

Using Music to Tap Into a Universal Neural Grammar

Daniel G. Mauro (dmauro@ccs.carleton.ca)

Institute of Cognitive Science, Carleton University,
Ottawa, Ontario, Canada K1S 5B6

Abstract

The human brain is exquisitely sensitive to musical stimuli. Cognitive neuroscientists and physicians are discovering that mere exposure to different musical forms can induce a wide variety of ‘extra-musical’ brain responses, alleviate the symptoms of challenging neurological disorders and accelerate physiological development in premature infants. I suggest that music has the capacity to enhance both normal and suboptimal neural functioning because there are parallels between the temporal properties of musical forms and the dynamic properties of distributed neural networks. According to this musical brain metaphor, the brain uses neural codes made up of rhythmic and frequency-based patterns that resemble musical structures. Viewing the brain as a dynamic system that operates according to ‘music-like’ principles provides a new and potentially useful approach for probing the neural underpinnings of cognition at the appropriate temporal scale. To this end, I introduce a theory of higher brain function referred to as the *Musical Brain Model*.

Musical Structures and Neural Codes

The Computational Theory of Mind (CTM) is ubiquitous in cognitive science. Fodor’s Language of Thought Hypothesis (LOTH) is probably the most well known formulation of the CTM. According to this theory, thinking takes place in an inner mental language that consists of a symbolic system of representations that is physically realized in the brain of thinkers. While the LOTH addresses the formal properties of *mentalese*, it says little about how this mental language might be neurally implemented. At the same time, many neuroscientists believe that higher order brain processes must operate according to a universal neural grammar, a set of syntactic principles for organizing neural events into hierarchically structured sequences. In this paper, I suggest that this universal neural language will turn out to have music-like properties and that music can therefore be used to tap into the neurophysiological details of that language.

In what follows, I survey a wealth of empirical findings that motivate the idea that music is relevant to understanding the brain at higher levels of organization. Music is a universal feature that has been found in all human cultures throughout recorded history. Cognitive neuroscientists are discovering that individuals without formal musical training possess both an inherent knowledge of musical structure and neural substrates dedicated to processing music. Moreover, the brain is surprisingly responsive to a range of musical stimuli. It is known that certain styles of music will alter brain chemistry, enhance immune function and improve cortical synchrony in healthy individuals and music-based therapies have been shown to alleviate the symptoms of a variety of neuropsychological

disorders. Much of this musical sensitivity – this propensity to understand and benefit from musical exposure, is already evident in infancy and therefore cannot be legitimately explained via long-term musical enculturation.

It would be of interest, then, to explain why infants seem to possess innate musical capacities and also how music is able to provide therapeutic benefits across a range of neurological disorders. Expressed another way, is there something about the dynamic super-organization of the brain that makes it so responsive to musical stimuli? According to the *Musical Brain Model* (MBM), the brain uses frequency and timing-based neural codes that resemble the structural building blocks of music and it is this fundamental similarity that underlies the ability of music to enhance both normal and suboptimal neural functioning in humans. As such, music can be viewed as an appropriate research tool with which to explore the dynamic workings of the mind and brain. The MBM makes these notions more explicit within a combined theoretical/methodological framework that is intended to: a) explain diverse experimental findings from a range of music-related neuroscience literature, b) propose the idea of a *dynamically* oriented neural language of the brain and c) introduce a systematic music-based methodology for investigating the structural details of that language.

The Musical Sensitivity of the Brain

Increasingly, cognitive scientists are beginning to appreciate that a deeper study of musical processing may offer a unique window into the brain and that music is an untapped resource that can be utilized to investigate general properties of cognition (Zatorre, 2003). Indeed, recent research in the field of music cognition addresses a broad range of important issues that are potentially relevant to understanding general principles of higher brain function, including the functional and neural architecture of language and music, music-related deficits and modularity of brain processing and music as a model for understanding sensorimotor coupling and complex sequence learning in the brain. In this section, I survey a variety of music-related neural phenomena which are intended to highlight the brain’s exceptional sensitivity to music and thereby motivate key assumptions of the Musical Brain Model.

Extra-Musical Brain Responses

Listening to pieces from particular musical idioms has been shown to produce a wide range of neurophysiological and biochemical responses which appear to *occur over and above* the neural mechanisms involved in integrating

musical parameters into a coherent perceptual experience. In other words, our perception of the surface features of a particular piece of music relies on neural circuitry dedicated to processing musical structures, whereas accompanying emotional experiences or physiological responses are associated with the activation of additional brain structures (e.g., amygdala) and dynamic neural responses (e.g., hemispheric synchronization). Accordingly, I distinguish between the *cognitive* processing of musical patterns (see Lerdahl & Jackendoff, 1983) and the activation of what I will be referring to as ‘extra-musical’ brain responses that are induced by such patterns. These extra-musical responses are numerous and include changes in brain chemistry (e.g., serotonin) and physiology (e.g., heart rate), enhanced immune function, reduced levels of stress-related hormones and improved long-range cortical synchrony. While it is clear that extra-musical responses (EMRs) can influence the physical, emotional and cognitive states of neurologically intact individuals, EMRs also presumably underlie some of the positive consequences of using music in a therapeutic context. In particular, music has been successfully applied to a variety of disorders, including psychological syndromes (e.g., anxiety), neurological and cognitive disorders (e.g., Epilepsy, autism), language deficits (e.g., Broca’s aphasia) and movement disorders (e.g., Parkinson’s disease).

Music and Neural Development

If passive exposure to music can generate such a diversity of neural phenomena, one might expect that playing music would confer similar benefits. Indeed, musical training has been associated with changes in the size and organization of various neural structures (e.g., corpus callosum, planum temporale, somatosensory cortex) as well as enhanced performance in nonmusical cognitive domains (e.g., reading, verbal memory, spatial reasoning). Recent research suggests that these cognitive benefits may derive from early musical training which alters the developmental patterning of neural networks. Consistent with this idea, Altenmüller (2003) has discovered that the type and extent of musical training influences the complexity, distribution and number of music processing centers in the brain.

Music and Infants

The ability to perceive and understand music is not limited to adults. Remarkably, infants as young as 4 months old come equipped with a wide range of musical predispositions, including preferences for consonant intervals and logical rhythmic arrangements, sensitivity to musical phrase structure and contour and tendencies to perceptually group notes (Trehub, 2000). Furthermore, infants not only possess the ability to discriminate different musical structures, they also benefit from listening to music. Premature infants in neonatal intensive care units (NICUs) who are intermittently exposed to appropriately chosen music (e.g., lullabies) show increases in weight gain, enhanced behavioural states, more stable physiological measures and reduced hospital stays (Standley, 2001).

Musical Substrates are Widely Distributed

The fact that music induces a variety of extra-musical brain responses, therapeutic benefits and cognitive advantages in both adults and infants provides support for the claim that musical stimuli are activating widely distributed neural structures over and above those dedicated to music processing. Imaging and lesion studies reveal that different musical parameters are modularly processed in numerous cortical and subcortical structures in the temporal, parietal and frontal lobes of both hemispheres (Warren, 1999). Moreover, listening to music also activates substrates normally associated with the processing of other (nonmusical) cognitive modalities, including reward and emotion (Blood & Zatorre, 2001), language (Maess et al., 2001) and vision and motor function (Bodner et al., 2001).

The literature reviewed above illustrates the exceptional musical sensitivity of the brain. I argue that human proclivities to enjoy music, understand musical structures and derive therapeutic benefits from mere exposure to music cannot be adequately explained by musical enculturation (i.e. simple enjoyment-based arousal associated with long-term experiences with music). Although a minimal amount of musical exposure is certainly necessary for a basic appreciation of different musical forms, such exposure is insufficient to explain musical comprehension in infants, rehabilitation of complex neurological disorders or cross-cultural sensitivity to music (Krumhansl et al., 2000).

Outlining the Musical Brain Model

I suggest that this high degree of musical sensitivity is most easily understood by viewing the brain as a system that is ‘music-like’ in its design; that is, there are fundamental similarities between the temporal properties of music and the complex dynamic processes occurring in the human brain. For example, we can speak of ‘harmonies’ between communicating neural regions - the brain is a massively parallel device that coordinates nonlocal neural regions by means of common frequency signals. Similarly, we can refer to ‘rhythmic phrases’ of neuronal assemblies – temporal patterns embedded in neural firing sequences that can encode and represent information dynamically. These musical descriptions of brain activity are not to be considered mere metaphors but rather can provide clues towards a universal neural grammar. The Musical Brain Model makes these kinds of notions more explicit by means of four distinct, yet inter-related postulates: (1) Musical pieces consist of temporal sequences (rhythms) of frequency events (pitches) that are organized in serial (melody) and in parallel (harmony). (2) The brain processes information by means of temporal and frequency-based coding mechanisms that occur in serial and parallel neural pathways. (3) The acoustic ingredients with which musical pieces are created *synchronize* with rhythmic and frequency-based neural codes, thereby inducing a variety extra-musical brain responses. (4) Music can be used as a systematic tool for probing these dynamic brain coding mechanisms.

Postulate #1: Music Consists of Temporally Organized Frequency Events

The purpose of the first premise of the MBM is to define music in terms of its most basic constituent structures in order to establish a common frame of reference with which to compare musical structures and neural coding mechanisms. Most forms of music can be described in terms of three essential components: *melody*, *harmony* and *rhythm*. Melody consists of a horizontal sequence of pitches, where each individual pitch is composed of a fundamental frequency and a series of harmonic overtones. Harmony consists of vertical arrangements of pitches (chords) that support the melodic structure as it moves through time. While melody can be considered a *serial* organization of discrete frequency-based events, harmony involves a *parallel* organization of frequency events. The melodic and harmonic aspects of a piece are further organized in terms of temporal (rhythmic) structures. The essential components of rhythm are meter (regular alternation of accented beats) and phrasing (temporal pattern of musical events). Thus, within the context of the Musical Brain Model, music may be defined as a patterned temporal sequence (rhythms) of discrete frequency events (pitches) that are organized in the serial (melody) and parallel (harmony) dimensions.

Postulate #2: The Brain Organizes Information in Terms of Frequency Codes and Temporal Codes

According to the second premise of the MBM, frequency codes and temporal codes are the fundamental building blocks of higher brain function - they are the means by which information is organized, represented and coordinated in the brain. Within the neurosciences, brain waves were once considered an epiphenomenon, signs of the brain's idling activity. However, a recent upsurge in EEG research reflects a growing emphasis on the functional importance of the brain's oscillatory and rhythmic activity. Brain rhythms have both a frequency component and a temporal component. I survey evidence showing how the brain uses frequency-based codes to represent and organize information and then consider the importance of timing sequences as potential neural coding mechanisms.

Frequency Codes Neural oscillations and neuronal spiking can be characterized in terms of *frequency*, usually expressed in Hertz (the number of cycles/events that occur per unit time). Frequencies are ubiquitous as a form of information throughout the brain. For example, stimulus intensity in various modalities (e.g., loudness, brightness) is encoded by the average spiking frequency of neurons.

Although rate coding and frequency filtering are common behaviours of individual neurons, frequency information is also functionally important in large-scale brain activity. Oscillations in distributed neural networks are crucial to perceptual binding – the ability of the brain to integrate various aspects of sensory input into a coherent and unified

whole. In particular, coherent oscillations in the gamma frequency band (30 to 80 Hz) have been implicated in linking visual, olfactory and auditory percepts.

On the lower end of the frequency spectrum, the commonly known brain waves have been correlated with different states of awareness. For example, alpha waves (8–14 Hz) are prominent during relaxed states of awareness, while beta waves (15–30 Hz) typically accompany an alert or highly focused mental state. Interestingly, both very high frequency and ultra slow oscillations have been recently identified in cortical and subcortical structures, such as the hippocampus (200 Hz ripple oscillations), somatosensory cortex (600 Hz) and lateral geniculate thalamus (.025 -.01 Hz). Very high frequency oscillations are considered important for information encoding processes (e.g., memory consolidation) while ultra-slow oscillations may be involved in integrating complex cognitive functions. The fact that brain oscillations are found in widely distributed neural structures and exist across a range of frequency bands suggests that the frequency-based component of rhythms serves an important functional role in coordinating large scale brain activity.

Temporal Codes Neuronal oscillations in the gamma frequency band may be important for integrating short-term perceptual processes (e.g., object recognition), but they are insufficient to explain cognitive functions which occur over longer time scales. Modes of cognition as diverse as language and spatial temporal reasoning require the sequential ordering and manipulation of discrete information over time. This kind of temporally extended cognitive processing depends on the precise synchronization of neural events over multiple time scales. Thus, temporal codes are an ideal way with which the brain can dynamically represent information. Three main types of coding mechanisms have been described in the literature, two of which are time-related: *time-of-arrival* (e.g., latency codes, inter-neuronal synchrony codes); *temporal pattern* (e.g., complex pattern codes, interspike interval codes); and *connectivity* (e.g., labelled-line, spatial-pattern codes). Combining these 3 coding archetypes provides for a rich variety of timing-based neural codes that could subserve different information processing functions in the brain.

Postulate #3: Neural Coding Mechanisms Entrain with Musical Structures

The third postulate of the MBM links the first two premises by isolating shared principles of organization between musical structures and dynamic neural processes. According to the Musical Brain Model, our propensity to respond favourably to music is a direct consequence of how the brain is constituted. Specifically, the basic acoustic ingredients with which *most* musical forms are created (e.g., organized rhythms and frequencies) are *structurally* similar to temporal and frequency-based brain coding mechanisms. I suggest that certain properties of musical stimuli *engage* dynamic neural mechanisms by means of *entrainment*.

Entrainment Entrainment is the principle whereby two or more *systems* synchronize their rhythmic activity. It is known that the pendulums of grandfather clocks that are placed in close proximity will begin to swing in synchrony, or *entrain* to one another. The phenomenon of entrainment is common in biological systems and is evident in dynamic brain-environment interactions. The brain is very responsive to external rhythms, particularly in the auditory realm. Music with certain rhythmic parameters is capable of triggering specific brain waves and physiological responses. For example, slow Baroque music (60 bpm) will induce alpha rhythms in the listener and slow down heart and respiration rates; in contrast, music with driving rhythms or fast tempos (e.g., rock, heavy metal) can stimulate beta wave activity and speed up heart and respiratory rates. Entrainment of brain rhythms with musical rhythms can be explained in terms of *forced oscillations*. In contrast to spontaneously occurring brain oscillations, forced oscillations are those that are continuously driven by an external periodic or rhythmic stimulus.

Explaining Musical Sensitivity The principle of entrainment provides a plausible mechanism for explaining the brain's musical sensitivity (i.e. the existence of diverse extra-musical responses). Rhythm is central to music and is therefore crucial to uncovering links between musical elements and dynamic brain organization. In particular, *meter* and *phrasing* comprise the essential elements of rhythm. Meter provides the predictable structured temporal grid upon which musical elements are embedded, while phrasing is variable and gives shape to musical fragments by organizing pitches into complex temporal patterns. Brain oscillations may *entrain* to the purely metrical aspects of musical rhythms by phase-locking to repeatedly occurring patterns of accented beats. Moreover, because meter is hierarchical in nature, metrical structures on several temporal levels may simultaneously drive neural oscillations in multiple frequency ranges.

Postulate #4: Using Music as a Methodological Tool for Investigating Neural Phenomena

According to the first three postulates of the Musical Brain Model, rhythmic and frequency-based neural codes entrain to musical structures to which they are similar. These postulates form the theoretical basis for the final postulate of the MBM, which describes the use of music as a systematic methodology for probing the brain. There are three aspects to the methodology. First, when certain types of musical stimuli activate corresponding brain mechanisms, *global* extra-musical responses will be generated (e.g., enhanced cortical synchrony). Second, the nature of these extra-musical responses will be correlated with specific structural elements in the music (e.g., meter). By means of refined experimentation, it should be possible to extract the musical elements that are responsible for each type of response. Third, once these musical constituents are isolated, we may be able to infer something about

corresponding brain mechanisms (e.g., theta rhythms); that is, the musical structures responsible for evoking a particular brain activation pattern may provide clues as to the nature of the neural mechanism underlying that response.

A new research paradigm is emerging in which music-based procedures are demonstrating positive therapeutic effects for a variety of serious neurological disorders, including Epilepsy, Parkinson's Disease and Broca's aphasia. The implicit rationale underlying these musical therapies is that suboptimal neural functioning can be enhanced by applying an appropriately chosen rhythmic auditory or musical stimulus that synchronizes with relevant neural processes. I examine three such music-therapeutic approaches in order to illustrate the methodological component of the Musical Brain Model.

Epilepsy Hughes et al. (1998) discovered that a majority of epileptic patients (some of whom were in a coma) demonstrated reduced seizure activity while listening to certain styles of music. In particular, the music of Mozart and Bach produced dramatic decreases in EEG epileptiform activity. After analyzing the music of more than 55 composers, Hughes and Fino (2000) concluded that these clinical improvements were linked to long-term periodic changes in the music. Specifically, only composers whose music revealed periodicities on the order of 10 to 60 seconds produced the beneficial effect. They postulated that music with long-term periodicities may be resonating with similar kinds of brain rhythms. One candidate is the cyclic alternating pattern (CAP), a 20 – 40 second rhythmic brain cycle which is considered to be an integrating mechanism for different regions of the central nervous system. This example illustrates the three part nature of the MBM methodology: (1) Listening to music produced a reduction in seizure activity (global extra-musical response). (2) This response was correlated with long-term periodicities in the music (causal musical structure). (3) This musical structure may be enhancing certain long term periodic brain rhythms, such as the CAP (underlying neural mechanism).

Movement Disorders Rhythmic therapy has been successfully used to rehabilitate motor function in various movement disorders (e.g., Parkinson's Disease, Huntington's Disease). Thaut et al. (1999) found that rhythmic auditory stimulation (RAS) produced sustained improvements in movement performance (e.g., walking and arm movements) that were more pronounced than gains derived from conventional physical therapy. In order to explain the facilitating effects of RAS, Thaut et al. suggested that auditory neural rhythms may be stimulating motor impulses in the cerebellum. This example nicely illustrates the MBM methodology: (1) Rhythmic auditory stimulation produced enhancements in motor function (global extra-musical response). (2) This response was correlated with simple auditory rhythms of a certain frequency (causal structure). (3) This musical structure may

improve the timing of motor movements by synchronizing cerebellar rhythms (underlying neural mechanism).

Language Disorders It has been discovered that singing ability is preserved in many individuals who have impairments in producing speech. Based on this finding, a technique called ‘Melodic Intonation Therapy’ (MIT) has been utilized in the treatment of expressive aphasia. In MIT, patients progress from *singing* short linguistic phrases that are embedded into simple melodic patterns to repeating the same phrases using normal speech prosody. Albert, Sparks and Heim (1973) applied this technique to severely expressive aphasics and observed substantial improvements in vocabulary and grammatical structure over a six week period. The MBM methodology is as follows: (1) Singing simple linguistic phrases facilitated rehabilitation of speech functions (global extra-musical response). (2) This response was mediated by the element of musical melody (causal musical structure). (3) This musical structure may activate neural processes that overlap with those governing language prosody (underlying neural mechanism).

Music-Based Approaches in Clinical Settings The preceding examples provide just a sampling of the various ways in which music has been used in therapeutic contexts. The efficacy of these music-based techniques in alleviating the symptoms of such diverse disorders suggests that there is something special about the temporal and frequency-based structures inherent in music and their relationship to dynamic neural coding mechanisms. In particular, musical (and auditory rhythmic) stimuli seem to be able to affect long-term positive changes and to impose order on disorganized or suboptimal neural processes. Studying these musically induced neural enhancements, particularly in clinical populations, may therefore provide important clues from which we can infer general properties of neural organization.

Why Music is Ideal for Probing the Brain

Having introduced the basic components of the Musical Brain Model, I now highlight some additional reasons why using a music-based methodology is useful for probing dynamic neural phenomena.

Temporal Principles First, both the brain and music are organized according to temporal principles. Processes associated with musical comprehension necessarily unfold over extended periods of time (seconds to minutes) - temporal scales that are comparable to the neural processes underlying complex *cognitive* abilities (e.g., language, spatial-temporal reasoning). Thus, examining the brain’s responses to the time-based structures inherent in music (e.g., rhythm, meter, tempo) may provide an ideal method for getting at real-time neural processing mechanisms at different temporal scales.

Musical-Neural Specificity Second, different forms of music activate distributed brain regions in unique ways. If specificity of musical structure is mirrored in specificity of neural response, then systematically manipulating musical parameters and detecting associated brain activity may inform us about the nature of dynamic neural processes. Imaging and EEG studies indicate that the brain responds predictably to different styles or pieces of music (Petsche et al., 1993). It appears that both the pattern and degree of neural activation is influenced by the particular organization of musical parameters. For example, EEG coherence patterns within the different frequency bands have distinct neurophysiological *signatures* that correspond to the style of music that is being perceived (e.g., Bach, Beethoven, Schoenberg). Furthermore, the degree to which large-scale neural mechanisms resonate with musical forms will depend on the temporal complexity of the musical stimulus. Certain pieces of music (e.g. Mozart’s sonata in D Major for 2 pianos, K 448) have been shown to activate widely distributed neural structures (temporal, prefrontal, occipital, cerebellum), while other pieces (e.g., Beethoven’s *fur Elise*) only engage basic auditory/music processing centers.

Language-Like Structures A third reason for using music to probe the brain is that music has language-like properties that could offer potential insights into the structural details of the brain’s dynamic neural grammar. Perceiving music involves detecting complex symbolic relationships between groupings of discrete auditory events that are hierarchically organized into structured sequences according to syntactic principles. Similarly, higher brain function is governed by highly ordered temporal and frequency-based neuronal events that may be organized according to a kind of *neural syntax* - a set of principles for combining discrete neural events into structured sequences.

Despite the obvious similarities between music and language, music differs from language in that its primitive elements (i.e. notes) do not contain explicit content or arbitrarily assigned meaning. For example, while the meaning of a linguistic utterance is (largely) fixed by the meanings of the individual words and the way those words are combined, the interpretation of a passage of music is almost entirely determined by its acoustic structure – by the temporal context in which its component elements are organized. Being (largely) devoid of *extrinsic* meaning, musical forms are therefore ideal for understanding the brain and associated cognitive processes. Extra-musical responses that are induced by particular musical pieces can be directly attributed to psychoacoustic properties of those pieces; in other words, it is the musical structures themselves that stimulate dynamic neural mechanisms (not some externally derived content that is carried in those structures, as is the case with language). The language of thought (LOT) hypothesis suggests that the mind is a symbol processing system that is organized in language-like ways. The structural details of the *neural* language underlying that representational system may turn out to be intimately related

to the basic elements of musical organization. Indeed, the idea of a ‘musical brain’ provides an evolutionary explanation for the existence of music: Humans intrinsically understand, enjoy, and benefit from music precisely because properties of external musical forms mirror internal principles of neural organization.

Music as Methodology in Cognitive Science

Music is much more than a casual form of entertainment. It is a remarkably engaging and complex temporal phenomenon from which human minds seem to derive much physical, emotional and intellectual pleasure. The degree to which music is able to influence so many aspects of neural and cognitive functioning suggests that music, approached in a scientific vein, may become a powerful research tool for discovering general properties of the mind and brain. Indeed, Janata et al. (2002) believe that “the use of tonal music as a stimulus for probing the cognitive machinery of the human brain has an allure that derives, in part, from the geometric properties of the theoretical and cognitive structures involved in specifying the distance relationships among individual pitches, pitch classes (chroma), pitch combinations (chords), and keys.” In a recent fMRI study, Janata et al. discovered that patterns of Western tonal musical structure appear to be mirrored in patterns of human brain activity. Increasingly, experimental findings point to this kind of intimate relationship between aspects of musical structure and dynamic neural organization.

In this paper, I introduced both a theoretical framework and a methodological paradigm for tapping into this putative link between music and brain. According to the Musical Brain Model, the neural coding mechanisms with which the brain processes information are reflected in the basic ingredients of music. Because of this fundamental similarity, structural elements inherent in particular musical forms may produce specific extra-musical brain responses by synchronizing appropriate neural mechanisms.

If the basic premise of the MBM is correct, then music may turn out to be a useful noninvasive top-down approach for exploring the mind/brain - music is a complex and highly structured temporal stimulus that occurs over time scales that are ideal for probing the neural underpinnings of complex cognitive processes. The existing cognitive neuroscience of music literature can guide this research program by providing clues as to which musical styles to utilize and how these styles may be linked with specific brain activation patterns. By systematically manipulating the basic elements of different musical forms it will be possible to generate predictable extra-musical responses. Continual refinement of the experimental paradigm should produce increasingly specific brain responses, from which it may be possible to infer underlying neural mechanisms. Ideally, the findings associated with this musical methodology can be integrated with results from existing neuroscience approaches in order to produce converging evidence about a universal neural grammar of the brain.

References

- Altenmüller, E. O. (2003). How many music centers are in the brain? In I. Peretz & R. Zatorre (Eds.), *The cognitive neuroscience of music*. New York: Oxford University Press.
- Albert, M. L., Sparks, R. W., & Heim, N. A. (1973). Melodic intonation therapy for aphasia. *Archives in Neurology*, 29, 130-131.
- Blood, A. J., & Zatorre, R. J. (2001). Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *Trends in Cognitive Science*, 98, 11818 -11823.
- Bodner, M., Muftuler, L. T., Nalcioglu, O., & Shaw, G. L. (2001). fMRI study relevant to the Mozart effect: brain areas involved in spatial-temporal reasoning. *Neurological Research*, 23, 683-690.
- Hughes, J. R. Daboul, Y., Fino, J. J., & Shaw, G. L. (1998). The “Mozart effect” on epileptiform activity. *Clinical Electroencephalography*, 29, 109-119.
- Hughes, J. R., & Fino, J. J. (2000). The Mozart Effect: Distinctive aspects of the music – A clue to brain coding? *Clinical Electroencephalography*, 31, 94-103.
- Janata, P., Birk, J. L., Van Horn, J. D., Leman, M., Tillmann, B., & Bharucha, J. J. (2002). The cortical topography of tonal structures underlying western music. *Science*, 298, 2167-2170.
- Krumhansl, C.L., Toivanen, P., Eerola, T., Jarvinen T., & Louhivuori, J. (2000). Cross-cultural cognition: Cognitive methodology applied to North Sami Yoiks. *Cognition*, 76, 13-53.
- Lerdahl, F., & Jackendoff, R. (1983). *A generative theory of tonal music*. Cambridge, MA: The MIT Press.
- Maess, B., Koelsch, S., Gunter, T. C., & Friederici, A. D. (2001). Musical syntax is processed in Broca’s area: an MEG study. *Nature Neuroscience*, 4, 540-545.
- Petsche, H., Richter, P., Von Stein, A., Etlinger, S. C., & Filz, O. (1993). EEG Coherence and musical thinking. *Music Perception*, 11, 117 - 151
- Standley, J. M.. (2002). A meta-analysis of the efficacy of music therapy for premature infants. *Journal of Pediatric Nursing*, 17, 107-113.
- Thaut, M. H., Kenyon, G. P., Schauer, M. L., & McIntosh, G. C. (1999). The connection between rhythmicity and brain function: Implications for therapy of movement disorders. *IEEE Engineering in Medicine and Biology*, 6, 101-108.
- Trehub, S.E. (2001). Human processing predispositions and musical universals. In N. L. Wallin, B. Merker & S. Brown (Eds.), *The origins of music*. Cambridge, Massachusetts: The MIT Press.
- Warren, J. D. (1999). Variations on the musical brain. *Journal of the Royal Society of Medicine*, 92, 571-575.
- Zatorre, R. J. (2003). Music and the brain. *Annals of the New York Academy of Sciences*, 999, 4-14.