specific *musical anhedonia*:[27,28] people who are insensitive to the rewarding aspects of music despite normal hedonic responses to other sensory and aesthetic stimuli, and normal auditory perceptual abilities.[29] The existence of this unique population raises many important questions. Some of these questions include:

1. The nature versus nurture of musical reward sensitivity: Does musical anhedonia run in families? When and how did it develop? What, if any, genetic underpinnings might predispose an individual toward musical anhedonia? What is its developmental trajectory?
2. Domain-specificity versus domain-generality of reward sensitivity: Are there specific neural pathways for music reward that are separate from general reward? What are the neural pathways through which specific stimuli (such as music) come to have privileged access to the reward system? What endows a certain stimulus with privileged access to the reward system?
3. Psychological associations and clinical comorbidity: What are the associations between musical anhedonia and psychological traits, both in the normal range (e.g., big five personality traits) and clinical populations? What is the comorbidity between musical anhedonia and personality, mood, and communication disorders?
4. The evolution of music: To what extent do nonhuman animals also show reward sensitivity to music? Have there been people with musical anhedonia for as long as there has been music? By extension, if people with musical anhedonia have survived for generations with no apparent disadvantage alongside the rest of the population who have normal reward sensitivity to music, then the lack of reward sensitivity to music seems not to affect their survival. If this is the case, then why do we seek out music?

Here, we review the recent cognitive neuroscience evidence for musical engagement of the reward system, as well as an extreme end of the spectrum of individual differences in sensitivity to music reward in specific musical anhedonia. Based on our review of the literature, we propose a model that accounts for the nature of the auditory access to the human reward system, and its disruption in musical anhedonia.

Roles of the auditory and reward systems in musical pleasure

Involvement of the reward system

Some of the earliest works investigating the neural substrates of music listening focused on neural responses to highly pleasurable music. This work revealed that highly pleasurable subjective responses to music were correlated with activity in emotion- and reward-related brain regions, such as the amygdala and VS.[30–32] For example, one of the seminal functional neuroimaging studies of music listening focused on the neural correlates of musical chills, which are highly pleasurable responses to music.[31] In this study, the authors used positron emission tomography (PET) imaging to identify brain regions associated with musical chills evoked by highly pleasing, self-selected music. They found that activity in the VS, amygdala, and mPFC was correlated with participant ratings of chill intensity—stronger musical chills were associated with greater activity in these regions. This work laid the foundation for much of the subsequent music- and emotion-related research.

Later work sought to characterize more precisely the timing of activity in reward-related regions during the anticipation and experience of musical chills. Salimpoor and colleagues identified that activity in the NAcc increased during the peak emotional response to music (i.e., musical chills), while activity in the caudate was greatest during the anticipation of musical chills.[33] To complement these functional magnetic resonance imaging (fMRI) results, the authors used PET imaging to directly examine the role of dopamine in response to musical chills. Increased dopamine transmission was observed in both the dorsal and ventral striatum during the most pleasurable aspects of music, that is, those musical moments that evoked chills. The regions with the greatest changes in dopamine binding were the right-hemisphere caudate and NAcc. This study directly implicates dopamine release during musical pleasure, indicating that rewarding music has similar properties to other rewarding experiences, such as monetary gain and social stimulation.

While this work indicates that pleasurable music engages similar brain structures to other rewarding experiences, more recent work has investigated the idea that music itself can serve as a reward. One recent fMRI study investigated the neural responses to music in a reward-learning context.[34] Taking an established reward prediction error task and substituting music (where consonant music is assumed as a reward, and dissonant music is punishment), the authors identified that the NAcc responded to reward prediction errors in music. Interestingly, this suggests that the NAcc responds similarly to musical reward as to other pleasurable experiences, such as a monetary reward. One important caveat to mention here is that consonance is not always naturally rewarding, nor dissonance naturally displeasing.[17,35,36] As such, using consonant music as a reward is a somewhat artificial paradigm that may not translate into listening to music in a more naturalistic context. Still, the results of this study indicate that music itself can serve as a reward, and engages the same brain regions as other rewarding stimuli.

In addition to neuroimaging results, deep brain stimulation (DBS) has also pointed to the role of the NAcc in musical pleasure.[37] In one case study, a patient undergoing DBS to the NAcc for obsessive-compulsive disorder was found to show substantial changes in musical reward. Specifically, during DBS, the patient felt an intense pleasure while listening to the music of Johnny Cash, at the exclusion of any other musical artists or genres. That is, NAcc stimulation led to intense musical pleasure, although only for a single musical artist. While it is unclear why stimulation of the NAcc may modulate musical preferences so drastically, this provides converging evidence that the NAcc is involved in musical reward.

Interactions between the auditory and reward systems

While it seems clear that the reward system, and more specifically, the NAcc plays an important role in musical reward, further work has pointed to the role of the NAcc in a broader network, including interactions with the auditory system and other structures within the reward system.

While not specifically investigating musical reward or pleasure, prior work has identified the functional network underlying music-evoked "joy."[38] This work first identified increased overall activity in the auditory cortex (AC) for joyful (as compared with fearful) music. This suggests that the AC plays a role in musical emotions beyond simply

responding to acoustical features of the music. This finding is paralleled in research on visual aesthetics, showing that visual cortical regions respond more strongly to aesthetically appealing faces and artworks.[39,40] When investigating interactions between neural regions using functional connectivity analyses, the authors identified increased connectivity between the AC and reward-related regions during joyful music.[38] Similarly, and more specifically focusing on musical reward, one fMRI study indicated that interactions between the NAcc and auditory cortices predicted the reward value of a piece of music.[41] In this task, participants listened to several novel musical excerpts and were asked to identify how much money they were willing to spend to purchase the pieces of music. The reward value (i.e., the amount of money spent) was positively correlated with activity in the NAcc and connectivity between the NAcc and superior temporal gyrus (STG). More rewarding pieces of music were associated with both greater activity and connectivity of these regions. This work suggests that structures in the dopamine reward network work in consort with sensory regions critical for auditory perception while listening to highly pleasurable music.

A recent paper sought to test the prediction that a key aspect of music-evoked pleasure is surprise, and that surprising moments in music would be associated with greater NAcc activity and connectivity between the NAcc and STG.[42] Here, participants listened to entire musical pieces, which included several "surprising" moments (as identified by trained musical experts). The authors found that increasing surprise was associated with greater activity in both STG and VS, but that this was modulated by individual differences in musical reward. That is, individuals who had a higher tendency to experience music as pleasurable (based on continuous ratings of pleasantness while listening to music) showed greater changes in NAcc activity during musical surprise, as compared with individuals with less of a tendency to find music pleasurable. However, this effect was not seen in the STG activity. The authors also investigated the connectivity between the NAcc and STG during surprising moments and found that individuals with high musical pleasure showed greater connectivity between these regions during certain musical pieces. This suggests that not only musical pleasure during listening, but individual differences in musical pleasure also influence activity within and connectivity between reward and auditory regions.

Structural imaging provides converging support for the evidence found using functional connectivity methods, suggesting that individual differences in musical reward are related to connectivity between auditory and reward-related regions. In one study, authors investigated individual differences in musical reward experience and its relationship to structural connectivity of the STG.[43] Using a seed region in the posterior STG, they identified that individuals who more frequently experienced chills during music listening had higher tract volume (i.e., greater white matter connectivity) between the pSTG and emotion-related regions, including the anterior insula (aIns) and mPFC. The NAcc was not higher in tract volume in the individuals who experienced chills; however, tracts from the NAcc were a moderator of the relationship between chills and tract volume in the pSTG to emotion-related regions. Among participants who experienced chills, those who showed less volume in the pSTG−NAcc tract had a larger volume from pSTG to the anterior insula and mPFC. This inverse relationship between auditory−NAcc and auditory-to-emotion-related connectivity patterns was not observed in participants who did not experience chills. STG connections to aIns and orbitofrontal cortex (OFC) may include parts of the arcuate fasciculus/superior longitudinal fasciculus, extreme capsule fiber system, uncinate fasciculus, and inferior frontooccipital fasciculus. In contrast, it is unclear how the tracts identified between the STG and NAcc relate to known white matter pathways. Tractography studies show that seeding the NAcc shows mainly projections to the frontal and temporal cortices;[44] while some tracts go toward the temporal lobe, the STG is not a known terminal of tracts from the NAcc. We, therefore, expect that the tracts we identify between the STG and NAcc may belong to multiple white matter pathways, or could be connected through one or more shared common regions. While further validation is still necessary, this intriguing moderating relationship between the reward center and auditory pathways to other brain regions suggests that individual differences in aesthetic responses to music may differentially regulate the role of dopaminergic pathways in the interface between sensory and reward processing. As with the functional connectivity literature, this suggests that

stronger connections between auditory and reward-related regions are associated with increased musical pleasure on an individual-differences level.

Finally, brain stimulation studies also support the idea that connectivity between auditory and reward structures is a critical neural substrate of musical reward.[45] Mas-Herrero and colleagues[45] used transcranial magnetic stimulation (TMS) to excite or inhibit frontostriatal pathways during musical listening. Participants listened to both experimenter- and self-selected music that was chosen to elicit highly pleasurable emotional responses. During the task, participants listened to the musical selections while continuously rating their felt pleasure. Following each musical piece, participants indicated how much money they were willing to spend to purchase the experimenter-selected music. During excitation of the frontostriatal pathways via intermittent theta-burst stimulation, participants reported greater subjective pleasure and were willing to spend more money to purchase the experimenter-selected music; the opposite result was found during inhibition of the frontostriatal pathway. While not directly testing the involvement of the AC or auditory–striatal connectivity, this study provides evidence that connectivity of reward-related brain regions is causally involved in musical reward.

Musical anhedonia

Definition, prevalence, and measurement

The term "musical anhedonia" first appeared to describe an individual reporting a selective loss in emotional responses to music following brain damage.[46] While this term was first used in 2011,[46] case studies of patients exhibiting signs of musical anhedonia were reported as early as 1993.[47] Since this initial use of the term, "musical anhedonia" has come to describe more broadly a selective lack of pleasurable responses to music, even in individuals without brain damage. We distinguish between these two types of musical anhedonia: either present in individuals without any neurological damage (which we refer to as musical anhedonia without brain damage), or acquired musical anhedonia following brain damage. This distinction is similar to the distinction between congenital and acquired amusia, which are well-characterized deficits in music perception.[48,49] In terms of prevalence, work indicates that a small portion (ranging from 5% to 10%[27,28]) of the general population exhibits musical anhedonia without brain damage. Acquired musical anhedonia is likely even rarer. Most work on acquired musical anhedonia has been individual case studies, although one large group study (approximately 80 patients with focal brain damage) indicated only one possible case of acquired musical anhedonia.[50]

One defining aspect of musical anhedonia is that an individual classified as musically anhedonic must show normal hedonic responses to other rewarding stimuli. For example, individuals with musical anhedonia display typical responses to other rewarding stimuli, including visual art, emotional (nonmusical) sounds, and monetary reward.[28,29] That is, individuals with musical anhedonia report subjective feelings of pleasure and display physiological responses to these other types of rewarding stimuli, but not to music. A second defining characteristic is that the lack of rewarding responses to music must not be accompanied by a deficit in musical perception. That is, a lack of pleasure in response to music, if due to a perceptual deficit, such as hearing loss or congenital amusia, would *not* be considered musical anhedonia. Neuropsychological studies have illustrated a double dissociation between musical reward and music perception; for example, case studies have identified individuals with severe deficits in music perception who still have rewarding responses to music,[51] and case studies of patients with musical anhedonia illustrate preserved musical perceptual abilities.[46,52]

In early cases of acquired musical anhedonia, the criterion for classification as musically anhedonic was simply self-report: patients reported a loss of musical pleasure following brain damage. For musical anhedonia without brain damage, the standard measure is currently the Barcelona Musical Reward Questionnaire (BMRQ).[27] This questionnaire consists of 20 items on which individuals report their level of agreement (e.g., "I get emotional listening to certain pieces of music"). These items represent a range of musical experiences and can be classified into one of five categories: musical seeking, emotion evocation, mood regulation, sensorymotor, and social reward. Typically, participants are classified as musically anhedonic if scoring below 65 on the BMRQ[28,53] (see Fig. 1 for a depiction of the distribution of BMRQ scores). To rule out general anhedonia, individuals must display normal scores on a general anhedonia scale, such as the

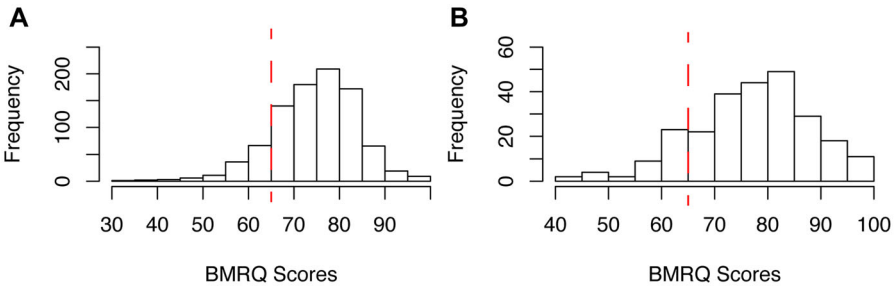

Figure 1. **Distribution of BMRQ scores from the (A) Spanish and (B) English versions of the scale. The number of participants is indicated by the height of the bar. Dashed red line indicates the cutoff score for musical anhedonia (65) as used in subsequent studies. This roughly corresponds to the lowest 10th percentile of scores. Data from Mas-Herrero *et al.*[27]**

Physical Anhedonia Scale[54] or the Snaith–Hamilton Pleasure Scale.[55] To rule out perceptual deficits, individuals must perform in the normal range on tests of musical perception, the most commonly used being the Montreal Battery for the Evaluation of Amusia.[56] In sum, to be characterized as having musical anhedonia, an individual must report a *selective* lack of musical pleasure *without* showing deficits in music perception. While musical anhedonia is typically defined by self-report, below we review experimental findings using psychophysiological, neuroimaging, pharmacological, and neuropsychological methods to identify physiological and neural correlates of musical anhedonia with and without brain damage.

Experimental findings

Psychophysiological

Physiologically, individuals with musical anhedonia show limited responses to musical pleasure.[28,53] In one of the earliest studies of musical anhedonia, participants performed a monetary incentive delay task and a musical listening task while heart rate (HR) and skin conductance responses (SCRs) were measured.[28] Individuals with musical anhedonia, as defined by the BMRQ, showed significantly reduced SCR and HR during "high pleasure" moments in the music (particularly the most pleasing musical moments, those that commonly evoke musical chills in nonmusically anhedonic individuals), as compared with individuals with normal and highly hedonic scores on the BMRQ. Conversely, musically anhedonic individuals showed nearly identical physiological responses to monetary rewards as individuals scoring higher on the BMRQ. This indicates that individuals with musical anhedonia do not simply have deficits in physiological responsiveness to reward in general, but display a selective lack of physiological responsiveness to highly pleasing music (Fig. 2).

Pharmacological

As discussed above, neuroimaging work has indicated that subcortical structures in the dopaminergic system, more specifically those in the VS, are involved in musical reward. While this work indirectly investigates the role of dopamine in musical pleasure, pharmacological studies have been used to directly manipulate dopaminergic function during music listening. Ferreri and colleagues administered a dopamine precursor (levodopa), a dopamine antagonist (risperidone), or placebo (lactose) to participants prior to listening to music.[57] After receiving the drug or placebo, participants listened to experimenter- and self-selected music while continuously rating the pleasure they experienced. Additionally, participants completed an auction task, where they indicated whether or not they would purchase the music with their own money. Participants were more likely to report high pleasure, show increased skin conductance, and spend more money to purchase the music after receiving levodopa than risperidone. Taken together, these results suggest that increases in dopamine are associated with increased musical pleasure, from a subjective, physiological, and motivational perspective, and that the converse is associated with decreases in dopamine. This work also suggests a causal role of dopamine in musical pleasure, such that increasing dopamine leads to increased musical pleasure, and decreasing dopamine leads to musical anhedonia.

In a similar vein, Mallik and colleagues administered a μ-opioid antagonist naltrexone (NTX) to individuals while listening to music and

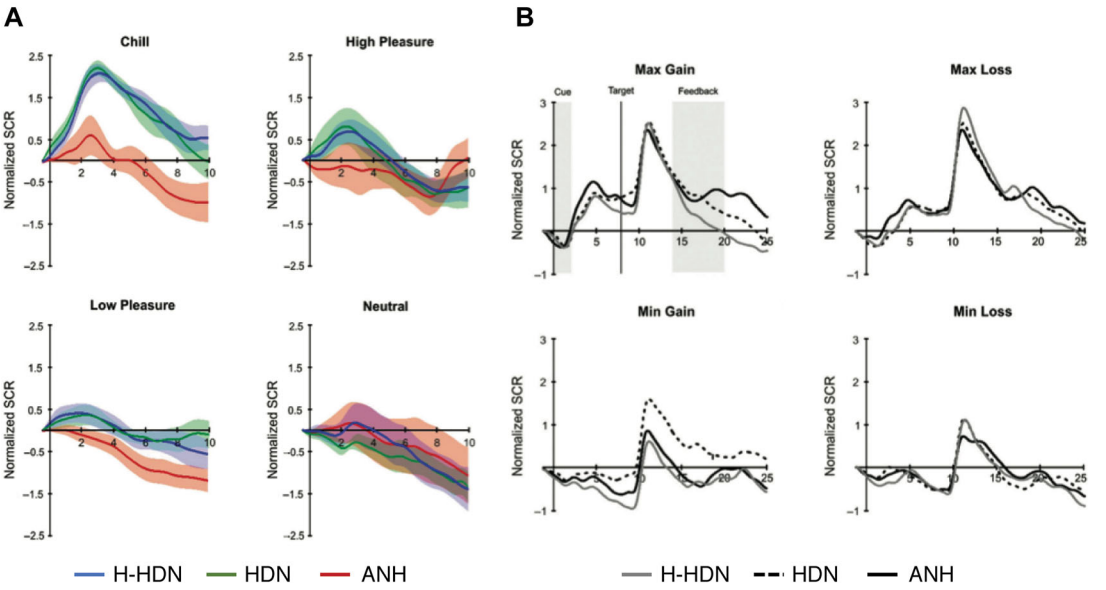

Figure 2. (A) Skin conductance responses to musical chills, high pleasure, low pleasure, and neutral moments during music listening. Musically anhedonic individuals (ANH) show decreased SCR compared with hedonic (HDN) and highly hedonic (H-HDN) individuals. (B) Skin conductance responses to a delayed monetary incentive task. There were no statistically significant differences between groups for this task. From Mas-Herrero *et al.*[28] Reproduced with permission from the publisher.

undergoing physiological recordings.[58] While not directly modulating dopamine, NTX blocks μ-opioid receptors and has been shown to induce general anhedonia. After receiving NTX, participants reported significantly less pleasure while listening to pleasurable music (music that was self-selected by the participants to be highly pleasurable). NTX had no effect on subjective pleasure during listening to "neutral" music (experimenter-selected music that had been previously rated as neutral by participants). Similarly, NTX administration was associated with reduced zygomatic and corrugator muscle activity while listening to both pleasurable and neutral music. The authors suggest that this indicates reduced emotional responsiveness to music, as well as a subjective reduction in musical pleasure. Overall, these results suggest a possible role for opioid receptors in musical anhedonia and musical reward more broadly.

Neuroimaging

As with peripheral physiological responsiveness, individuals with musical anhedonia also show reduced neural activity in response to musical, but not monetary, reward. Martínez-Molina and colleagues compared musically anhedonic participants to participants with typical hedonic responses to music (hedonic) and participants with high sensitivity to musical reward (hyperhedonic).[53] Participants completed both music listening and monetary reward tasks while undergoing fMRI and physiological recordings. Replicating their prior work,[28] musically anhedonic individuals showed reduced SCR to musical, but not monetary, reward. Additionally, participants with normal and high musical reward showed increased activity in the NAcc (bilateral) during both musical and monetary rewards. However, the individuals with musical anhedonia only showed increased NAcc activity during monetary, but *not* musical reward (Fig. 2A). This indicates that musical anhedonia is correlated with a lack of responsiveness to music in reward-related brain regions. That is, individuals with musical anhedonia show both impairments in peripheral physiological responses and neural responses to typically rewarding musical moments.

In addition to showing decreased NAcc activity to musical reward, musically anhedonic individuals also showed reduced connectivity between reward and auditory regions.[53] Here, the authors performed whole-brain psychophysiological interaction analysis to investigate connectivity between

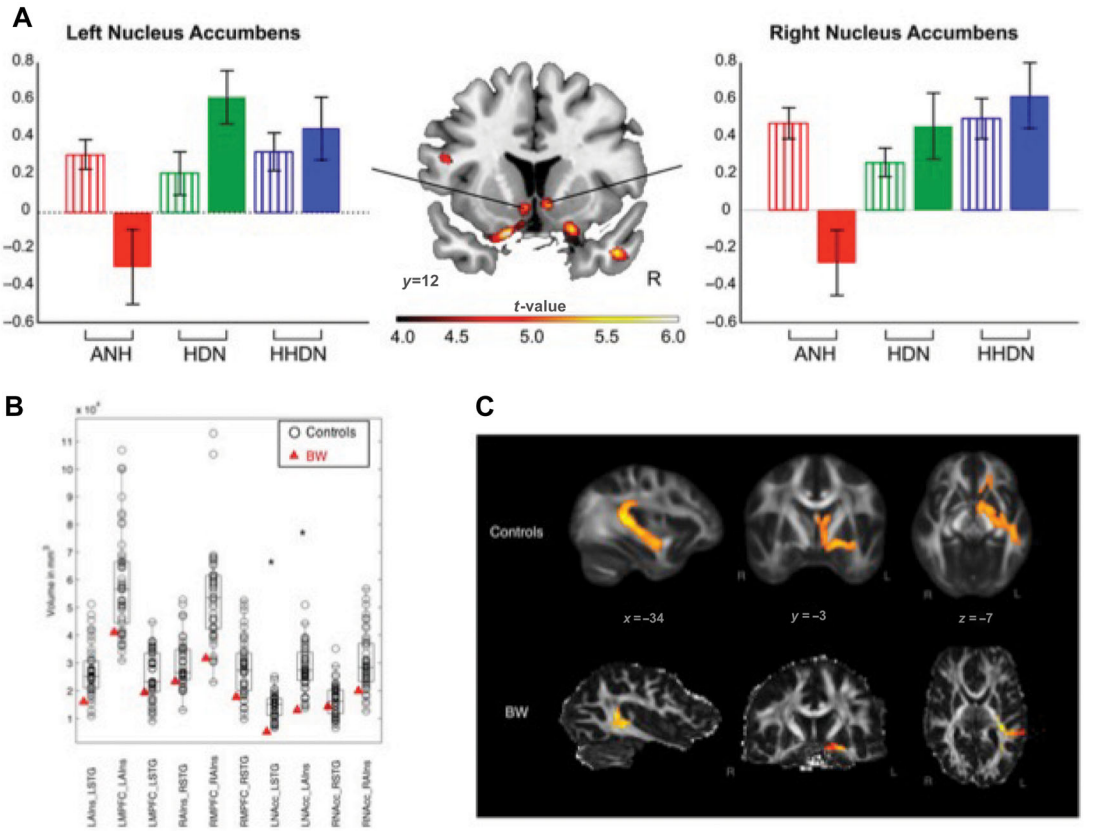

Figure 3. (A) Bar graphs represent contrast estimates with SEM of the NAcc peak in the group by task contrast. Striped bars represent the gambling task, while solid bars represent the musical task. From Martínez-Molina *et al.*[53] (B) Volume of each tract comparing patient BW with healthy comparisons. From Loui *et al.*[59] (C) Averaged tract between the STG and NAcc for controls (top) and patient BW (bottom). From Loui *et al.*[59] ANH, anhedonic; HDN, hedonic; HHDN, highly hedonic.

bilateral superior temporal gyri (STG) and the rest of the brain. They found decreased connectivity between the right STG and the right NAcc during music listening in musically anhedonic participants, which was significantly lower than the connectivity between the STG and NAcc in typically hedonic and highly hedonic individuals. This suggests that not only is the NAcc less active during music listening in musically anhedonic individuals, but that musical anhedonia is associated with deficits in the connectivity between regions critical for auditory perception and regions critical for reward and motivation more broadly.

Complementing these functional imaging results is recent work investigating the structural connectivity of musical anhedonia. Loui and colleagues[59] identified an individual case study with severe musical anhedonia (patient BW). Compared with healthy control subjects, BW showed significantly lower tract volume but higher fractional anisotropy in white matter tracts between the left STG and the left NAcc (Fig. 3B and C). This is similar to the result described above using functional imaging; however, the structural analysis revealed decreased tract volume between the *left* NAcc and STG, whereas the functional result indicated decreased connectivity between the *right* NAcc and STG. As current research on the neural correlates of musical anhedonia is still relatively sparse, future research will need to further examine the possible laterality effects of musical anhedonia.

A recent group-level study investigated the connectivity between the STG and NAcc, via the OFC, and how this connectivity varied as a function of individual differences in musical reward.[60] The authors identified a relationship between musical

Table 1. Summary of results from neuropsychological studies of acquired musical anhedonia

Citation	Study type	Lesion location	Lesion hemisphere
Mazzoni *et al.*[47]	Case	Temporoparietal	RH
Griffiths *et al.*[61]	Case	Insula/amygdala	LH
Satoh *et al.*[46]	Case	Temporoparietal, frontal	RH
Hirel *et al.*[62]	Case	Superior temporal gyrus	RH
Satoh *et al.*[52]	Case	Putamen	RH
Belfi *et al.*[50]	Group	n/a	n/a

reward, as measured by the BMRQ, and connectivity between the STG and OFC, in a tract that likely passes through the aIns. This relationship was observed only in the right hemisphere—individuals with musical anhedonia showed higher levels of axial diffusivity in this pathway. However, when looking at connectivity between the OFC and NAcc, they identified significant relationships with BMRQ scores in both hemispheres. In examining the individual differences among the healthy control subjects, Loui *et al.*[59] also found that tracts from both the left and right STG showed significant correlations with individual differences in music reward. These included tracts between the left STG and aIns, between the right STG and mPFC, and between the right STG and NAcc. Among these, the right STG and mPFC correspond well to the findings by Martínez-Molina *et al.*[53] on tracts between the STG and OFC, whereas the aIns was not reported. While Loui *et al.*[59] found significant correlations in tracts between the STG and NAcc, Martínez-Molina *et al.*[53] found that most of their sample had very few streamlines directly between the STG and NAcc; however, the latter sample contained more participants who were musically anhedonic as defined by the BMRQ. Across the two papers, the fact that the sample with more musical anhedonics had fewer streamlines may suggest that the tracts are related to music and reward; furthermore, rather than being a direct pathway, these streamlines belong to more than one white matter pathway and/or may run through multiple other waystations. Overall, these results suggest that connectivity between the auditory and reward systems varies as a function of individual differences in musical reward, and is a key component of specific musical anhedonia.

Neuropsychological

While neuroimaging results have converged to indicate decreased activity and connectivity between auditory and reward regions in musical anhedonia without brain damage, neuropsychological evidence has been somewhat mixed. While group-level studies of musical anhedonia without brain damage are possible, given a prevalence of around 3–10% of the healthy population, most studies of acquired musical anhedonia are isolated case studies (see a summary of the following case studies in Table 1 and a visual depiction of the lesion locations in Fig. 4).

The first identified case of musical anhedonia reports a patient with a lesion to the right temporoparietal area. Prior to his brain injury, he was an amateur guitar player. After his brain injury, he showed no cognitive deficits, but complained of a lack of appreciation of music, saying that it sounded unemotional and detached. The authors state that he "presented with loss of the gestalt capacity to process music, with the consequent loss of aesthetic pleasure."[47] However, he performed normally on tasks that assessed structural aspects of the music, such as identifying aspects of rhythm, melody, and harmony. When listening to piano and orchestral pieces, the patient complained that the music sounded "flat" with "no emotion."

Chronologically, the second reported case is a patient with lesions to the left insula and amygdala, who showed preserved musical perceptual abilities but a lack of emotional response to music.[61] The patient held a job as a radio announcer and previously had derived great pleasure from listening to music. Prior to his injury, the patient would feel intense emotional "transformations," similar to musical chills, when listening to certain Rachmaninoff preludes. After his injury, the patient no longer felt this highly pleasurable response when listening to these same pieces. In addition, he had a general loss of pleasurable emotional responses to music. He did not lose any general musical perceptual abilities and did not show signs of anhedonia for any other activities.

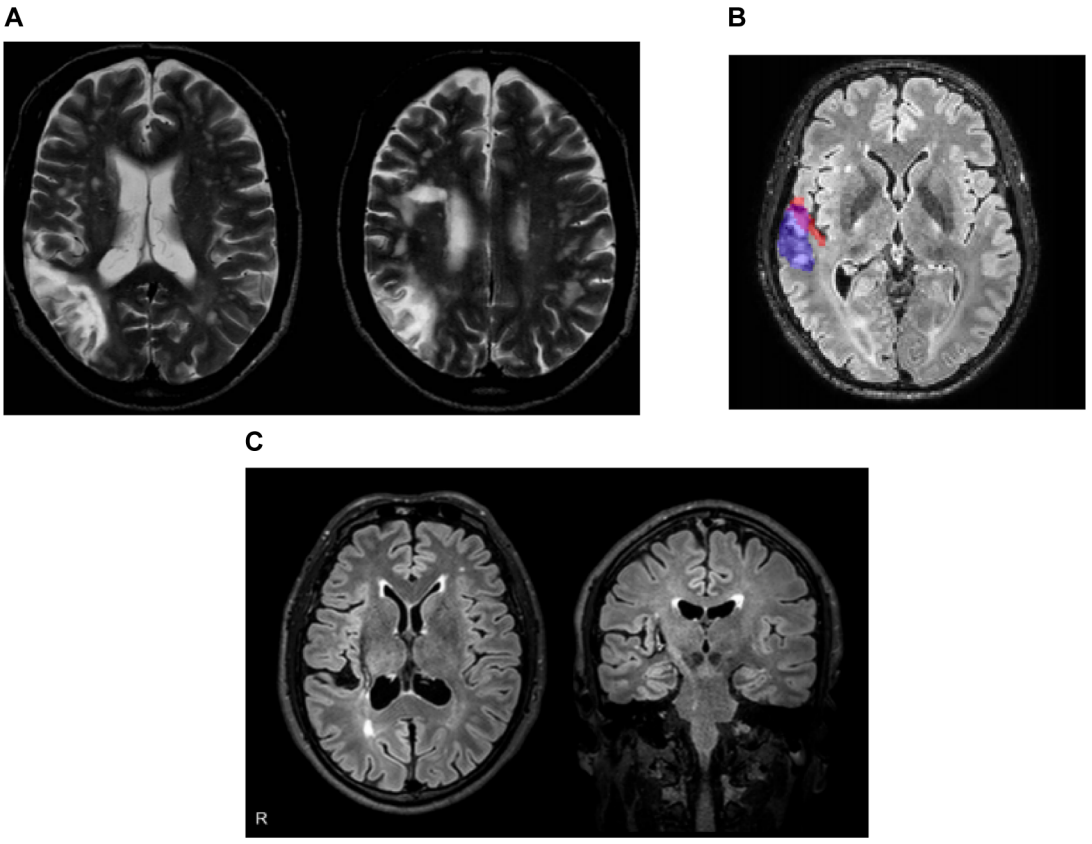

Figure 4. **Lesion locations from three previously published cases of acquired musical anhedonia. All reproduced with permission of the publishers. (A) T2-weighted MRI depicting a lesion to the RH inferior parietal lobule. Reproduced from Satoh *et al.*[46] with permission from the publisher (Taylor & Francis Ltd). (B) FLAIR-sequence MRI depicting a lesion to the RH superior temporal gyrus (depicted in purple, Heschl's gyrus is depicted in pink). Reproduced from Hirel *et al.*[62] (C) FLAIR-sequence MRI depicting a lesion to the RH putamen. All images in radiological convention (right hemisphere on the left side of the page). Reproduced from Satoh *et al.*[52] with permission from the publisher (Taylor & Francis Ltd).**

A third case reports on a patient with damage to the right inferior parietal lobule. After his stroke, he complained of an inability to experience emotion from listening to music. This patient was "unable to have an emotional experience at any time when listening to music; he could not elicit interest in any music, even his favorite music or artists."[46] He did not show this loss of pleasure in any other activities, including eating food, viewing works of art, and spending time with his family. The patient also performed in the normal range on music perceptual tests and showed normal emotion identification in music. Therefore, this patient showed only the selective loss of pleasure when listening to music, which the authors were the first to coin as "musical anhedonia." A fourth case was reported in French of an amateur musician with a lesion to the right superior temporal lobe after an ischemic stroke.[62]

A fifth and final case study reports a patient with acquired musical anhedonia following hemorrhage to the right hemisphere putamen.[52] This individual was a professional musician who, after his brain injury, had no subjective experience of emotion in response to music. Prior to his brain lesion, he frequently felt musical chills, but this did not occur following his lesion. He could recognize music and had intact music perception and could perform music as well as before his injury. He reported continued enjoyment and pleasure from other activities, such as viewing art and eating food. Here, the authors describe musical anhedonia as a "disconnection syndrome," since this patient had

damage to the white matter tract connecting the insula to the AC. This conception of musical anhedonia as a disconnection syndrome is consistent with neuroimaging findings of impaired connectivity between auditory and reward regions.

Only one prior neuropsychological study has attempted to identify musical anhedonia in a large group of patients with focal brain damage. Belfi and colleagues studied 78 patients with focal brain damage to a wide variety of brain regions.[50] Patients completed the BMRQ to assess their current musical reward state, as well as a retrospective questionnaire of their musical behaviors and feelings prior to and following their brain injury. As there is no standard threshold for diagnosing acquired musical anhedonia following brain damage other than subjective report by the patient, participants in this study were classified as musically anhedonic if they scored more than 1.5 SD below the mean on either the BMRQ or the retrospective questionnaire, while subsequently presenting normally on a scale to measure generalized anhedonia. In addition to self-report, collaterals (a close relative or friend) completed a questionnaire asking about changes in the patients' musical behaviors following their brain injuries. Despite a large population of brain-damaged patients, only a single patient presented with a possible case of musical anhedonia. This individual had damage to the right hemisphere putamen and internal capsule, which is consistent with damage found in a prior case study.[52]

It is worth briefly noting here that individuals with brain damage can also exhibit extremely high hedonic responses to music, or an "abnormal craving for music," which has been termed "musicophilia."[63] As with musical anhedonia, musicophilia has not been widely studied. However, prior work indicates that musicophilia is a somewhat common symptom of certain neurological disorders, which has shed light onto the neural substrates of this abnormal hedonic response to music.[63–65] Individuals with frontotemporal dementia who experience musicophilia have increased gray matter volume in the left hemisphere hippocampus and decreased gray matter volume in the posterior parietal cortex, medial OFC, and frontal pole. The authors suggest that, in this group of patients, musicophilia reflects a shift toward enjoyment of abstract activities due to impairments in social behaviors.[63] A more recent study in patients with dementia indicated that musicophilia was associated with gray matter decreases in a network including both the striatum and AC.[65] This seems consistent with the idea that changes in musical reward are associated with changes in the connectivity of the auditory and reward systems. However, the directionality of this effect—that is, whether damage to these systems leads to *less* enjoyment of music (musical anhedonia) or *more* enjoyment of music (musicophilia) is still unclear.

Overall, the neuropsychological results suggest two things: first, it appears that acquired musical anhedonia is quite rare, most likely rarer than musical anhedonia in the healthy population. When taken from a clinical perspective, this may suggest one reason why music therapy can be used successfully in a wide variety of neurological disorders.[66–70] It could be the case that intact musical reward is necessary for successful music therapy. Therefore, the use of music in neurological disorders may be beneficial precisely because the ability to enjoy music is relatively resistant to neurological damage. Prior work using music therapy in stroke patients has suggested that this may be the case; for example, recent work investigated the relationship between musical reward and outcomes of music-supported therapy in patients with subacute stroke.[71] Patients who experienced greater musical reward (as measured on the sensorimotor component of the BMRQ) showed more improvement in motor symptoms after receiving music-supported therapy than patients who had less of a capacity to experience pleasure from music.

Second, the above results indicate that acquired musical anhedonia can be the result of brain damage to a variety of regions. It may be surprising, given the consistency of neuroimaging results in healthy individuals with musical anhedonia, that case studies of acquired musical anhedonia show quite heterogeneous lesion locations. In looking for commonalities between the reported case studies of acquired musical anhedonia, there seems to be somewhat consistent damage in reward- and emotion-related regions, as regions in the striatum, amygdala, and insula are implicated in several of reported case studies. Still, as with neuroimaging results, the possible laterality effects are unknown, although the reported case studies are majority right-hemisphere lesions.

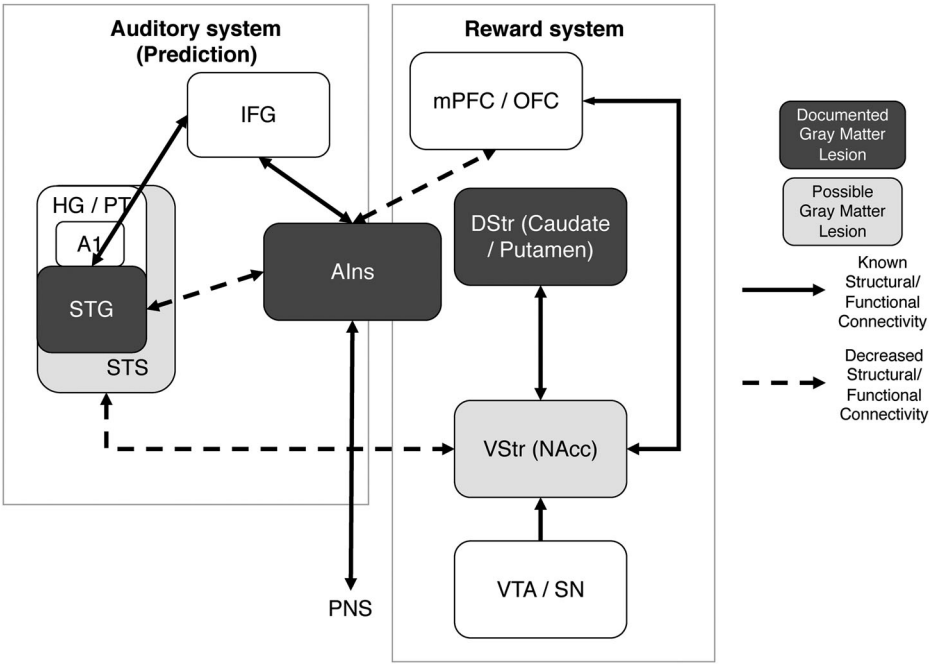

Figure 5. **A neuroanatomical model of musical reward. Dark gray regions indicate known lesions in musical anhedonia. Light gray regions indicate possible lesions. Solid arrows indicate known patterns of structural or functional connectivity, and dashed arrows indicate known differences in structural or functional connectivity that are related to decreased musical reward. A1, primary auditory cortex; HG/PT, Heschl's gyrus/planum temporale; STG, superior temporal gyrus; STS, superior temporal sulcus; IFG, inferior frontal gyrus; aIns, anterior insula; mPFC/OFC, medial prefrontal cortex/orbitofrontal cortex; NAcc, nucleus accumbens; VTA/SN, ventral tegmental area/substantia nigra; DStr, dorsal striatum; PNS, peripheral nervous system.**

What is the nature of the interaction between auditory to reward systems?

Having reviewed the literature on musical anhedonia and individual differences in music reward sensitivity, it is clear that music can engage the human reward system. The AC and surrounding areas in the superior temporal lobe show structural and functional connectivity to areas in the human reward system and individual differences in these connectivity patterns predict differences in reward sensitivity. Specifically, the belt and parabelt regions of the auditory system, centering around the STG, which receives input from primary auditory regions, are structurally and functionally connected to other regions involved in higher order auditory processing, such as the divisions of the inferior frontal gyrus, as well as the aINS. The aINS, with its dense connections to the peripheral nervous system, as well as to the OFC and ventromedial prefrontal cortex, can be thought of as an integrative region that serves both reward and auditory functions.[72] In addition, the STG is structurally and functionally connected to the NAcc, which is connected to the caudate, mPFC, and SN via the dopaminergic system. Thus, the STG, aIns, and NAcc are three central regions that overlap in their connectivity patterns with both classic auditory and classic reward regions, as seen from multiple studies reviewed above. The best available evidence suggests that these core regions, and the auditory and reward-sensitive regions that surround them, constitute the key auditory prediction and reward network that enables the experience of musical reward, and the lack thereof in musical anhedonia. Figure 5 lays out our neuroanatomical model of musical reward; this model shows the regions of interest as well as the connections within and between the auditory and reward systems.

The model raises important questions for future studies:

1. To what extent do the connections between each anatomical region reflect direct structural

connections? On the other hand, to what extent do these connections reflect functional coupling as a result of routing through other regions and/or multiple white matter pathways? These questions can be addressed in future research by closely comparing the results of structural and functional connectivity studies *in vivo* with results from dissection and tracer studies.

2. How do perturbations in one node of the identified system affect other nodes in the system? These can be addressed using a combination of brain stimulation (e.g., TMS/transcranial direct current stimulation/transcranial alternating current stimulation), functional neuroimaging, and computational modeling, with additional insights from different special populations, such as those with focal brain injury or neurodegenerative disorders.
3. Is the aINS truly part of both auditory and reward systems, and if so, is it equally engaged by other systems? In that regard, ample work suggests that the insula is involved in detecting salient events and switching between large-scale networks;[73] the present model is consistent with this view.

By defining such a model, we hope to ground future investigations concerning how specific regions might interact in such a way that enables music to acquire its reward value. In that regard, Meyer has long posited that the systematic fulfillment and violation of our expectations gives rise to emotion and meaning in music.[74] These expectations can be implicitly learned from exposure to musical stimuli as well as from sounds that adhere to gestalt principles,[75] analogous to statistical learning for language.[76] Bregman,[75] writing in the context of auditory gestalt psychology, makes a distinction between primitive perceptual and schema-driven organization. While he posits that primitives could be innate (but see Refs. 17 and 77), schema- or hypothesis-driven organization is driven by top-down knowledge that informs expectations, both of which are implicitly or statistically learned. Among different expectations, Huron further articulates a continuum ranging from schematic expectations to veridical expectations, with dynamically adaptive expectations in between.[78]

It is noteworthy that Meyer's seminal work intuited the now-influential free-energy principle.[79] The free-energy principle posits that organisms maintain homeostasis in their environment by continuously forming predictions and testing them to minimize prediction error.[80] Prediction is a function of perception, and minimizing prediction error is a function of learned actions. Hierarchical predictive coding[81] was demonstrated to explain receptive field effects in neurons of the visual cortex; this provides some confirmation for the idea that perception is a form of prediction. Evidence for predictive coding in the AC comes from fitting a model of prediction errors, derived from the stimulus sequence, on single-unit recordings from the AC of the anesthetized cat, which showed that prediction errors were a good fit for neuronal activity.[82] Ongoing efforts are underway to translate this model to human fMRI, electroencephalography, or magnetoencephalography data to identify neural substrates of predictive coding with sensitivity and precision.[83]

Predictive coding models of the perceptual system are related to reward prediction error models of the reward system, which have shown that dopaminergic neurons respond to predictive cues that code for reward, thus motivating reinforcement learning.[19] In the domain of music, Gold *et al.* showed that musical stimuli, specifically chords and chord progressions with consonant or dissonant endings, can generate rewards and reward prediction errors that motivate learning in a reinforcement-learning protocol.[34] This result shows that because of the systematic relationship between consonance and pleasure at least in most westernized listeners, music itself—specifically, consonant chord endings to chord progressions—can function both as a prediction (in this case, the chord progression) and a reward (in this case, consonant endings as opposed to dissonant endings).

In the above paradigm, musical chord progressions were designed to be both the predictive cue and the reward, such that listening to the music sets up the expectation for a reward. Two questions that follow from this study are: (1) Do musical anhedonics fail to learn the association between musical prediction and reward? and (2) In everyday listening situations where music is not explicitly set up as a reinforcement learning paradigm, when

does music serve as the predictive cue, and when does it serve as the reward?

While the answers to these two questions will be key to understanding how music becomes rewarding,[84] here, we point to one of the novel contributions of our model, which suggests a dissociation between different forms of predictions. Although there are connections between regions in the auditory and reward systems, many of the areas and connections within the auditory system, such as between the STG and IFG, are not in the reward system. This suggests that not all auditory predictions become rewarding. In other words, our model predicts that different connections from STG/STS have different functional consequences, depending on whether they activate the reward system.

Nevertheless, the fact that predictive processes are most likely involved calls for an active view of listening, where the brain is constantly forming predictions and testing them to form prediction errors.[85] This active view of perception, a novel interpretation of the classic enactive view by Varela *et al.*,[86] stands in contrast to the classic, bottom-up view of the perception-to-cognition pathway.

This also differs in emphasis from a view of the AC (STG) as a waystation, accomplishing the function of filtering or attentional selection, or otherwise acting as a computational hub toward the different streams of higher level audition.[87] Dual-stream models of auditory perception, including speech and language, as well as music and singing, generally posit an action-oriented dorsal "where" pathway and a semantic- or object-oriented ventral "what" pathway.[88–90] These models need to be integrated with predictive coding accounts to reveal how biasing predictions might direct connections differentially to dorsal versus ventral streams, and how reward might motivate learning within each stream.

Summary

Taken together, studies from music and reward, specifically in musical anhedonia, point to the intricate, intimate, and flexible coupling between the auditory and reward systems. Because musical anhedonia is a specific disorder that affects the intersection of auditory and reward systems, it is a unique model system for understanding communications among disparate networks in the human brain, and how these distal communications might affect motivated behavior.

Acknowledgments

The authors would like to thank Finn Upham for facilitating their initial conversation on musical anhedonia on the So Strangely Podcast. Funding for the present work includes NSF-STTR #1720698 and a grant from Grammy Foundation to P.L.

Author contributions

Both authors contributed to the conception and writing of the manuscript.

Competing interests

The authors declare no competing interests.

References

1. Honing, H. 2018. On the biological basis of musicality. *Ann. N.Y. Acad. Sci.* **1423:** 51–56.
2. Belfi, A.M., A. Kasdan, J. Rowland, *et al.* 2018. Rapid timing of musical aesthetic judgments. *J. Exp. Psychol. Gen.* **147:** 1531–1543.
3. Brattico, E. & M. Pearce. 2013. The neuroaesthetics of music. *Psychol. Aesthet. Creat. Arts* **7:** 48–61.
4. Strait, D.L. & N. Kraus. 2014. Biological impact of auditory expertise across the lifespan: musicians as a model of auditory learning. *Hear. Res.* **308:** 109–121.
5. Habibi, A., V. Wirantana & A. Starr. 2014. Cortical activity during perception of musical rhythm; comparing musicians and non-musicians. *Psychomusicology* **24:** 125–135.
6. Doelling, K.B. & D. Poeppel. 2015. Cortical entrainment to music and its modulation by expertise. *Proc. Natl. Acad. Sci. USA* **112:** E6233–E6242.
7. Oechslin, M.S., D. Van De Ville, F. Lazeyras, *et al.* 2012. Degree of musical expertise modulates higher order brain functioning. *Cereb. Cortex* **23:** 2213–2224.
8. Honing, H. 2012. Without it no music: beat induction as a fundamental musical trait. *Ann. N.Y. Acad. Sci.* **1252:** 85–91.
9. Panksepp, J. 1995. The emotional sources of "chills" induced by music. *Music Percept.* **13:** 171–207.
10. Freeman, W.J. 1998. A neurobiological role of music in social bonding. In *The Origins of Music.* B.M.N. Wallin & S. Brown, Eds.: 411–424. Cambridge, MA: MIT Press.
11. Dunbar, R. 2012. Evolutionary basis of the social brain. In *Oxford Handbook of Social Neuroscience*. J. Decety & J. Cacioppo, Eds.: 28–38. Oxford University Press.
12. Savage, P.E., S. Brown, E. Sakai, *et al.* 2015. Statistical universals reveal the structures and functions of human music. *Proc. Natl. Acad. Sci. USA* **112:** 8987–8992.
13. Mehr, S.A., M. Singh, H. York, *et al.* 2018. Form and function in human song. *Curr. Biol.* **28:** 356–368.e5.
14. Trainor, L.J. & L.K. Cirelli. 2015. Rhythm and interpersonal synchrony in early social development. *Ann. N.Y. Acad. Sci.* **1337:** 45–52.

15. Tarr, B., J. Launay & R.I.M. Dunbar. 2014. Music and social bonding: "self-other" merging and neurohormonal mechanisms. *Front. Psychol*. **5:** 1–10.
16. Cirelli, L.K., Z.B. Jurewicz & S.E. Trehub. 2019. Effects of maternal singing style on mother–infant arousal and behavior. *J. Cogn. Neurosci.* **26:** 1–8.
17. McDermott, J.H., A.F. Schultz, E.A. Undurraga, *et al*. 2016. Indifference to dissonance in native Amazonians reveals cultural variation in music perception. *Nature* **535:** 547–550.
18. Olds, J. & P. Milner. 1954. Positive reinforcement produced by electrical stimulation of septal area and other regions of rat brain. *J. Comp. Physiol. Psychol.* **47:** 419–427.
19. Schultz, W., P. Dayan & P.R. Montague. 1997. Neural substrate of prediction and reward. *Science* **275:** 1593–1599.
20. Purves, D., R. Cabeza, S.A. Huettel, *et al.* 2008. *Cognitive Neuroscience*. Sunderland: Sinauer Associates, Inc.
21. Knutson, B., A. Westdorp, E. Kaiser, *et al*. 2000. FMRI visualization of brain activity during a monetary incentive delay task. *Neuroimage* **12:** 20–27.
22. Izuma, K., D.N. Saito & N. Sadato. 2008. Processing of social and monetary rewards in the human striatum. *Neuron* **58:** 284–294.
23. Spreckelmeyer, K.N., S. Krach, G. Kohls, *et al*. 2009. Anticipation of monetary and social reward differently activates mesolimbic brain structures in men and women. *Soc. Cogn. Affect. Neurosci.* **4:** 158–165.
24. Zatorre, R.J. 2018. Why do we love music? *Cerebrum* **2018:** pii: cer-16-18.
25. Dube, L. & J. Le Bel. 2003. The content and structure of laypeople's concept of pleasure. *Cogn. Emot.* **17:** 263–295.
26. Silvia, P.J. & E.C. Nusbaum. 2011. On personality and piloerection: individual differences in aesthetic chills and other unusual aesthetic experiences. *Psychol. Aesthet. Creat. Arts* **5:** 208–214.
27. Mas-Herrero, E., J. Marco-Pallares, U. Lorenzo-Seva, *et al*. 2013. Individual differences in music reward experiences. *Music Percept*. **31:** 118–138.
28. Mas-Herrero, E., R.J. Zatorre, A. Rodriguez-Fornells, *et al*. 2014. Dissociation between musical and monetary reward responses in specific musical anhedonia. *Curr. Biol.* **24:** 1–6.
29. Mas-Herrero, E., M. Karhulahti, J. Marco-Pallares, *et al*. 2018. The impact of visual art and emotional sounds in specific musical anhedonia. *Prog. Brain Res.* **237:** 399–413.
30. Blood, A.J., R.J. Zatorre, P. Bermudez, *et al*. 1999. Emotional responses to pleasant and unpleasant music correlate with activity in paralimbic brain regions. *Nat. Neurosci.* **2:** 382–387.
31. Blood, A.J. & R.J. Zatorre. 2001. Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *Proc. Natl. Acad. Sci. USA* **98:** 11818–11823.
32. Menon, V. & D.J. Levitin. 2005. The rewards of music listening: response and physiological connectivity of the mesolimbic system. *Neuroimage* **28:** 175–184.
33. Salimpoor, V.N., M. Benovoy, K. Larcher, *et al.* 2011. Anatomically distinct dopamine release during anticipation and experience of peak emotion to music. *Nat. Neurosci.* **14:** 257–262.
34. Gold, B.P., E. Mas-Herrero, Y. Zeighami, *et al*. 2019. Musical reward prediction errors engage the nucleus accumbens and motivate learning. *Proc. Natl. Acad. Sci. USA* **116:** 1–6.
35. Popescu, T., M.P. Neuser, M. Neuwirth, *et al*. 2019. The pleasantness of sensory dissonance is mediated by musical style and expertise. *Sci. Rep.* **9:** 1–11.
36. Dellacherie, D., M. Roy, L. Hugueville, *et al.* 2011. The effect of musical experience on emotional self-reports and psychophysiological responses to dissonance. *Psychophysiology* **48:** 337–349.
37. Mantione, M., M. Figee & D. Denys. 2014. A case of musical preference for Johnny Cash following deep brain stimulation of the nucleus accumbens. *Front. Behav. Neurosci.* **8:** 152.
38. Koelsch, S., S. Skouras, T. Fritz, *et al*. 2013. The roles of superficial amygdala and auditory cortex in music-evoked fear and joy. *Neuroimage* **81:** 49–60.
39. Belfi, A.M., E.A. Vessel, A. Brielmann, *et al*. 2019. Dynamics of aesthetic experience are reflected in the default-mode network. *Neuroimage* **188:** 584–597.
40. Chatterjee, A., A. Thomas, S.E. Smith, *et al*. 2009. The neural response to facial attractiveness. *Neuropsychology* **23:** 135–143.
41. Salimpoor, V.N., I. van den Bosch, N. Kovacevic, *et al.* 2013. Interactions between the nucleus accumbens and auditory cortices predict music reward value. *Science* **340:** 216–219.
42. Shany, O., N. Singer, B.P. Gold, *et al*. 2019. Surprise-related activation in the nucleus accumbens interacts with music-induced pleasantness. *Soc. Cogn. Affect. Neurosci.* **14:** 459–470.
43. Sachs, M.E., R.J. Ellis, G. Schlaug, *et al.* 2016. Brain connectivity reflects human aesthetic responses to music. *Soc. Cogn. Affect. Neurosci.* **11:** 884–891.
44. Baliki, M.N., A. Mansour, A.T. Baria, *et al*. 2013. Parceling human accumbens into putative core and shell dissoiates encoding of values for reward and pain. *J. Neurosci.* **33:** 16383–16393.
45. Mas-Herrero, E., A. Dagher & R.J. Zatorre. 2018. Modulating musical reward sensitivity up and down with transcranial magnetic stimulation. *Nat. Hum. Behav.* **2:** 27–32.
46. Satoh, M., T. Nakase, K. Nagata, *et al*. 2011. Musical anhedonia: selective loss of emotional experience in listening to music. *Neurocase* **17:** 410–417.
47. Mazzoni, M., P. Moretti, L. Pardossi, *et al*. 1993. A case of music imperception. *J. Neurol. Neurosurg. Psychiatry* **56:** 322–322.
48. Peretz, I. 2016. Neurobiology of congenital amusia. *Trends Cogn. Sci.* **20:** 857–867.
49. Särkämö, T., M. Tervaniemi, S. Soinila, *et al*. 2009. Cognitive deficits associated with acquired amusia after stroke: a neuropsychological follow-up study. *Neuropsychologia* **47:** 2642–2651.
50. Belfi, A.M., E. Evans, J. Heskje, *et al.* 2017. Musical anhedonia after focal brain damage. *Neuropsychologia* **97:** 29–37.
51. Matthews, B.R., C. Chang, M. De May, *et al*. 2009. Pleasurable emotional response to music: a case of neurodegenerative generalized auditory agnosia. *Neurocase* **15:** 248–259.

52. Satoh, M., N. Kato, K. Tabei, *et al*. 2016. A case of musical anhedonia due to right putaminal hemorrhage: a disconnection syndrome between the auditory cortex and insula. *Neurocase* **22:** 518–525.
53. Martínez-Molina, N., E. Mas-Herrero, A. Rodríguez-Fornells, *et al*. 2016. Neural correlates of specific musical anhedonia. *Proc. Natl. Acad. Sci. USA* **113:** E7337–E7345.
54. Chapman, L.J., J.P. Chapman & M.L. Raulin. 1976. Scales for physical and social anhedonia. *J. Abnorm. Psychol.* **85:** 374–382.
55. Snaith, R.P., M. Hamilton, S. Morley, *et al*. 1995. A scale for the assessment of hedonic tone: the Snaith–Hamilton Pleasure Scale. *Br. J. Psychiatry* **167:** 99–103.
56. Peretz, I., A.S. Champod & K. Hyde. 2003. Varieties of musical disorders: the Montreal battery of evaluation of amusia. *Ann. N.Y. Acad. Sci.* **999:** 58–75.
57. Ferreri, L., E. Mas-Herrero, R.J. Zatorre, *et al*. 2019. Dopamine modulates the reward experiences elicited by music. *Proc. Natl. Acad. Sci. USA* **116:** 3793–3798.
58. Mallik, A., M.L. Chanda & D.J. Levitin. 2017. Anhedonia to music and mu-opioids: evidence from the administration of naltrexone. *Sci. Rep.* **7:** 41952.
59. Loui, P., S. Patterson, M.E. Sachs, *et al*. 2017. White matter correlates of musical anhedonia: implications for evolution of music. *Front. Psychol.* **8:** 1–10.
60. Martinez-Molina, N., E. Mas-Herrero, A. Rodríguez-Fornells, *et al*. 2019. White matter microstructure reflects individual differences in music reward sensitivity. *J. Neurosci.* **39:** 5018–5027.
61. Griffiths, T.D., J.D. Warren, J.L. Dean, *et al*. 2004. "When the feeling's gone": a selective loss of musical emotion. *J. Neurol. Neurosurg. Psychiatry* **75:** 341–345.
62. Hirel, C., Y. Leveque, G. Deiana, *et al*. 2014. Acquired amusia and musical anhedonia. *Rev. Neurol. (Paris)* **170:** 536–540.
63. Fletcher, P.D., L.E. Downey, P. Witoonpanich, *et al*. 2013. The brain basis of musicophilia: evidence from frontotemporal lobar degeneration. *Front. Psychol.* **4:** 1–8.
64. Rohrer, J.D., S.J. Smith & J.D. Warren. 2006. Craving for music after treatment for partial epilepsy. *Epilepsia* **47:** 939–940.
65. Fletcher, P.D., L.E. Downey, H.L. Golden, *et al*. 2015. Auditory hedonic phenotypes in dementia: a behavioural and neuroanatomical analysis. *Cortex* **67:** 95–105.
66. Geretsegger, M., U. Holck & C. Gold. 2012. Randomised controlled trial of improvisational music therapy's effectiveness for children with autism spectrum disorders (TIME-A): study protocol. *BMC Pediatr*. **12:** 1–9.
67. Pacchetti, C., F. Mancini, R. Aglieri, *et al*. 2000. Active music therapy in Parkinson's disease: an integrative method for motor and emotional rehabilitation. *Psychosom. Med.* **62:** 386–393.
68. Janata, P. 2011. Effects of widespread and frequent personalized music programming on agitation and depression in assisted living facility residents with Alzheimer-type dementia. *Music Med*. **4:** 8–15.
69. Guétin, S., F. Portet, M.C. Picot, *et al*. 2009. Effect of music therapy on anxiety and depression in patients with Alzheimer's type dementia: randomised, controlled study. *Dement. Geriatr. Cogn. Disord.* **28:** 36–46.
70. Sung, H.-C., A.M. Chang & W.-L. Lee. 2010. A preferred music listening intervention to reduce anxiety in older adults with dementia in nursing homes. *J. Clin. Nurs.* **19:** 1056–1064.
71. Grau-Sánchez, J., E. Duarte, N. Ramos-Escobar, *et al*. 2018. Music-supported therapy in the rehabilitation of subacute stroke patients: a randomized controlled trial. *Ann. N.Y. Acad. Sci.* **1423:** 318–328.
72. Craig, A.D. 2009. How do you feel—now? The anterior insula and human awareness. *Nat. Rev. Neurosci.* **10:** 59–70.
73. Menon, V. & L.Q. Uddin. 2010. Saliency, switching, attention, and control: a network model of insula function. *Brain Struct. Funct.* **214:** 655–667.
74. Meyer, L.B. 1956. *Emotion and Meaning in Music*. Chicago, IL: University of Chicago Press.
75. Bregman, A.S. 1994. *Auditory Scene Analysis: The Perceptual Organization of Sound*. Cambridge, Mass: MIT Press.
76. Saffran, J.R., R.N. Aslin & E.L. Newport. 2007. Statistical learning by 8-month-old infants. *Science* **274:** 1926–1928.
77. Woods, K.J. & J.H. McDermott. 2018. Schema learning for the cocktail party problem. *Proc. Natl. Acad. Sci. USA* **115:** 3313–3322.
78. Huron, D. 2006. *Sweet Anticipation: Music and the Psychology of Expectation*. Cambridge, MA: Oxford University Press.
79. Friston, K., J. Kilner & L. Harrison. 2006. A free energy principle for the brain. *J. Physiol. Paris* **100:** 70–87.
80. Friston, K. 2010. The free-energy principle: a unified brain theory? *Nat. Rev. Neurosci.* **11:** 127–138.
81. Rao, R.P.N. & D.H. Ballard. 1999. Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. *Nat. Neuroscience* **2:** 79–87.
82. Rubin, J., N. Ulanovsky, I. Nelken, *et al*. 2016. The representation of prediction error in auditory cortex. *PLoS Comput. Biol.* **12:** 1–28.
83. Heilbron, M. & M. Chait. 2018. Great expectations: is there evidence for predictive coding in auditory cortex? *Neuroscience* **389:** 54–73.
84. Salimpoor, V.N., D.H. Zald, R.J. Zatorre, *et al*. 2015. Predictions and the brain: how musical sounds become rewarding. *Trends Cogn. Sci.* **19:** 86–91.
85. Koelsch, S., P. Vuust & K. Friston. 2019. Predictive processes and the peculiar case of music. *Trends Cogn. Sci.* **23:** 63–77.
86. Varela, F.J., E. Thompson & E. Rosch. 1991. *The Embodied Mind: Cognitive Science and Human Experience*. Cambridge, MA: MIT Press.
87. Griffiths, T.D., S. Kumar, J.D. Warren, *et al*. 2007. Approaches to the cortical analysis of auditory objects. *Hear. Res.* **229:** 46–53.
88. Hickok, G. & D. Poeppel. 2007. The cortical organization of speech processing. *Nat. Neurosci.* **8:** 393–402.
89. Rauschecker, J.P. 2012. Ventral and dorsal streams in the evolution of speech and language. *Front. Evol. Neurosci.* **4:** 5–8.
90. Loui, P. 2015. A dual-stream neuroanatomy of singing. *Music Percept*. **32:** 232–241.