Music and Neuroscience

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(2002) Flohr, J. & Hodges, D. Music and neuroscience. In R. Colwell & C. Richardson (eds.). *Second Handbook of Research on Music Teaching and Learning*, 991-1008. NY: Oxford University Press.

Chapter Introduction

Relationships among the brain, music, and musical abilities are of interest to musicians, psychologists, and neuroscientists. The purpose of this chapter is to provide a detailed and critical overview of the neuroscientific research dealing with music and music education. Unfortunately, a direct translation from neuroscience research into music education at this time is very problematic. Although our understanding of brain and behavior has increased at an exponential rate over the past 10 years, the theories of brain functioning and our understanding of the neurobiological forces that shape musical behavior are still in their infancy. The focus will be on ideas helpful to music education from what is known about music and the brain. The chapter is organized into three sections.

1. Strategies for conducting neuromusical research. A review of the methodological approaches to conducting neuroscientific research in music. The neuroscience tools reviewed in this section have in many ways revolutionized our ability to examine both the function and structure of the brain.[1]
2. Overall development. A review of findings relating to overall development, selected topics, theories and theoretical areas.
3. Future Directions. A generalized summary of findings and recommendations and considerations for future research directions.

Strategies for Conducting Neuromusical Research

How does one go about studying the phenomenon of music in the brain? The brain's immense complexity in combination with the subtleties and intricacies of human musical behavior, mean that conducting neuromusical research is difficult at best. Although there have been tremendous advancements in research tools, no single strategy is able to provide comprehensive answers. Rather, information from every approach possible must be combined to create a more complete understanding. The purpose of this section is to review current strategies, giving for each a rationale for its appropriateness and a critique of its strengths and weaknesses. Only minimal attention is paid to results, as that information is covered more thoroughly in the section on findings.

Throughout this chapter the reader should keep in mind two points. First, the brain is only part of a much larger system that includes the central nervous system (brain and spinal cord) and peripheral nerves (afferent nerve fibers and their receptors, which send messages to the brain, and efferent nerve fibers and their muscles and glands, which take messages from the brain). In addition, the brain regulates the release of hormones into the bloodstream, so that, in effect, the brain extends throughout the body. The second point has to do with mind-brain disagreements. Are the mind and brain one and the same or are mind and brain separate entities? Untangling such a Gordian knot is beyond the scope of this chapter. Some researchers work from a more purely neurological viewpoint, concerned mainly with physiological processes. Others work from a more cognitive or mental approach. The reader should be aware that modern cognitive neuroscience is beginning to bridge this gap. The concept of psychoneuroimmunology is one that recognizes the interconnections among the mind, brain, and body. Music, of course, is a phenomenon that arises out of interactions among all three.

This section is based on six categories: animal research, fetal and infant research, research on brain-damaged individuals, hemispheric asymmetry research, brain imaging research, neuromotor research, and affective research. These categories are based on a combination of methodologies and subject groupings. They appear to fit most closely with the way the literature is organized and reported. From animals we can learn about antecedents to human musical behavior. From infants we can learn about the brain's wiring for music, relatively independent from the influence of experience. Studying brain-damaged individuals provides the opportunity to isolate areas of the brain involved in musical processing. Hemispheric asymmetry research seeks to reveal how the brain is organized. Brain imaging research provides a window into the working brain. Neuromotor research is concerned with how the brain monitors both expressive (i.e., musical performance) and receptive (i.e., music listening) experiences. Finally, affective research looks into the brain's involvement in emotional responses to music.

Animal Research

Although studying animals may seem like an unusual place to begin, this has been a standard approach in psychology (e.g., Pavlov's dog) and is continued in cognitive neuroscience. Investigating the ways animals process sounds gives neuroscientists useful information about human sound processing. Most animals have devices for detecting, analyzing, and responding to sounds. Once a sound has been detected, the animal analyzes it for "meaning," and this meaning shapes behavior. A housecat demonstrates this when it comes running into the kitchen at the sound of the can opener. When humans listen to music, the process is similar in that we analyze the sound for meaning and that meaning shapes our responses.

Significant insights into human musicality can be gained particularly by investigating sound-making and responding behaviors in such species as birds, whales, dolphins, monkeys and apes.[2] Sight (e.g., seen in displays of aggression or mating behavior) or smell (e.g., marking territory) are ways animals can communicate. But sound has certain advantages in that it can travel long distances rapidly, operate during day or night, and encode complex and changing messages.[3] Therefore, many species have developed sophisticated sound making behaviors (not only vocalizations but also other noises such as chest thumping among gorillas). To assume that animal sounds have nothing to do with human music would be to ignore a significant amount of information and would be counter to linkages found in other types of behavior (e.g., language and social organization).

The opposite is equally true; one cannot automatically assume that there is a direct correlation between animal sounds and human music. Thus, one of the first issues to be dealt with is whether or not animals actually create music. This is a difficult question and one that may elude a definitive answer. It is tempting to anthropomorphize animal sounds; after all, we call it bird*song* because that is what it sounds like to us. But is it music to the animals? Certainly most animal sounds have to do with territoriality, courtship and mating rituals, and signaling (e.g., alarm calls).[4] Slater remarks that with more than 4,000 species of songbirds alone, and all the varied forms and patterns of their songs, it would not be difficult to find many seemingly musical characteristics embedded in their songs, but that this would most likely be coincidental.[5] Even where birdsongs are more complex, varied, or elaborate than is strictly necessary for biological function, they may be so to achieve distinctiveness. If the point of sound making is to communicate, it will do no good if the message is lost in a sonic environment rife with many voices. In a cacophonous habitat where many sounds are competing for "airspace," distinctiveness is an advantage. Krause's niche hypothesis is that each species produces sounds that occupy a particular bandwidth in the overall acoustic spectrum, along with unique rhythm patterns, tonal qualities, and so on.[6] This insures that the message will not get lost amongst all the other sounds. Having said that, however, does not preclude an animal deriving pleasure from the act of making sounds. Until we can gain access to their inner worlds, the most we can do is speculate.

In the meantime, this research strategy informs two concerns of music psychologists: (1) What are the evolutionary antecedents of human musicality? (2) What "extra" cognitive structures and processes do humans possess beyond those of other animals that allow for the degree of musicality expressed in all cultures? In the first instance, the sounds of nature (what Krause terms "biophony"[7]) most likely exerted strong influences on early hominid sound making. It would be quite natural for us to mimic the sounds around us. Of course, with our sophisticated brains, it would not take long for us to move beyond mere mimicry to elaboration, extension, synthesis, and eventually the creation of novel sounds. In time, we would develop our own niche in the biophony. This line of research is important in developing a theory of an evolutionary basis for music.[8]

The second concern feeds more directly into the larger question of neuromusicology. For example, animals rely on absolute frequency analysis[9] rather than on relative pitch as we do.[10] Thus, while various animals can be trained to choose between two songs, they fail miserably if those songs are transposed. By contrast, our adult musicality is possible, in large part, because we deal with pitch relationships. Yankee Doodle, for instance, is recognizable to us at any pitch center.

There are other cognitive limitations among animals as well. For example, musical forms ranging from simple verse-chorus alternations to lengthy symphonic movements are possible because of our ability to retain musical information for long periods of time. Yet dolphins represent the best animals can do and they can only recognize the second A section of a simple ABA form if each section is no more than two seconds long.[11] Once again, however, it must be recognized that testing animals on their capacity for processing human music seems patently unfair. Nevertheless, this line of research does provide evidence of some of the neural mechanisms humans possess that allow for our musicality.

Fetal and Infant Research

In order to understand how the brain is predisposed to music, it would be ideal to look at the brain in a "pure" state, that is, without the influence of the environment. Since this is impossible, studying fetal and infant responses to music allows us to approach a "pure" state with minimal environmental influence. The limitations and difficulties of using babies as subjects seem apparent, but there is much useful information to be gained from this approach. A growing body of literature is focusing on fetal responses to music because in the last trimester before birth, the fetus is capable of responding to sounds in the womb. Researchers can gauge fetal responses by monitoring heart rate and through bodily movements.[12]

Almost immediately after birth, babies can orient toward sounds and soon after that can pick out the sounds of the mother's voice.[13] A significant amount of the interactions between a newborn and its caretakers is based on two-way sound manipulations. The caretakers sing lullabies and talk "baby talk" and there are musical crib mobiles and toys. "Motherese speech," a term psychologists have coined to refer to the type of baby talk typically spoken to infants, emphasizes pitch, timbre, dynamic inflections, and rhythm patterns in order to convey meaning.[14] Clearly, the baby cannot interpret the meaning of words, but does learn to interpret the emotional content. Likewise, the baby learns early on to communicate by manipulating these same sonic elements to express mood states such as hunger, pain, fear, happiness, love, and so on. From this line of research, it is clear that infant musical behaviors are exhibited primarily because of inherited mechanisms.[15] While learning takes place from the outset, babies do not need systematic, formal instruction in order to respond to music, speech, and other sounds.

Research on Brain-Damaged Individuals

Another approach that has a long history in neuroscience is to look at individuals who suffer from some form of brain damage, either from trauma, genetic defect, or aging. Studying persons who have suffered a tumor, stroke, or lesion indicates that some individuals suffer from aphasia (loss of language) but not amusia (loss of music) or vice versa. This lends support to the notion that music and language are dissociated; that is, that music and language are represented, at least to a large degree, by separate neural systems.[16] Both are umbrella terms, in that there are many different forms of aphasia (e.g., loss of speech, comprehension, or the ability to read or write) and amusia (e.g., loss of ability to track pitch, or rhythm, or timbre or loss of familiar tune recognition). Because of the complexity and modularity of both systems, it is also possible that many brain regions are implicated in both language and music.[17] (For more details on modularity see the subsequent discussion under that subheading.)

A common research paradigm is to ask brain-damaged subjects to do a variety of music-related tasks. Their inability to do a task successfully (when compared to a person with an undamaged brain) is then linked to anatomical lesion sites. Several notes of caution must be inserted. First, a damaged brain is different from a normal brain, and the assumption that it is operating like the normal brain with the exception of the damaged portion is not necessarily warranted. Second, for older studies in the literature, anatomical lesion sites are not given very precisely; sometimes reports are as vague as “damage on the left side.” Third, the case with music is somewhat different than the case with language. While one can reasonably assume that an adult has language competency, adult musical skills may vary all the way from minimal (even including “tone deafness”) to highly professional. Thus, if a brain-damaged person cannot do a given musical task—such as match pitches, recognize familiar tunes, or read music—care must be taken to insure that he or she had such skills prior to the trauma.[18]

A second class of subjects is those with inherited cognitive limitations. Musical savants are cognitively impaired but capable of amazing musical feats.[19] Individuals with Williams Syndrome often have cognitive "peaks" and "valleys" and music appears to be something many of them can do quite well.[20] Musical behaviors are only possible in such individuals due to the presence of specific neural structures. Williams Syndrome, in particular, is a fertile area for research in that it may ultimately be possible to link research on genetics (Williams Syndrome results from a microdeletion on chromosome 7) with neuroscientific and behavioral data.

A third class of subjects involves those suffering from cognitive dementias due to aging (especially Alzheimer's). Individuals with prior musical backgrounds may retain procedural skills (e.g., singing or playing an instrument) in spite of declining linguistic fluency.[21] In at least one case, an Alzheimer's patient was able to sing the words to familiar songs even though she could no longer communicate via language.[22] Interestingly, music (among other things) is being recommended to elders as a means of staving off the ravages of Alzheimer's.[23] The presence of musical skills, in the absence of linguistic and other skills, once again denotes neural structures devoted to musical processing.

Hemispheric Asymmetry Research

Hemispheric asymmetry, sometimes referred to as cerebral dominance, is concerned with possible differences between the two hemispheres, both in type of processing (e.g., sequential versus holistic) or in responsibility (i.e., which side is more responsible for particular tasks). Although a variety of strategies can be employed—most notably studying brain damaged individuals (discussed previously) and brain imaging (discussed subsequently)—the focus of this brief discussion will be on dichotic listening tasks.

Dichotic listening tasks have been widely used as a means of comparing one side of the brain's performance with the other. Basically, the technique is to present conflicting signals to the right and left ears via headphones. Approximately seventy percent of the fibers in the auditory pathway are contralateral, meaning that they go from the inner ear to the auditory cortex in the opposite hemisphere. Thus, although both sides receive all the information from each ear, signals from the right ear are more strongly represented in the left hemisphere and vice versa.[24] Contralateral response times are faster than ipsilateral (from one inner ear to the auditory cortex on the same side)[25] and can occlude impulses arriving along ipsilateral pathways.[26] In a typical experiment, subjects might hear a nonsense syllable such as "bleh" in the right ear and "teh" in the left ear (stimuli must be nonsensical, as real words would be immediately recognized). They are then presented with four foils and asked to identify the one they heard. Over a number of trials, consistency in picking out the right ear signal would indicate processing dominance by the left hemisphere and vice versa.

A major limitation of this technique for music research is that the stimuli can be no longer than two seconds. If they are longer, the brain can go back and forth, picking up enough information from each ear to enable recognition of both stimuli possible. Obviously, only limited musical meaning can be found in two-second fragments. Also, stimulus variables (the type of sound/music being used), task variables (whether subjects are asked to make global or local decisions), and subject variables (amount of training, gender, handedness, etc.), can make dramatic differences in the results. Sergent was highly critical of this line of research and felt that all such data could be discarded.[27]

For a period of time, primarily during the 1970s, much was made of music being in the right side of the brain. This over-simplification has since been modified. Music is *not* in the right side of the brain alone; both sides are involved. In fact, sophisticated musical processing most likely involves the front-back, top-bottom, left and right sides of the brain in widely distributed, but locally specialized neural networks. Furthermore, selectively changing the focus of attention radically alters brain activation patterns.[28] Further implications of this line of research are discussed subsequently.

Brain Imaging Research

Modern neuroscientists have a broad range of highly sophisticated research tools at their disposal. These include EEG (electroencephalography), ERP (event-related potentials derived from EEG), MEG (magnetoencephalography), SQUID (superconducting quantum interference device), MRI (magnetic resonance imaging), fMRI (functional magnetic resonance imaging), PET (positron emission tomography), and TMS (transcranial magnetic stimulation discussed in the section on neuromotor responses). Space does not allow for much more than a brief description of each of these technologies (see Figure 1). Because of limited access to equipment, costs involved, and related issues; typical neuroimaging experiments are conducted with a very small number of subjects.

EEG and ERP

Due to neural activity, the brain constantly produces a small amount of electrical current that can be measured. EEG measures the summed activity of millions of brain cells under electrodes placed in various places around the skull.[29] Data are interpreted in terms of frequency (Hz), amplitude (microvolts), form, and distribution (sometimes converted into a brain map). Most often reported are frequency components, including delta (0.5—4.0 Hz), theta (4.5—8.0 Hz), alpha (8.5—12.0 Hz), and beta waves (12.5—32.0 Hz). EEG has been used for some time to study different levels of arousal and is now being employed to study cognitive processes in general and music processing specifically.[30]

While EEG tracks the brain's electrical activity over time, ERP examines the brain's immediate response to a stimulus in millisecond (ms) intervals. A computer averages EEG readings following multiple presentations of a stimulus. This allows extraneous aspects of the EEG to be cancelled out, while electrical activity occurring in time-locked response to the stimulus is revealed.[31] ERP data are evaluated for directional changes in the wave pattern (either positive or negative), intensity level (amplitude), and latency (time lapse). A P300 wave indicates a positive wave whose maximum amplitude occurred approximately 300 ms after the stimulus, while a N400 wave is a negative wave form occurring approximately 400 ms after the stimulus. The P300 has been more frequently studied in relation to music. It is hypothesized to be an indicator of “working” memory, comparing incoming stimuli to stored memories, and has been linked to the detection of musical events.[32]

MEG and SQUID

The brain’s electrical activity produces a magnetic field that can be measured just outside the skull through MEG, giving location information about neural activity. SQUID provides refined spatial information, in millimeters, and precise temporal resolution, in milliseconds.[33] This approach has been used in only a few studies related to music.[34]

MRI and fMRI

MRI provides very precise information about anatomical structures under the skin, but does not provide information about function.[35] It has been used to show structural features of musician’s brains.[36] A newer development, fMRI does provide data about both location and function. Currently, there is considerable interest in finding a way to use fMRI to study music. The difficulty is that both MRI and fMRI are very noisy environments for the subjects. The camera's motion within the scanner generates rhythmical noise that competes with musical perception. While it is possible to extract speech or other non-musical sounds from the ambient noise, it is not so easily done with music. Regular headphones cannot be used, due to the strong magnet. Researchers are attempting to deliver musical stimuli through pneumatic tubes or to develop better anti-noise cancellation devices. If these problems are solved, fMRI should prove to be a very valuable approach for studying music cognition.

PET

In PET, radioactively tagged oxygen, water, or glucose is inhaled or injected into the bloodstream. PET scans then detect brain metabolism or regional cerebral blood flow (rCBF) while the subject engages in an assigned task.[37] By means of paired-image subtraction (subtracting the activations of one task from another), areas of the brain most active during a specific task are identified.[38] Areas of deactivation (i.e., less active than during rest) also provide useful information. Because PET provides information about function but not location, it is mapped onto MRI data. The combination of the two tells neuroscientists “what” is going on “where.” PET is a powerful technique that is revealing important information about music processing.[39]

Taken collectively, these various brain imaging techniques are opening up new understandings about the brain in general and about music cognition specifically. The most rapid advancements are being made in this field and music psychologists, music educators, and music therapists should be aware of new findings as they are reported.

Neuromotor Research

Musical responses are both expressive (i.e., performing) and receptive (i.e., listening). Musical performance activates motor control areas in the brain to such a high degree that musicians may be considered small-muscle athletes.[40] A PET study of eight professional pianists confirmed this as motor systems in the brain were strongly activated during performance.[41] Transcranial Magnetic Stimulation (TMS), a technique for mapping neuromotor pathways, was used with 15 subjects to show that the motor cortex controlling the fingers increased in response to piano exercises, both actual and imagined.[42] Researchers used magnetic source imaging to compare nine string players with six non-musicians; the main finding was that the string players had greater neuronal activity and a larger area in the right primary somatosensory cortex that controls the fingers of the left hand than controls.[43] These effects were greater for those who started playing at a young age.

Highly precise and rhythmically coordinated movements are critical for musical performance and investigators are beginning to identify timing mechanisms in the brain.[44] A related issue is focal dystonia, a neuromotor problem in which the brain and hands (or other body parts) fail to communicate properly.[45] Several concert pianists have had major careers curtailed due to a focal dystonia in one hand. Highly practiced movements seem to be most affected, while other uses of the hand remain functional.

In the receptive mode, Thaut and colleagues have produced an impressive body of work on how Parkinsonian and stroke patients can regain motor function (e.g., walking or grasping) through rhythmic entrainment.[46] Rhythmic timing embedded in music serves as a cue to motor system timing mechanisms in the brain.

Affective Research

Data gathering techniques for studying affective responses to music fall into three categories: verbal reports, behavioral observations, and physiological responses.[47] In terms of finding out the brain's role in emotional responses to music, current strategies are quite limited. Recently, PET scans of ten amateur musicians indicated that different brain regions were activated in response to positive and negative music listening experiences.[48] Another avenue of approach is found in biochemical analyses of blood samples.[49] Music can elicit changes in such biochemicals as endorphins, cortisol, ACTH (adrenocorticotropic hormone), interleukin-1, and secretory immunoglobin A. The brain-music-biochemical relationship is not yet well understood, but does hold some promise. In particular, studies in psychoneuroimmunology are being used in music medicine to document the physiological effects (e.g., changes in blood chemistry) that music has on the body.[50] Fear and anxiety can be reduced in many clinical situations through the use of music.

Each of these research strategies has advantages and disadvantages. It is important to integrate findings from the various approaches into a more coherent whole. Where data from different techniques are in disagreement, efforts must be undertaken to resolve discrepancies. Wherever possible, it would be helpful to attack the same problem with more than one strategy. Particularly in the area of neuroimaging, it is important to keep up with new technologies and possibilities (e.g., with development of better sound delivery systems in fMRI).

Overall development

To what extent do genes specify the intricate working of the human brain? To what extent are the intricate workings of the brain acquired as a result of experiences? New advances in neuroscience have addressed the ancient "nature versus nurture" debate. In general, neuroscience research has shown nature or nurture alone do not determine brain development. Human brains at the prenatal stages are already interacting with the environment.[51] The brain appears to be more plastic and malleable during the first decade of life than in adulthood. According to Thatcher studies have shown that 40% of short-term and 70% of long-term connections in the brain are influenced by heredity. Therefore, 30% to 60% of the brain's connections come from environmental influences or an interaction of heredity and environmental influences.[52] Nelson and Bloom cite numerous demonstrations that show how positive or negative early experiences can alter both the structure and function of the brain.[53] Also, it is important to remember that a child's brain is not the same as an adult brain. There is agreement that during the first decade of life a child typically has up to twice as much neural activity and connections compared to adults.[54] The brain makes connections during the prenatal period and throughout life.[55] Some connections are found to be predetermined genetically, and others develop from environmental influences.[56]

Children as early as one day of age are able to make cognitive choices about their environment.[57] There are clear additive and regressive events in brain development. As shown in Figure 2 a child at birth may have the largest number of neurons that she or he will ever have. After the age of two years, the number of neurons remains nearly the same until 65 years of age. Synapses, the connection between neurons, form in the brain and change as the child develops.[58] During early childhood the percent of adult cortical levels of myelin and glial are increasing and may be influenced by the environment. Myelination of the nerve axons increases the efficiency of neural transmission. The glial cell is a major cell type in the brain that nourishes neurons. Interestingly, a study of Einstein's brain showed his brain had significantly more glial cells than the brain of the average human.[59] There are several glial subtypes but there is not yet enough information to consider an active role for the glial cells in behavioral development.[60] Also note that Figure 2 illustrates a decrease in the level of synapses between the approximate ages of 2 and 8 years. This decrease, theorized to be a type of "synaptic pruning," may occur because networks atrophy over time due to unused or less used connections. Brains do not make more connections and stop. It appears the brain makes more connections than it needs and then deletes unused or less used connections by the process of synaptic pruning. Although there is much growth and activity during the young years, there is evidence that there is room for change in the later years and recent research indicates that the adult brain is able to produce new cells (e.g., in the hippocampus of adult humans).[61] The complex interaction of innate abilities and environment will continue to be a viable mode of research. The complexity of the interaction between innate abilities and environment may also depend on the variability inherent in individual differences.[62] Possible individual differences include emotional traits, temperament, and cognitive and intellectual propensities.

Four concepts central to brain development are addressed in this section: critical periods, optimal periods, windows of opportunity, and plasticity. Critical period refers to the idea that there are time frames in which there will be no development or stunted development if certain stimulation is not present. The brain may be open to experience of a particular kind only during narrow periods of time. Missing a critical period in learning would be as if you were playing the solo triangle part in a symphony and didn't play your quarter note after the 30 measures rest. You missed your chance and the triangle is no longer needed or useful. There are many examples from animals in which experience must be timed very precisely to have an impact. A classic research example investigated the vision of 23 kittens.[63] Nobel Prize winners Hubel and Wiesel covered one eye of newborn kittens. The kittens grew up with only one eye in use. A few months later the covered eye was opened but it was in effect not connected to the brain. What makes this a 'critical' period is the finding that if the cats are later given visual stimulation, they are unable to use the stimulation to see. When deprived of visual stimulation in the covered eye until after the critical period, the part of their brain dealing with optical sensory data does not develop. One way of looking at critical periods is to imagine a sort of biological clock that it only opens during a certain period of development. An alternate view may be that experience has changed the brain so that the animal or person perceives and interprets the world in a different way. The experiences influence neural wiring and the neural wiring has an effect on recognition and/or interpretation of new sensory data. It is presently unknown if the critical period is due to biological clock mechanisms, the brain structures that have developed, or an interaction of the two. There may be critical periods in musical development and the search for these periods provides a fertile ground for research.

Authors often write about optimal periods as if they were critical periods, although presently there are no identified critical periods in musical development. An optimal period is used to refer to those periods in which development will be faster or easier. For example, it is easier to learn to sing in tune during the ages of 3-6 years than at 25-28 years of age. It may also be easier or more efficient to learn the language of classical, jazz or any style of music before the age of six. The period in all these cases is optimal rather than critical. There is no evidence to support the notion that a child cannot learn to sing if she or he does not have music experiences before, for example, six years of age.

There are indications of possible critical periods in music. For example, the music educator Gordon advanced the idea of developmental music aptitude.[64] He has found that children's scores on measures of musical aptitude do not change significantly after the age of approximately nine years. A few studies indicate optimal periods and point toward possible critical periods for music training. A group of adults with a history of violin training and a group of adults without violin training had their brains mapped using MEG.[65] The area of the somatosensory cortex representing the fingers of the left fingering hand was larger than that in the contralateral hemisphere representing the right bow hand and also larger than the corresponding area in non-musicians. This finding was consistent with reports of adult human amputees.[66] A possible critical period was indicated by a trend for the effect to be larger for individuals who had begun music training before the age of 10. Another optimal period and possible critical period was seen in a study of violin training where in a sample of 60 musicians and non-musicians those who started training before the age of 7 years exhibited increased corpus callosum size.[67]

Windows of opportunity refers to the idea that there are general time frames in which optimal or critical development will take place. The fact that writers often do not specify the window of opportunity as critical or optimal leads to much confusion. It is important to underline the difference between optimal and critical period when talking about windows of opportunity for brain development. For example, it is an overstatement of neuroscientific research to say that there is a window of opportunity for music during the ages of 3-7 years and if a parent does not give the child a chance during those ages, the child will not be musical. Bruer writes, "For most learning, particularly learning culturally transmitted skills and knowledge such as reading, mathematics, and music, the windows of experience-dependent opportunity never close."[68] On the other hand, there are indications of how early experience changes the way the brain works. Language research demonstrates how the six-month to twelve-month window of development is important and an optimal period for sound organization.[69] One study of 18 very young babies showed no brain activity differences while listening to native language and foreign language sounds. After a few months native and foreign language stimuli produced a difference in left hemisphere activity.[70] The finding may mean that changes in the way a baby hears the sound produces changes in the brain. Are music sounds in general and music sounds of the culture processed in the same way as language sounds during the second six months of life? If so, that period in an infant's life would be an optimal window of opportunity that may help children learn music faster or more efficiently than music education later in life.

Work with older populations has shown that there are further chances for the brain to adapt or rewire itself. It is prudent to question the simplistic view that the brain becomes increasingly difficult to modify beyond early childhood. Much brain development occurs in early childhood, but the brain is far from completed even at the end of adolescence. After accidental brain damage, for example, the brain may reassign function from the damaged part of the brain to an uninjured area.[71] This idea of how the physical structure of the brain changes as a result of experience is referred to as brain plasticity.[72] Plasticity refers to the notion that the brain is very adaptable, fluid, or plastic in the way in which it can adapt. Involvement in music may help keep the brain fluid or more fluid than no musical involvement throughout the human lifespan. A study of 678 nuns has indicated that rich experiences, including music, in older age will help keep the brain pliable and adaptable.[73] The study with nuns suggests that the adult brain can reorganize in response to positive experiences in the environment as well as negative experiences in the case of injury.

Theories and Theoretical Frameworks

A theory or at least a conjecture of what may happen when an idea is applied to a situation usually drives research. Neuroscience research is not different in this sense although neuroscientists are not at a stage of precisely unified theories of music and the brain. There are several current theories that warrant attention. Students and scientists are able to use the experimental theories in their own research by testing a theory in new situations or previously studied situations. Various models of brain function and architecture have been proposed over the past century.[74] An examination of current theories and studies that support them reveals that while some emphasize brain structure, others emphasize function. Many of these theories will undoubtedly be proven incorrect with time, some may be combined with others or new theories, many will be modified, and a few may even stand the test of time. The following theories have been selected from among many in the field because each has possible application to music education. The theories and theoretical areas are presented in alphabetical order of keyword.

Developmental shifts

The theory concerning development shift refers to the idea that at certain times of significant changes, shifts, or "brain spurts" occur in brain development.[75] These changes are thought to be part of the human biological developmental program. The shifts can be modified by the environment but are part of a normal developmental sequence. The notion finds its roots in cognitive theory (e.g., Piaget[76]) and the neurological basis for at least one developmental shift from the ages of five to seven has been related to cognitive theory. Sameroff and Haith compiled several articles that point to the efficacy of the idea that a child's brain chemistry and electrical activity inherently change in significant ways between the ages of five and seven.[77] Flohr and Miller lend support to this idea in relation to music with a series of EEG studies with thirteen young children.[78] One finding was that children at age seven exhibited significant EEG brain alpha activity differences to contrasting styles of music that were not present when the same children were five years of age. Music by Vivaldi stimulated different brain responses from the children than Irish folk song music while the children listened to the music and tapped rhythm sticks. These differences occurred in the motor strip and the temporal areas. The differences lend support to the idea of a developmental shift in music processing. Barber and colleagues also found brain activity differences in response to different styles of music.[79] Subjects in their study were 21 adult musicians and 25 non-musicians.

Future research investigating the theory of developmental shift will probably have much to say to music educators and educators in general. For example, when are the neurological attributes of a child best able to process sounds from music or language? Are most seven-year-old children ready (in the neurological sense) for abstract symbols in music or is it more appropriate at an earlier or later age? Developmental research since Zimmerman's pioneering cognitive research has affected music education.[80]

Developmental 'shift' and development research are fertile fields for music education and neurological researchers to collaborate.

Expert or Habituation

Another theory, "expert" or "habituation" (or even "efficiency") theory seeks to explain observed decreases in brain activity during certain tasks. One might expect to observe an increase in 'thinking' brain activity of a subject during a cognitive task. The opposite phenomenon has been found; experts and students after training show decreases in brain activity as opposed to novices engaged in the same cognitive task. Some studies have supported the idea that less energy or brain electrical activity may be used to perform a task in an expert's brain than in a novice's brain.[81] The idea is that the brain of a novice learner is less efficient and expends more energy when confronted with a challenging task than the brain of an expert learner.[82] Thus, music instruction should enable children to expend less energy during musical tasks.

There is, however, an alternative idea of why the decreases in activity are observed. Petsche and colleagues suggested that the reduced temporal lobe activity in the beta frequency bands of 75 healthy college students was related to habituation from listening to music.[83] It can be posited that the subjects developed a habituated type of cortical activity in their listening to music after they were involved in a period of music training. Habituation in an expert musician can also be thought of as the musician going on 'automatic pilot' while performing the music. She or he has learned the piece so well that the motor systems and cerebellum take over the performance and other areas in the cerebral cortex are deactivated thereby producing less electrical or chemical activity. Parsons and colleagues have found a similar result in their PET scan studies with musicians.[84] Cerebral blood flow in a musician's frontal cortex decreased as the musician performed music on keyboard as opposed to rest. The reduction in PET scan activity may lend support to the idea that the expert (or a person with training) uses less energy in a well-learned task. However, the expert performer also exhibits greater activation in other areas during performance and the current data do not show if there is less energy expended in the motor cortex among expert performers, which is what the expert theory would predict. The identified decreases in the research are clearly linked to expert musicians and students involved in music instruction. Future research will help determine the mechanisms involved.

Emotion or Affective Response

Research combining affective response and music may join to provide theories and research findings that explain aspects of cognition. Emotions in general (or more broadly affective responses) are difficult to study and much less emotion research has been done than cognition research. Nevertheless, progress is being made in the understanding of relationships between emotion and musical behavior. The emotional import of music experience is a strong component of music and music instruction.[85] Reimer reminds us "Teaching and learning music, then, have been understood to be valuable because they improve people's abilities to gain meaningful, gratifying musical experiences."[86]

Neuroscientists today have learned much about the organizing and structuring processes of neural connections and emotional response systems that influence higher thought processes. The way in which cognition is affected may occur "through a complex web of bi-directional processing between cortical and subcortical brain structures, neurochemicals and hormones, and through communication between central nervous system processing (including the brain and spinal cord) and the peripheral systems (including the autonomic nervous system and the somatic system)."[87] A significant area of progress is in the brain's effect on the body and emotions through the release of hormones, the area of neurochemistry.[88]

Investigators used PET to examine cerebral blood flow (CBF) changes related to affective responses to music.[89] Ten participants were scanned while listening to six versions of a novel musical passage varying systematically in degree of dissonance. CBF was observed in paralimbic and neocortical regions as a function of dissonance and of perceived pleasantness/unpleasantness of the music. The authors suggest that music may recruit neural mechanisms similar to those previously associated with pleasant/unpleasant emotional states, but different from those underlying other components of music perception, and emotions such as fear.

Modularity and connectionism

Many theories have elements of modularity or connectionism. The theory of "modules" in neuropsychological research refers to the idea that processes relating to music or language, for example, are carried out in distinct brain structures. Extreme modular theory would argue that these regions or modules are largely autonomous. On the other hand is connectionism, a theoretical approach that takes a holistic view of the brain. Connectionism argues that the brain functions as a whole and that a part of the brain can be recruited for multiple tasks. Either viewpoint in its extreme form may fail to explain research results and these two theories may not be mutually exclusive.

Current neuroimaging data suggest that the neural mechanisms supporting music are distributed throughout the brain.[90] The modular idea is combined with a ‘connection’ idea of interplay among modules. A module of music engages several different brain areas in a coordinated activity and is composed of sub-modules (e.g., musical syntax operators, timbre operators, and rhythm operators).[91] The sub-modules are distributed in various regions throughout the brain. At this point of the theory, each sub-module appears to be a specialized piece of neural machinery. For a music task such as playing a C major scale on the piano, the musical brain would have to integrate several sub-modules in a coordinated activity. There may be modules or super-modules or mechanisms that coordinate among different modules.

Research findings about hemispheric differences and localization can be explained with modular theory in the sense that modular theory regards different submodules each to be a specialized piece of neural machinery. For example, there is a neural network for language and another for music; in each case the neural networks link together locally specialized modules. These modules are largely autonomous, each doing its own work, although it is possible that some modules may be recruited for differing tasks (e.g., prosody for language and certain musical functions may be subserved by the same systems). Increasing evidence is pointing to modularity in music processing and the data support what is already known about language.[92] In addition, anatomical variances are a consideration in modular theory. Perhaps music training affects the actual size of brain areas that are important modules in music making. For example, the left planum temporale is larger among musicians with absolute pitch; musicians who started serious study before the age of seven, and among those with Williams Syndrome.[93]

In his work on the effect of music on spatial reasoning, Parsons found that the cerebellum is activated in a coordinated effort with areas of the cortex in music activity.[94]

Hetland has used the term 'rhythm theory' to describe Parson's module theory of music and spatial tasks.[95] The rhythmic elements of music (hence rhythm theory) operating in the cerebellum coordinated with areas in the cortex may be responsible for increasing ability to perform spatial-temporal mental rotation tasks. The rhythm theory is a module theory in the way that it explains how different areas of the brain work together.

Altenmüller and others attempted to demonstrate changes in cortical activity patterns with nine participants (average age = 13.8 years) after a 5-week period of music training.[96] The results suggested that musical training produced certain cortical brain activity patterns in different areas of the brain and that these activity patterns may depend on the applied teaching strategies. Flohr, Miller, and Persellin also reported EEG activity changes in different areas of the brain after a 7-week period with 22 preschool children (average age = 5.25 years) receiving music instruction versus children receiving regular classroom instruction.[97] The module theory supports the results of both studies in that different areas of the brain containing sub-modules operate in a coordinated activity. However, in the second study by Flohr and others, results showed an increase in some areas of the brain contrasted by a decrease in other areas. The module theory does not specify whether the sub-modules produce increased or decreased electrical activity. In addition, an increase in one module along with a decrease in another part of the brain may represent the way in which the brain relegates processing resources.

The term coherence may be viewed within the modular theory although coherence has been used to support connectionism. Connectionist models postulate "cognition occurs through a network of linked nodes. The nodes integrate activation through their excitatory and inhibitory links." [98] Coherence reflects the number and strength of coordination between different brain locations. Some authors believe that coherence demonstrates evidence of anatomical connections and information exchange between two brain locations.[99] Brain imaging studies have shown a relationship between music listening or music instruction and increased coherence activities in children.[100]

Coherence studies lend support to the idea that music instruction for children at an early age will promote more profuse and efficient connections. For example, Malyrenko and colleagues found that an exposure to music of one hour per day over a six-month period was found to have an effect on the brain electrical activity in a sample of 43 four-year-old preschool children. Brain bioelectric activity parameters indicated that listening to music resulted in an enhancement of the coherence function.[101] R. deBeus ran a coherence analysis on 20 preschool children's EEG data.[102] In a baseline, resting condition and while listening to music, deBeus found increased connectivity for a music-training group versus a no music-training group. Coherence patterns differentiated children with and without music training during a resting condition, and showed similar patterns as those identified by other researchers comparing trained musicians versus untrained musicians. The listening to music condition identified connections including a topographical pattern of auditory analysis, increased working memory activity, increased activity among musically sensitive areas, and increased activity between hemispheres. Two limiting points about coherence are important to note. First, coherence values are not well accepted by all neuroscientists and second, skilled performers in comparison with low-level performers in other fields (e.g., a high-level chess player with a non-chess player, a high-level mathematician with a mathematically unskilled person) would presumably show differences.

Multiple Intelligences

In Frames of Mind and later in Intelligence Reframed Gardner describes the concept of multiple intelligences.[103] Performing, listening to music, improvising, or composing music may require the use of at least eight intelligences. The eight types of intelligence used in music activities may include: music, visual-spatial (in the sense that instruments, e.g., cello, percussion, or piano, have a visual-spatial element), bodily kinesthetic (the way in which fine and gross movement functions in the perception of musical motion and is used in performing music), interpersonal (e.g., conductor and orchestral member), intrapersonal (e.g., expression of feelings through music), language as in singing, spiritual intelligence (e.g., in performance of sacred music, deriving spiritual meaning and interpretation in music), and logical-mathematical (e.g., rhythm durations). Neurological research has indicated that many parts of the brain are utilized as children are engaged in music making activities. The multiple intelligences idea may help explain why other types of intelligence are seemingly affected by music instruction. The theory that several kinds of thinking are required to learn and make music has been called a "near" transfer theory.[104] The quality of music instruction[105] or combination of activities used in music instruction could help facilitate the transfer. One should not expect transfer from music to other skills unless significant learning has occurred in music. The idea of multiple intelligences and "near" transfer may help explain the ways in which brain activity is affected by music instruction.[106]

Trion Theory

Shaw proposed a "trion" cortical model for the "coding of certain aspects of musical structure and perception" and defines the trion model as "a highly structured mathematical realization of the Mountcastle organization principle in which the cortical column is the basic neural network of the cortex and is comprised of sub-unit minicolumns, our idealized trions."[107] The cortex is to a large extent organized into vertical column of neurons. Shaw proposed that when the brain patterns predicted by his theoretical model were mapped onto pitches and instruments, recognizable human styles of music were found. Shaw's trion model provided a theoretical background for the much publicized and controversial "Mozart effect" studies.[108] This trion theory suggests that the musical and spatial processing areas of the brain are in some way shared, proximal, or overlapping. Thus, the relationship of music and spatial processing are linked by neurological connections in the cortex. Shaw and others write that a prewired neural connection is suggested because of the short-term effect of music instruction on spatial abilities.[109]

Any theory including the trion theory is difficult to test with current brain imaging techniques. However, an EEG study and a study outlining a new method of analysis for EEG data have been used to empirically test the trion theory.[110] In the EEG study a carry over of brain activity from listening to music to a spatial test was observed in three of seven subjects. The lack of effect in the other four subjects was perhaps due to individual differences, problems in application of the theory, the lack of a general effect, or other unknown causes. Research comparing and combining trion theory with other theories will be an interesting area for future research.

Neural Networks and Wiring

The concept of neural networks and wiring of the brain has appeared in our recent popular press and there is a notion or theory that music (or other environmental experiences) “rewire” the neural networks of the brain. The idea is that babies are born with a basic ‘wiring’ of neural networks. As the child interacts with the environment, the brain builds new connections between existing networks. The number of connections increase and also the way in which the data are transferred is changed. As a child grows, connections are made and changed (see Figure 2). One notion is that music and music instruction may affect the way, number, and quality of connections that are being made during development. The idea that the environment—and music can be part of the environment—interacts with heredity and influences the amount and quality of neural connections is not controversial. One research problem is that our knowledge does not include the extent to which music affects the connections.

Theories taken as a whole are not necessarily mutually exclusive and may in combination explain many of the effects of music on brain activity, musical development, and general development. One or two theories (e.g., modular and affective response) may prove to be useful in combination with another theory or prove the other theory to be incorrect.

General Findings

1) Human development hinges on the interplay between nature and nurture. Recent brain research challenges old assumptions about talent and innate ability—that the genes humans are born with determine how the brain develops. In general, neuroscience research has shown that nature or nurture alone do not determine brain development. The complex interaction among innate abilities, environment and also the variability inherent in individual differences influences brain development. Although there is much growth and activity during the young years, there is evidence that there is room for change in the brain during the later years.

2) Early care and nurture have a decisive, long-lasting impact on how people develop, their ability to learn, and their capacity to regulate their own emotions.[111] Children as young as one day of age are able to make cognitive choices about their environment, including musical choices.

3) Experience changes the physiological structure and operation of our brains. Music and music instruction have an effect on brain activity. Studies using various brain imaging techniques have documented some of these changes and also differences between trained and untrained musicians.

4) There is fertile ground for research in the several theories of brain function and structure. These theories need to be tested, modified, and combined with research and new techniques of imaging the human brain. Students and scientists may use brain theories in their research by testing a theory in new situations or previously studied situations.

5) The human brain has a remarkable capacity to change, but timing is often important and at some points crucial. Windows of opportunity are either optimal windows or critical windows. Extant research has not yet determined critical windows of opportunity for music education.

6) Improved technology will permit further investigation of the influence of music on the brain. A clearer understanding of how music and music-related tasks are manifested in the activity of the brain is an initial step in developing better instructional strategies for music education.

7) For a period of time, beginning in the 1970s, much has been made of music being in the right side of the brain. This over-simplification has been modified. Music is *not* in the right side of the brain alone; both sides are involved; in fact, sophisticated musical processing most likely involves the front-back, top-bottom, left and right sides of the brain in widely distributed, but locally specialized neural networks.

8) It is important to keep results of recent brain research in perspective. Neuroscience findings can be overstated.[112] On the other hand, it is easy to discount neuroscience findings because of problems with the use of new technology, difficulties interpreting data, and unproven brain theory. The neuroscience technologies are complicated and in evolution. Researchers and consumers of research need familiarity with the limits of each technique to properly assess validity of research.

9) It is important not to overstate and emphasize the non-musical outcomes of the influence of music on brain development. For example, if a small number of studies are used to emphasize a possible link between music study and mathematical skill, it becomes easy to interpret the goal of music study as the production of good mathematicians. There are clear and meaningful musical outcomes of music education.[113] The expressive import of music does not need a non-musical outcome to justify music education.

Future Directions

Future directions for neuroscience and music research probably will and should include:

1) Development and validation of theories of music learning and brain development supported by neuroscientific research. For example, one research problem is that our knowledge does not include the extent to which music affects the brain connections.
2) Increased infant research. Studying fetal and infant responses to music allows us to study the human brain with the least possible effect of prior environmental influence.
3) Music and neuroscience research may reveal activities that will help children develop musical skills more efficiently and effectively. Families and parents will be given information on specific enjoyable, interactive music strategies.
4) More projects dealing with the relation of music to emotion and temperament.
5) Continuing focus on music cognition. How does the human brain organize musical sounds into meaningful experiences? What are the developmental sequences in music cognition? Is music cognition completely autonomous or are there relationships among various intelligences?
6) Increased use of more than one type of brain imaging to test theories through improvements in brain imaging technology and neurochemistry. [114]
7) Increased collaboration between cognitive neuroscientists, neurobiologists, philosophers, and musicians. There is an increasing interest among neuroscientists in the study of music and the brain. Neuroscientists are interested in using music as a way in which other brain activity may be studied as well as examining music by itself. For example, music is different from language and can be used as a contrast in experiments designed to investigate brain activity and language.[115]
8) Continued movement toward research with greater external validity. For example, focus on musical stimuli and musically valid tasks.
9) Better education of the general public and music education profession so that patience is developed for basic research and sophisticated findings are not reduced to promotional “sound bites.”

10) Music educators and philosophers may bring to future neuroscience research the appreciation for the fluidity, creative constructs, and context-specificity of music. Music is more than sonorous stimuli; it is connected to cognitive, affective, kinesthetic, and social processes of each individual.

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