



Understanding Music in the Brain: Neural Processing, Training, and Cultural Contexts

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Abstract:

Music, characterized by structural components such as pitch, rhythm, and tonality, is processed within the brain in ways that raise fundamental questions about universality and cultural specificity. Some researchers hold that music processing is universal, with the reason being that all humans use the same neural machinery for processing rhythm, pitch, and general musical structure. Others note that musical perception and interpretation are moderated by experience and exposure. This disagreement raises a basic question: is music perception best explained by universal neural mechanisms or by training and cultural familiarity? This paper presents examples from EEG studies to exemplify how neural activity mirrors early sensory and higher-level aspects of auditory coding. Such research demonstrates that trained musicians tend to show more accurate neural encoding for musical features such as pitch and timing and how, even without formal training, individuals exposed to music from their own culture and to foreign music can still discriminate between these tonal patterns much more efficiently. In addition, cross-cultural data show that experience with language and daily rhythmic entrainment contribute to the development of auditory skills as well, demonstrating how understanding music cannot be reduced to practice alone. Taken together, these findings discredit the notion of an entirely universal perception of music; while most humans perceive music itself, both cultural convention and the degree of individual training determine the depth and richness of music perception. The integration of neural composition, auditory exposure, and socio-cultural surroundings furnishes a more unified theory of music processing and understanding, highlighting the necessity to embrace biological, experiential, and cultural elements in music perception studies.

Introduction:

Music is a critical part of society, shaping religion, culture, and family dynamics, with its comprehension being a combination of both cognitive and neural processes (Cross, 2006; Koelsch, 2014). Since different people comprehend music and its multiple parts in unique ways, which range from different interpretations of fundamental aspects such as pitch and rhythm to more complex ones such as harmony and tonality, it raises a central question: What factors account for these differences in music comprehension?

This review has chosen (1) neural architecture (Humphries et al., 2010); (2) experience and training (Wong et al., 2007; Mankel & Bidelman, 2018); and (3) cultural frameworks (Morrison & Demorest, 2009; Mehr et al., 2019) as the three most important factors to discuss. Together, these influences will spark important queries about the impact that these factors have on our musical knowledge and on our efficiency in encoding and interpreting musical patterns. In addition, they support a broader argument that music comprehension is not universal, nor shaped by any single element, but modified through unique interactions between these various aspects of human perception and cognition.

Tonotopic Organization and the Auditory Pathway

Auditory perception forms the foundation for the comprehension of music, with the listener's cultural exposure influencing how they interpret and respond to musical information (Thompson et al., 2005). Studying these processes can help us understand why people hear and interpret sounds differently (Mankel & Bidelman, 2018). It starts with the cochlea, part of the inner ear, containing tonotopically organized hair cells. While high frequencies activate cells towards the base of the cochlea, low frequencies activate hair cells towards the apex. Signals

generated by activating the hair cells are then sent along the auditory nerve through multiple subcortical regions, including the medial geniculate nucleus (MGN), before reaching the primary auditory cortex.

The tonotopic organization in this area directly supports the brain's ability to detect pitch, serving as a neural foundation for perceiving more subtle musical elements, such as melody and harmony. Individual differences in auditory ability further shape how complex sounds are encoded, producing variation in musical understanding (Humphries et al., 2010). Since these later regions integrate sound for perception, memory, and interpretation, this suggests that fundamental auditory encoding is not entirely universal but is shaped by numerous factors.

Neurophysiological Techniques for Studying Music Perception

Building on this anatomical foundation, researchers use neurophysiological techniques to observe how these auditory processes occur in real time and across different levels of the auditory pathway. One of the generally used techniques is electroencephalography (EEG), which records brain activity using scalp electrodes depicting neural activity with millisecond-level temporal precision. From the brain activity measured in EEGs, researchers extract ERPs, which show how the brain responds to individual sounds. In addition, this activity also captures frequency-following responses (FFRs), which are brief brainstem responses that indicate how the brain tracks pitch (Bidelman et al., 2013; Mankel & Bidelman, 2018).

However, it is important to note that while FFRs mostly convey pitch perception, they do not fully reflect cortical contributions to auditory processing. This distinction suggests that FFRs primarily reflect automatic processing in the early stages of the auditory pathway, whereas ERPs capture processing that occurs later as sound is integrated for perception and interpretation. (Coffey et al., 2016). It means that when combined, both FFRs and ERPs work off each other to create a more holistic framework for understanding how the brain transforms basic sound features into meaningful musical experiences.

Experience and Neural Mechanisms in Music Perception

Neural Benefits of Musical Expertise

Expanding on this methodological framework, larger studies that utilize both musicians and nonmusicians demonstrate how experience enhances the neural coding of sound. For instance, trained listeners are better at telling apart pitch, rhythm, and timbre than nonmusicians (Neelamegarajan et al., 2024). In these studies that utilize ERPs and FFRs, musically experienced subjects typically exhibit stronger and more reliable neural responses, reflecting faster and more precise auditory encoding (Coffey et al., 2016; Coffey et al., 2017). In addition to accuracy, these listeners are also able to process sound better, exemplifying less neural effort in recognizing patterns than nonmusicians, suggesting that training not only improves perception but also makes the brain work more efficiently. Collectively, this evidence highlights how auditory expertise plays a vital role in dictating the way that the brain organizes sounds, making it an especially crucial factor to consider. Furthermore, these findings reinforce the central claim that while biological mechanisms do play an important role in the foundation of auditory processing, it is experience and training that deepen and refine the brain's capacity to perceive music.

Neural Limitations of Musical Expertise

Yet, despite these advantages, research also reveals how musical expertise benefits are not universal, underscoring important neural limitations to what training alone can achieve. To illustrate this, Mankel & Bidelman (2018) examined twenty-eight young adults with normal hearing and less than three years of professional music training. Participants were allocated

evenly into high- and low-musicality groups based on perception ability, rather than training history. Subcortical neural activity—brain activity below the cortex—was measured using EEGs in two listening environments: speech with and without background noise. They found that while each group identified speech in both conditions, the high musicality group better discriminated sound both in quiet and noisy conditions, suggesting more efficient neural encoding. This was further confirmed by the stronger FFRs in this group, reflecting faster pitch and rhythmic timing processing. Individuals who demonstrated strong frequency-following responses (FFRs) with little formal training were labeled "musical sleepers" (Mankel & Bidelman, 2018).

These results suggest that musical ability is something that can emerge even without extensive training, pointing out the role of innate sensitivity and everyday experience when it comes to someone's level of music comprehension. In fact, musical training by itself can't improve all aspects of auditory ability; for example, it does not improve the detection of "interrupted sounds" in which the brain must reconstruct missing input masked by noise (Neelamegarajan et al., 2024). This nuance underscores that expertise strengthens certain neural pathways while leaving others unchanged, leading to the understanding that training has limits and that musical ability cannot be explained by practice alone.

When taken together, these findings support the broader claim that music processing reflects not just one factor, such as experience, but is an interplay of many different factors—including biology, sensitivity, and training—that work together to create a diverse and unique capacity for each individual.

Influence of Language and Everyday Listening

With the results of the musical sleeper experiment suggesting that musical ability can emerge even without extensive training, it raises the question of whether other factors—such as language—might provide additional pathways for shaping auditory skills. For example, Wong et al. (2007) presented Mandarin syllables to both tone-language and non-tone-language speakers. These syllables are distinguished by rising, falling, or level pitch patterns, in which tone languages change the meaning of words. From this experiment, they found that the speakers of the tone language, whose native vocabulary relies on pitch to signal meaning, had significantly stronger brain responses to pitch than speakers of non-tone languages. Similarly, Tierney and Kraus (2013) suggested that rhythmic ability in everyday contexts can strengthen how the brain processes timing in sound by exemplifying that individuals who were better at beat synchronization also had more consistent brain responses to rhythm.

Both studies highlight how other factors besides training, such as language, can have an impact on one's ability to understand music and together support the idea that music perception cannot be explained by just one single factor, such as training, but rather requires the interplay of several different influences to fully account for the richness and variability of how individuals perceive music.

ERP Evidence of Explicit, Higher-Order Processing

Considering prior research indicating that FFRs reflect rapid and automatic but not necessarily higher-level cortical processing (Coffey et al., 2016), it is still especially important to consider the role of conscious brain activity in music perception. This can be done by drawing back to the study on musical sleepers by Mankel & Bidelman (2018). Within the study, although the higher-musicality group—often referred to as 'musical sleepers'—did exhibit strong early auditory encoding, they still struggled to comprehend more higher-level aspects of listening that require attention and awareness.

To address these more complex processes, scientists utilize event-related potentials (ERPs) to record explicit, conscious processes like attention, discrimination, and memory. This difference between implicit (automatic) and explicit (controlled) neural operations implies that although innate auditory skills do play an important role in comprehension of music, it requires the help of other factors like musical expertise to process higher-level aspects of listening (Mankel & Bidelman, 2018; Coffey et al., 2017).

These findings strengthen the idea that while universal, automatic responses can form the foundation of music perception, it is the depth and complexity of understanding that emerges through the combination of training and cultural experience, challenging the notion that musical perception is truly universal.

Integration: How Biology and Experience Shape Music Comprehension

In summary, through the use of EEG, ERPs, and FFRs, it is clear that neural wiring uniqueness, focus of attention, and auditory training account for why individuals are more sensitive to pitch, rhythm, and harmony. Ultimately, it substantiates the hypothesis that music comprehension is conditioned by the biology, experience, and culture of an individual.

Cultural Influences on Music Perception

Behavioral Evidence of Cultural Exposure

While training and natural talent can help improve how the brain encodes musical information, research suggests that cultural familiarity can add another layer of depth into how music is perceived and prioritized (Bidelman et al., 2013; Wong et al., 2007). Morrison & Demorest (2009) offer a comprehensive review of decades of research exemplifying how early cultural exposure to certain tonal systems can fundamentally change the listeners' subsequent music perception. Across the studies they reviewed, participants completed behavioral tasks such as melody recognition and tonal pattern identification to assess how early cultural exposure influenced perceptual sensitivity to native versus non-native tonal systems. Their synthesis of both cross-cultural and developmental studies of participants' responses to culturally distinct musical patterns suggested that even minimal exposure can affect basic auditory processes. For example, listeners showed high accuracy when it came to recognizing and recalling melodies that were composed in their native tonal framework compared to those from unfamiliar systems, even when the melodies were on equal levels of difficulty. Building on this trend, Wong et al. (2007) found that native speakers of Mandarin—a tone language—showed enhanced neural encoding of pitch compared to that of English speakers, further illustrating how cultural and linguistic background can directly shape auditory perception.

Together, these experiments suggest that culture actively shapes the auditory system of the brain for processing pitch, rhythm, and tonal patterns. This further suggests that cultural exposure not only heightens sensitivity to familiar musical patterns but also determines the boundaries of what listeners can easily differentiate, interpret, and appreciate, corroborating the view that music perception is the product of the collective efforts of biology, training, and culture.

Cross-Cultural Considerations

While the studies of Morrison & Demorest (2009) and Wong et al. (2007) are good at highlighting the role of cultural exposure, it is important to note that research involving cultural influences in music perception sometimes tends to focus specifically on Western tonal systems, with music such as pop, classical, or jazz music being dominant. Therefore, the question of whether brain responses are due to universal musical features or just familiarity with Western tonal systems requires more cross-cultural data (Cross, 2006).

One study that can address this gap is the large-scale cross-cultural analysis that was done by Mehr et al. (2019). In this study they compiled data from thousands of songs that spanned over three hundred societies containing diverse geographic and cultural backgrounds. Rather than selecting a fixed number of songs per culture, the dataset was built from available recordings and detailed ethnographic reports, allowing for both broad coverage and variation at the same time. Mehr et al. (2019) found that while certain acoustic features—like lullabies being slower and softer or dance songs being faster—appeared consistently across many societies, listeners' ability to identify the purpose of songs from unfamiliar cultures was relatively low, averaging about 42%.

When combined into one, this reinforces the idea that music perception is not driven by universal mechanisms alone but is a product of the combined contributions of biology, experience, and culture. This evidence suggests that while cross-cultural similarities can bind acoustic features to social roles in humans, cultural context remains necessary for interpretation. Broad cues like tempo or dynamics may be recognized across societies, yet the meaning held by them—sacred, celebratory, or mournful—is dependent on cultural learning. At most, these convergences of sound provide a foundation, while deeper layers of perception and meaning emerge from specific cultural frameworks.

Summary of Cultural and Neural Interactions

In summary, research such as Morrison & Demorest's (2009) behavioral studies and Wong et al.'s (2007) ERP evidence highlights the importance of not just considering the ways in which musical training and natural ability shape our brain but also how cultural background plays a role in that process of tuning our brain's responses to familiar musical patterns as well.

Conclusion

Understanding how humans perceive music requires starting at the most fundamental level of auditory processing in the ear and brain. It is inside these regions where basic elements like pitch, tone, and rhythm are detected. Higher brain processes then build on this foundation, enabling the integration of attention, pattern recognition, and memory. For example, studies on musical sleepers, tone-language speakers, and different cultures show that both universal brain functions and cultural experiences are important influences, making each person's perception unique and distinctive. While further research should combine neural, behavioral, and cross-cultural perspectives to clarify how auditory encoding interacts with both training and culture, ultimately, music perception is a reflection of the combined contributions of biology, experience, and culture, shaping a unique experience for each listener.

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