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Chapter I

NEUROMUSICAL RESEARCH: AN OVERVIEW OF THE LITERATURE

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ABSTRACT

With growing interest in the neuroscience of music among both neuroscientists and music educators, the task of reviewing the extant neuromusical research has become more exciting, if not a bit more complicated due to the diversity of topics and the increasing number of available studies. We provide an overview of neuromusical research by discussing its historical foundations (especially with the advancements of imaging technologies), support from ancillary areas (anthropology, ethnomusicology, ethology, and music psychology), support from fetal and infant responses to music, and support from studies of special musicians (prodigies, savants, Williams Syndrome musicians, and Alzheimer's patients). The main section presents findings and implications from recent neuroimaging studies by dividing the research into five categories: (1) Perception and Cognition, (2) Affective Responses, (3) Musical Performance, (4) Learning, and (5) Genetic Factors. Several broad conclusions regarding the state of human musicality are presented in the concluding section. Among these conclusions, perhaps the most valuable evidence that neuromusical research currently holds for educators is that musicality is a birthright of all people and that music processing is inherent to some degree in all humans.

Humanity has long wondered about the mind. Before Descartes proposed "I think, therefore, I am" or even before Plato and Aristotle ever contemplated the psyche, the oldest brain map on record was being drawn upon papyrus in Egypt almost 5,000 years ago[1]. Today, as neuroscientists draw increasingly detailed maps of the brain, they are pursuing an age-old

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[1] The Edwin Smith Surgical papyrus describes several case studies of neurological disorders and offers the oldest recorded use of the word "brain" (Minagar, Ragheb, & Kelley, 2003)

curiosity. Recently, a fascinating agenda gaining the attention of the neuroscience community has been the way the brain engages in musical processes. Perhaps the rising interest in neuromusical research is due to music's status as a human constant. Evidence of music has been confirmed in every civilization throughout history (Chailley, 1964) and based on research in anthropology (Merriam, 1964), enthnomusicology (Blacking, 1973), and psychology (Gardner, 1983), there is strong evidence to suggest that not only is music a cultural invariant, but that every person is born with the potential for some form of meaningful musical experiences.

While the connection between musical behaviors and brain processes has been apparent, advancements in imaging technologies are leading to more sophisticated investigations of music processing than ever before. Though valuable evidence can be gleaned from ancillary areas such as anthropology or from observational or behavioral studies, many exciting discoveries have come from measuring brain activations directly. Currently, neuroscience has at its disposal a broad array of imaging tools and ongoing refinements are making these tools even more powerful.

The purpose of this chapter is to survey the neuromusical research literature and to report on the general findings. No attempt to cite every study is made, as they are now far too numerous. Rather, broad, general conclusions are drawn and supported by a few representative studies. The chapter begins with three brief sections—an historical perspective, support from ancillary areas, and support from special musician populations—and the main section presents findings from brain imaging studies and related neuromusical literature.

A Brief Historical Perspective

German neurologists conducted some of the pioneering work beginning in the latter half of the 19th century (Henson, 1977), including August Knoblauch, who coined the term amusia (i.e., the loss of musical abilities) and began to make clinical diagnoses (Johnson & Graziano, 2003). However, experiments involving direct measurements of brain activations to musical stimuli did not occur until much later. Three types of studies relevant to an understanding of music and the brain began to appear near mid-20th century. Two clinicians prepared a battery of tests to determine the extent of amusia following brain damage (Botez & Wertheim, 1959; Wertheim & Botez, 1961). Studies using dichotic listening tasks began appearing in the 1960s in an attempt to determine contributions of the left and right hemispheres toward musical behaviors (e.g., Kimura, 1964)[2]. Finally, experiments on musical behaviors using the electroencephalogram (EEG) began to be published in the 1970s (Wagner & Hannon, 1975). One of the earliest, if not the first, comprehensive reviews of music and brain research was published in 1977 (Critchley & Henson, 1977).

The advent of more powerful imaging technologies, such as PET, MRI, and fMRI have led to a steep rise in neuromusical research as can be seen in Figure 1. While redundancy

[2] Sergent (1993) subsequently found the limitations of this technique so considerable as to call into question any relevant findings.

among databases may account for some of the large numbers, it is clear that more and more neuroscientists are including music as a topic of interest.

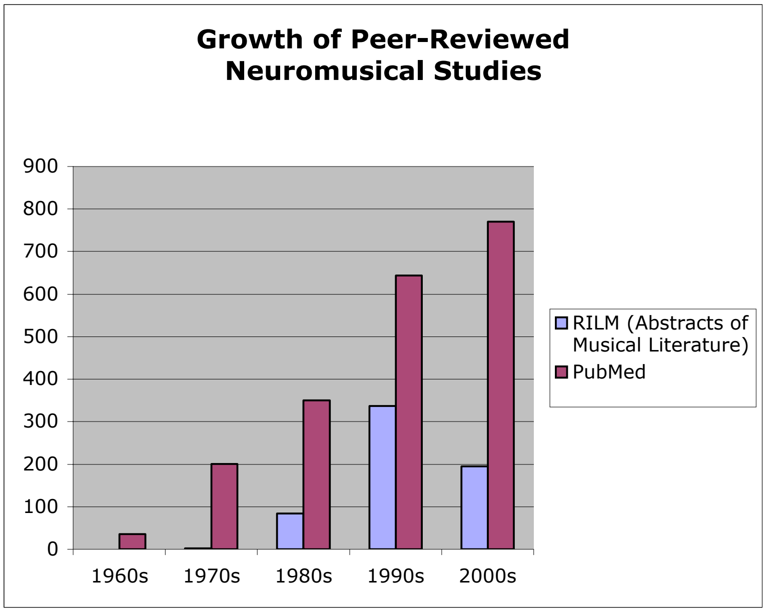

Figure 1. A graphic representation of the rising number of neuromusical studies (*y* axis) found in a keyword query for "music and brain" in two research databases of scientific journals during the past 45 years (*x* axis). Figures do not account for possible overlap (i.e., redundancy between databases).

Increasing attention to neuromusical research has led to three recent conferences and the attendant publications of proceedings (Avanzini et al., 2003; 2005; Zatorre & Peretz, 2001). As can be seen in 1, 170 articles have appeared in these three publications alone.

Table 1. Articles published from recent conference proceedings

Title of Book	NYAS Annals Vol.	Year	# of articles
The Biological Foundations of Music	930	2001	48
Neurosciences of Music	999	2003	69
Neurosciences of Music II	1060	2006	53
		Total	170

Another view of the scope of this literature can be seen in Table 2. Numbers may be taken as rough approximations of the frequency with which different technologies have been used to study music and the brain. Factors such as cost, access to equipment, and length of time the technology has been available play into the overall numbers.

Table 2. Keyword searches in selected online databases. A keyword search chart of potential neuromusical studies. RILM* and CAIRSS* are limited to music related research and thus, keyword searches within these databases were conducted using only neuroscience terms without using the keyword "music"

Neuromusical keyword search tallies (as of 12/4/05)	*PubMed*	*PsycINFO*	*RILM**	*CAIRSS**	*ERIC*	*Totals*
"Music" and "Brain"	951	691	830	1456	176	4104
"Music" and "EEG" (Electroencephalography)	293	138	81	115	5	632
"Music" and "MRI" (Magnetic Resonance Imaging)	190	14	13	26	1	244
"Music" and "fMRI" (functional Magnetic Resonance Imaging)	184	22	11	0	0	217
"Music" and "PET" (Positron Emission Tomography)	37	24	77	8	36	182
"Music" and "ERP" (Event-Related Potentials)	30	36	21	48	1	136
"Music" and "MEG" (Magnetoencephalography)	35	18	63	3	3	122
"Music" and "TMS" (Transcranial Magnetic Stimulation)	9	3	11	0	0	23
"Music" and "NIRS" (Near-Infra-red Spectroscopy)	2	0	0	0	0	2
"Music" and "DTI" (Diffusion Tensor Imaging)	2	0	0	0	0	2
Totals						5664

SUPPORT FROM ANCILLARY AREAS

Anthropology and Ethnomusicology

Anthropologists and ethnomusicologists have provided abundant evidence that all groups of human beings, always and everywhere, are musical (Chailley, 1964; Hood, 1971; Merriam, 1964; Nettl, 1983) and the ubiquity of music in all the world's cultures caused Blacking (1973) to claim that music is a species-specific trait. Lomax (1968) examined 233 cultures worldwide with a specialized coding and analysis technique called cantometrics. He determined that music, especially singing, is a universal form of human behavior. Although work on the genetic basis of musicality is just now beginning (Baharloo, Service, & Risch, 2000; Gregersen et al., 2000), anthropologists and ethnomusicologists provide strong support that there is a biological basis for musicality.

Ethology

The earth is filled with the sounds of animals and many of these sounds indicate sophisticated processes at work. In the rainforests of Borneo, male tree-hole frogs adjust the frequency of their calls over a wide range to match the resonating point of the logs in which they build their nests (Lardner & Lakim, 2002). Because it rains frequently, the logs fill up with varying levels of water thus changing the resonating point. Female tree-hole frogs routinely select males that do the best job of emitting a resonant sound.

Male humpback whales create extended vocalizations (i.e., compose songs) that are shared and recognized by members of a given pod (Gray et al., 2001). Over the course of a breeding season this song is varied so that by the next season it is completely changed (Payne, 2000). Whale vocalizations utilize many features that bear similarities to human music, such as improvisation, imitation, rhythm patterns, phrases, pitch intervals, formal structures, and even rhyming schemes.

Nearly half of the 9,000 species of birds are songbirds who, like whales, invest their songs with many of the same characteristics as human music (Gray et al., 2001; Whaling, 2000). Although males are the primary singers, antiphonal singing or duetting involves both males and females (Slater, 2000). In duetting, a male and female bird alternate phrases in an exchange so tightly interwoven it can sound as if only one bird is singing. Apes also engage in duetting, although singing, in general, is practiced perhaps by as little as 11% of primate species (Geissmann, 2000).

Granted that animals make sounds; what does this have to do with human musicality? A number of scholars have written intriguing accounts of an evolutionary basis of musicality (Wallin, Merker, & Brown, 2000). As with the literature from anthropology and ethnomusicology, studies of animal soundmaking provide strong circumstantial support for neural mechanisms in the human brain dedicated to music processing and musical behaviors.

Music Psychology

The field of music psychology has provided considerable information that provides circumstantial evidence about the brain's role in musical behavior. Journals, such as *Psychology of Music* and *Music Perception*, conferences and their attendant proceedings, such as the *Society for Music Perception and Cognition*, and books such as *Psychological Foundations of Musical Behavior* (Radocy & Boyle, 2003), *The Psychology of Music* (Deutsch, 1999), and *Handbook of Music Psychology* (Hodges, 1996) have led to an extensive knowledge base.

Much is known about the cognitive processes involved in specific musical operations and this information provides a strong foundation for neuroscientific investigations. For example, music conductors were faster and more accurate in pitch discrimination, temporal order judgments, and in spatially locating targets by sound than untrained controls (Hodges, Hairston, & Burdette, 2005). These same subjects also demonstrated a benefit from the combination of auditory and visual information that was not observed in control subjects when localizing visual targets. Subsequently, brain regions known as convergence zones for the integration of sensory input were identified as potential areas underlying the conductors' superior multisensory temporal order judgments.

SUPPORT FROM INDIRECT APPROACHES

Fetal and Infant Responses to Music

Studying fetal and infant responses is useful in that the role of learning is minimized in comparison to older subjects. Considerable evidence indicates that during the last trimester, a fetus responds to musical sounds (Lecanuet, 1996). Likewise, infants selectively respond to music at very early ages (Fassbender, 1996; Panneton, 1985), express preferences for consonance over dissonance (Trainor, Tsang, & Cheung, 2002) and possess many musical processing skills (e.g., detection of changes in melody, in terms of pitches, rhythms, tempo, and contour) (Trehub, 2001; 2003; 2004). In turn, infant preverbal speech and singing includes musical qualities such as timbre modulation, melodic contour, and timing (Fridman, 1973; Papousek, 1996; Trevarthen & Malloch, 2002). Research on fetal and infant responses to music provides strong confirmation of inherent neural networks that subserve musical processing.

Studies of Special Musicians

Special musicians include musical prodigies, savant syndrome musicians, Williams Syndrome musicians, and Alzheimer’s musicians. In each case, it would be difficult, if not impossible, to account for musical behaviors exhibited without the presence of relevant brain structures.

There are numerous musicological studies attesting to the brilliance of the young Mozart, along with more recent scientific explorations of his genius (Banks & Turner, 1991; Gedo, 1986). Révész (1925/1970) conducted a psychological study of a 20th century musical prodigy, Erwin Nyiregyházi. Gardner (1983) contends that music emerges earlier than any other “gift” and this is certainly exemplified in precocious violin students who may be as young as two years old (Suzuki, 1983).

Savant syndrome and Williams Syndrome musicians represent cognitively-impaired individuals who, despite severe limitations in other domains, display astonishing musical skills (Levitin & Bellugi, 1998; Miller, 1989). Musicians with Alzheimer’s disease may also fall into this category (Crystal, Grober, & Masur, 1989; Sacks, 1999). Providing further information about the role of the brain is the fact that some Alzheimer’s patients can sing when they can no longer speak coherently (Johnson & Ulatowska, 1995).

GENERAL FINDINGS FROM NEUROMUSICAL RESEARCH

Modern neuroscience has access to a wide variety of technologies and protocols to study the brain. These include studies of brain damage (i.e., connecting lesion sites to deficits in performance) as well as imaging tools such as positron emission tomography (PET), magnetic resonance imaging (MRI), functional MRI (fMRI), electroencephalography (EEG), event related potentials (ERP), transcranial magnetic stimulation (TMS), magnetoencephalography (MEG), and diffusion tensor imaging (DTI). Each of these approaches has strengths and weaknesses and it is always important to pool findings from different approaches for a more complete picture. Rather than organize the literature according to protocol, findings are arranged under the following rubrics: (1) Perception and Cognition, (2) Affective Responses, (3) Musical Performance, (4) Learning, and (5) Genetic Factors.

1. Perception and Cognition

Perception is based on the sensory information that is gathered by the brain regarding one's external and internal environment. On the other hand, the highest order of nervous function draws upon memory, emotion, and cognition for complex thought processes (Shepherd, 1994). To date, the majority of neuromusical research has focused on music perception since most of the musical stimuli measured thus far with human subjects are no more advanced than a musical phrase (Peretz & Zatorre, 2003). Before observing something as complicated as music at the cognitive level, many researchers have acknowledged the initial investigative value of using a bottom-up approach whereby each element of music processing is studied separately (Zatorre & McGill, 2005). The general idea to this reductionist approach is that by studying the specific neural substrates of music processing's discrete components (e.g., pitch, rhythm, or timbre), the foundation will be set for future studies to explore the gestalt of these discrete components in holistic musical experiences.

But identifying music's discrete components presents an intriguing dilemma because some of these components may be strictly delegated to the processing of music (e.g., melodic pitch relationships or metric rhythm patterns), while other components such as long-term memory are activated by multiple cognitive systems. Thus, in the current review of neuromusical perception studies, it is important to recognize that conclusions are frequently based on brain activations in response to a discrete musical element (e.g., pitch or rhythm) and not a holistic musical experience. For example, several neuroimaging studies support the common observation that right hemispheric regions are engaged in the perception of pitch (Kohlmetz et al., 2003; Kuriki et al., 2005; Peretz & Zatorre, 2005; Schneider et al., 2005; Shahin et al., 2003; Warrier & Zatorre, 2004) and that left hemispheric regions are engaged in the perception of rhythm (Bengtsson & Ullen, 2006; Di Pietro et al., 2004; Schneider et al., 2005; Vuust et al., 2005). However, this evidence only offers an informative insight into *part* of the human musical experience.

The entirety of music processing is much more complicated than an examination of the brain's hemispheric or localized parts—an idea that has been strengthened in the last few years by neuroimaging studies revealing widespread bilateral brain activity during discrete music processing tasks (Bunzeck et al., 2005; Kristeva et al., 2003; Kuck et al., 2003; Lo & Fook-Chong, 2004; Lo, Fook-Chong, Lau, & Tan, 2003; Popescu, Otsuka, & Ioannides, 2004; Satoh et al., 2003) and even some cases of more holistic musical experiences (e.g., piano performance of Bach) (Fox, 2001; Parsons, 2001; Parsons et al., 2005). Yet more data is needed, especially for generative holistic musical experiences such as composition and improvisation.

The available neuroimaging research of both discrete and holistic musical processes is still too limited to make many strong conclusions about the nature of music cognition and whether it is (a) specifically localized to distinct neural networks (i.e., modularity), (b) made up of shared neural networks that are associated with other brain processes (i.e., connectionism), or (c) perhaps a little bit of both. Recent studies addressing the level of music cognition have explored the possibility of connections between music and language processing (Koelsch et al., 2003; Koelsch et al., 2004; Levitin & Menon, 2003; Saffran, 2003; Schon, Magne, & Besson, 2004), or the role of brain regions mediating pleasure, autonomic and cognitive processes which contribute to the enjoyment and ubiquity of human musical experiences (Khalfa et al., 2005; Menon & Levitin, 2005).

Another important observation is that brain activation sites can be altered in response to changes in three variables: musical stimuli (e.g., “real” music as opposed to MIDI-generated chord sequences), tasks (e.g., holistic listening versus discrete features detection), and subjects (e.g., trained versus untrained). For example, musical training appears to increase the areas of brain activation during music processing (Cui et al., 2005; Koelsch et al., 2005; Schneider et al., 2005; Seung et al., 2005) as well as increase the efficiency of brain activity during musical tasks (Haslinger et al., 2004; Meister et al., 2005). Furthermore, while most people regardless of their musical experience are able to identify deviations from expected melodic, harmonic, and rhythmic outcomes (i.e. mismatched negativity), musically trained individuals appear to have an enhanced ability to detect these musical deviations (Besson, Faita, & Requin, 1994; Fujioka et al., 2004).

Changing any one of these experimental variables (stimuli, subjects, or tasks) may affect the location of brain activation sites; therefore, to say that musical element X (e.g., pitch) is associated with region Y (right auditory cortex) in every situation may not be true. Also, it should be noted that often there are activation sites that have been “subtracted out” due to the analysis process. In many protocols, activations in a baseline condition (e.g., passive listening to a musical passage) are subtracted from the activations in a task condition (e.g., listening for pitch changes in a similar musical passage). The resultant findings of brain activations during the task condition therefore do not show all the activations, only those “beyond” or in addition to the control condition. Thus, it is not so much that certain brain regions are inactive in the task condition, rather it is that they are active in a variety of conditions.

Pitch Perception

While certain aspects of pitch perception have been found to occur in the brainstem (Gulick, Gescheider, & Frisina, 1989), multiple neuroimaging studies have consistently observed that the right secondary auditory cortex is the area responsible for various types of pitch perception such as pitch discrimination (Schneider et al., 2005; Seung et al., 2005), amplitude modulation (i.e., changes in loudness) (Hart, Palmer, & Hall, 2003), and spectral shape awareness (i.e., timbre perception) (Hall et al., 2002; Kohlmetz et al., 2003; Schneider et al., 2005; Thivard et al., 2000; Warrier & Zatorre, 2004). Finally, studies into the perception of simultaneous different pitches (i.e., harmony) observed bilateral activation during music processing (Koelsch et al., 2002; Koelsch & Mulder, 2002; Maess et al., 2001; Satoh et al., 2003).

Rhythm Perception

In contrast to pitch perception, neuroimaging studies of temporal processes (i.e., rhythm perception) often involve the activation of regions in the left hemisphere (Bengtsson et al., 2005; Di Pietro et al., 2004; Schneider et al., 2005; Vuust et al., 2005). This was suspected even before neuroimaging was available based on observations that it is easier for more people to tap a complex, syncopated rhythm with the right hand than with the left, even when left-handed subjects are observed as well (Ibbotson & Morton, 1981). More recent findings have confirmed the left hemispheric dominance of temporal grouping through neuroimaging studies of rhythmic tapping exercises (Sakai et al., 1999) and brain lesion studies (Di Pietro et al., 2004; Penhune, Zatorre, & Feindel, 1999) as well as identifying the involvement of the cerebellum in rhythmic awareness (Janata & Grafton, 2003; Penhune, Zatorre, & Evans, 1998).

While the perception of rhythm has frequently implicated neural regions in the left hemisphere, metric grouping processes (i.e., beat perception) have been observed in the right hemisphere (Li et al., 2000; Penhune et al., 1999) or even bilaterally (Kuck et al., 2003) further strengthening the argument for holistic music processes occurring throughout the brain.

2. Affective Responses

For the average music lover, emotional responses to music are often cited when people attempt to describe why they value music. Philosophical investigations of emotion have produced several famous treatises on this complex relationship (Langer, 1967; Meyer, 1956; Reimer, 1989) and a recent book has brought the topic to the fore in music psychology (Juslin & Sloboda, 2001). Yet among neuroscientists, emotion and music has not received much attention, perhaps because of the difficulties involved. However, interest in this topic has increased of late.

Understandably, studying affective responses to music is problematic given the subjective nature of emotional experiences. Music is known to have a wide range of physiological effects on the human body including changes in heart rate, respiration, blood pressure, skin conductivity, skin temperature, muscle tension, and biochemical responses (Bartlett, 1996). Responses to music that change the body's chemistry have been of great interest in the medical field for the therapeutic benefits that musical experiences bring to patients. A small but intriguing body of research suggests that musical experiences combined with imagery strengthen the immune system by promoting the release of stress-reducing biochemicals such as interleukin-1 (Barlett, Kaufman, & Smeltekop, 1993) or by controlling the release of stress-related biochemicals such as cortisol (Tanioka et al., 1987) and immunoglobulin A (Tsao et al., 1991). The use of music is proving very successful for alleviating pain in patients, speeding up recovery time, and reducing drug dosages up to 50 percent (Spintge, 1992).

Music's effect on the release of neurotransmitters in the brain is gaining interest as well. Serotonin is a neurotransmitter commonly associated with feelings of satisfaction from expected outcomes, and dopamine is associated with feelings of pleasure based on novelty or newness. In a study of neurochemical responses to pleasant and unpleasant music, serotonin levels were significantly higher when subjects were exposed to music they found pleasing (Evers & Suhr, 2000). Another study with subjects exposed to pleasing music found that dopamine levels increased while connectivity between areas of the brain responsible for mediating reward, autonomic, and cognitive processes was observed (Menon & Levitin, 2005). Even rats with hypertension were able to reduce their blood pressure and increase their dopamine levels when they were exposed to Mozart (Sutoo & Akiyama, 2004).

In what was perhaps the earliest imaging study on this topic, subjects underwent PET scans while listening to a musical passage that varied in levels of dissonance (Blood et al., 1999). Paralimbic and neocortical regions covaried with the degree of perceived pleasantness/unpleasantness. Subsequently, Blood and Zatorre (2001) determined that pleasing music resulting in "chills" activated areas of the brain believed to be involved in the regulation of reward and motivation (e.g., the basal forebrain, brainstem, and the orbitofrontal cortex). In a third study, musically untrained subjects listened to unfamiliar music that they reported as having enjoyed (Brown, Martinez, & Parsons, 2004). Bilateral activations were distributed widely throughout limbic and paralimbic regions. These were stronger in the left hemisphere, which is consistent with hypotheses about positive emotions being more strongly registered on the left. Overall, brain regions activated were those concerned with emotion, reward, or motivation.

The musical activation of areas involved in mediating biological responses for rewarding stimuli (e.g., food or sex) is sparking new interest in emotion research because music appears to connect the rational parts of the modern brain with the survival-based systems of the primordial brainstem (Zatorre & McGill, 2005). Perhaps the importance that music has achieved throughout humanity is based on the way it appeals to both our feelings and our intellect.

3. Musical Performance

The act of making music is so intensely physical that neurologist Frank Wilson (1986) referred to musicians as small-muscle athletes. The sensorimotor cortex is responsible for interpreting incoming sensory information and controlling the muscles throughout the body. In conjunction, the basal ganglia control large groups of muscles in cooperative functions, and the cerebellum regulates intricate muscle movements and stores habituated motor patterns. The brain is highly adaptable and with repetitive training, the brain's homunculus (i.e., sensorimotor map) is reorganized accordingly (Kaas, 1991). For example, long-term musical training has been found to increase the area of the motor cortex responsible for controlling the fingers of violinists (Elbert et al., 1995) and pianists (Meister et al., 2005).

Very few imaging studies have been conducted while musicians were in the act of performing. Resultant activation sites for music making are extensive and diffuse. These include:

- Pianists (Parsons et al., 2005): primary motor cortex, corresponding somatosensory areas, inferior parietal cortex, supplementary motor area, motor cingulate, bilateral superior and middle temporal cortex, right thalamus, anterior and posterior cerebellum, superior and middle temporal cortex, planum polare, thalamus, basal ganglia, posterior cerebellum, dorsolateral premotor cortex, right insula, right supplementary motor area, lingual gyrus, and posterior cingulate. Also noted were strong deactivations in posterior cingulate, parahippocampus, precuneus, prefrontal, middle temporal, and posterior cerebellar cortices. Mental rehearsal of a piano exercise activates the same motor cortex areas as performing the actual piano exercise (Pascual-Leone et al., 1995).

- Violinists (Kristeva et al., 2003; Langheim et al., 2002; Nirkko et al., 2000): bilateral primary and secondary sensorimotor areas, supplementary motor and premotor areas, bilateral superior parietal lobule, right inferior frontal gyrus, bilateral mid-frontal gyri, and bilateral lateral cerebellum, bilateral frontal opercular, primary auditory cortex Many of these same areas, though with some differences, were activated during imagined performances.
- Singers (Brown et al., 2004): primary and secondary auditory cortices, primary motor cortex, frontal operculum, supplementary motor area, insula, posterior cerebellum, and basal ganglia.

Changing variables such as musical instrument or tasks performed results in changes in activation sites. Thus with so few studies in the literature, these findings perhaps hint at rather than definitively identify brain regions involved in musical performance. Perhaps a more important concept to be realized is that musical performance, indeed all musical behaviors, are subserved by widely-distributed, but locally-specialized neural networks.

Listening to music also generates motor responses such as toe-tapping and head nodding. Thaut and colleagues have harnessed this natural response in helping Parkinsonian and stroke patients regain motor control (McIntosh et al., 1997; McIntosh, Thaut, & Rice, 1996; Thaut et al., 1996). In fact, Rhythmic Auditory Stimulation (RAS), which involves rhythmic entrainment, has been listed as one of five research-supported treatments for motor rehabilitation (Hummelsheim, 1999; Mauritz, 2002).

Using fMRI, investigators determined that the cerebellum is involved when conscious processing is required for rhythmic tasks (e.g., tapping to a rhythm) but is not involved in subconscious processing, as when rhythmic cues elicit motor entrainment (Molinari et al., 2003; Thaut, 2003). Using MEG and PET, Thaut (2003) confirmed these findings by showing that rhythmic processing engages widely distributed cortical and subcortical neural networks. These investigations are laying a foundation for an understanding of why musical rhythms are effective in entraining motor behaviors.

4. Learning

The role of the brain in music learning is an exceedingly complex one and much more awaits discovery before definitive statements can be made. However, progress is being made at a rapid pace. Studies relating to music learning can be organized, somewhat arbitrarily, into those that deal with pruning and plasticity, and memory.

Neural Pruning and Plasticity

From birth on, genetic instructions and life experiences work together to sculpt the brain to its eventual adult configuration. In the first years of life, there is a massive overproduction of synapses by as much as 50% (Berk, 2004; Stiles, 2000). Throughout childhood, these synaptic connections are either strengthened with repeated use or deleted due to lack of use in a process called neural pruning (Chugani, Phelps, & Mazziota, 1993; Gopnik, Meltznoff, & Kuhl, 2001). Different regions of the brain shed synapses at different rates and at different times (Stiles, 2000; Thompson et al., 2000; Webb, Monk, & Nelson, 2001).

The anatomy and physiology of the brain are affected by a person's experiences throughout life (Stiles, 2000). Shaping neural pathways through life experiences is known as plasticity and these changes can occur either by positive influences (e.g., learning and training) or by negative influences (e.g., injury and illness) (Nelson & Bloom, 1997). For example, when one area of the brain is damaged, nearby neural pathways are sometimes able to reorganize and assume the responsibilities of the damaged areas (Taupin, 2006; N. Ward, 2005). Conversely, as behaviors are learned over time, the morphology of the brain changes.

Musicians' brains are models of neuroplasticity (Muente, Altenmueller, & Jaencke, 2002; Pantev et al., 2001; Ross, Olson, & Gore, 2003; Schlaug, 2001) as changes have been observed in such brain structures as the auditory cortex (Schlaug et al., 1995 a), the corpus callosum (Lee, Chen, & Schlaug, 2003; Schlaug et al., 1995 b), cerebellum (Hutchinson et al., 2003), gray matter (Gaser & Schlaug, 2003; Sluming et al., 2002), and the motor cortex (Elbert et al., 1995; Schlaug, 2001). In general, these changes are more pronounced when subjects started studying music seriously before the age of seven.

Four-year old children engaged in daily classical music listening activities for six months were found to have significant increases in brain activity as compared to controls (Malyrenko et al., 2003). Also, four-year olds receiving Suzuki training had greater auditory cortex responses to tonal stimuli than untrained children (Trainor, Shahin, & Roberts, 2003). Children aged four to six who received musical training exhibited EEG patterns during music listening activities, suggesting increased cognitive activity and greater relaxation than untrained children (Flohr, Persellin, & Miller, 1996).

Studying music beginning at an early age causes increases in the left auditory association cortex (Schlaug et al., 1995; Zatorre et al., 1998); alternatively it is possible that left–right ratios are a result of neural pruning in the right auditory association cortex among musicians (Keenan et al., 2001). Strengthening of neural connections is seen in the fact that auditory cortex in both hemispheres responding to piano tones is 25% larger among experienced musicians, again, the effect being greater for those who begin musical studies at an early age (Pantev et al., 1998). Instrumentalists (e.g., violinists and trumpeters) are more responsive to the tones of their own instrument (Pantev et al., 2001). Numerous studies have shown differences in electrical brain responses between trained and untrained musicians (Altenmueller et al., 2000; Faita & Besson, 1994; Lopez et al., 2003; Nager et al., 2003; Tervaniemi & Huotilainen, 2003). In general, musicians show faster and stronger electrical responses than controls, reflecting a greater ability to process musical information and to complete musical tasks successfully.

Based on their review of neuromusical research, Peretz and Zatorre write: "Musicians appear to recruit more neural tissue or to use it more efficiently than do nonmusicians" (2005, p.105). While it is becoming clear that musical processes affect neural development in various ways, a clearer understanding of the influence these experiences have on neural development and brain organization will require more longitudinal studies of musically-trained subjects for longer periods of time such as recording brain changes across the span of time a child receives music lessons. Such a study is now underway (Schlaug et al., 2005).

While genetic influences are likely at play as well (see subsequent discussion), this body of research demonstrates the effect of music learning experiences on the brain. The notion of neural plasticity in response to musical experiences was confirmed in an experiment by Bangert and Altenmueller (2003) in which they observed increases in motor cortex activations in as little as 20 minutes in beginners who received piano instruction. This is in contrast to professional pianists who showed less activation in primary and secondary motor cortex than controls, suggesting greater efficiency (Jaencke, Shah, & Peters, 2000). It appears that once the task is learned, and perhaps habituated (e.g., scales), fewer neural resources are required.

Memory

The experiences of life are stored in the brain in two ways: short term (i.e., working memory) and long-term memory. Investigations into the forms of musical working memory indicate that pitch recognition and tonal memory engage the right temporal cortex (Zatorre & Samson, 1991) and areas of the frontal cortex (Gaab et al., 2003). These findings suggest that musical working memory may be a specialized subsystem of general working memory (Marin & Perry, 1999).

In terms of long-term musical memory processes (e.g., recognizing familiar melodies), activation of the frontal cortex and left inferior temporal lobe is a key difference from musical working memory (Platel et al., 2003; Platel et al., 1997). Using musical imagery has been a useful method of measuring long-term musical memory by taking brain scans of subjects as they imagine (but do not hear) a familiar tune. Apparently, imagery accesses the perceptual systems that are involved in music cognition as demonstrated by activations of the secondary auditory cortices during imagined melodic rehearsals (Halpern & Zatorre, 1999; Zatorre et al., 1996), tonal sequences (Penhune et al., 1998; Yoo, Lee, & Choi, 2001) or even just isolated pitches (Halpern et al., 2004; Pepper, 2005). Furthermore, activation of the auditory cortex in the absence of acoustical stimuli suggests that musical memory is a subjective experience (Peretz & Zatorre, 2005).

Since it is one's memories that serve as the basis for subjectivity, much interest has been dedicated to how musical memories are formed, stored, and retrieved, and how this process may be implicated not only in the recognition of familiar musical stimuli, but in a greater sense, how musical memories may connect to affective responses, non-musical memories, and even serve to trigger personally reflective states of consciousness. It is interesting to note that the rostral medial prefrontal cortex (RMPFC), a region of the brain recently implicated in the working memory tracking of melodic tonality during multiple modulations (Janata et al., 2002), is also the region that has been associated with personal reflections of self-knowledge (Kelley et al., 2002), the cognitive evaluation and control of emotions (Ochsner & Gross, 2005), and the ability to maintain attentional monitoring of external stimuli in conjunction with non-stimulus internal goals (e.g., abstract thoughts) (Gilbert, Frith, & Burgess, 2005).

There is also evidence that the RMPFC is one of the last regions of the brain to deteriorate in Alzheimer's patients (Thompson et al., 2003), an observation made even more fascinating given the way that Alzheimer's patients are sometimes able to engage in musical activities long after other cognitive functions have been lost (Crystal et al., 1989; Cuddy & Duffin, 2005; Johnson & Ulatowska, 1995). Janata (2005) suggests that the significance of the RMPFC may be a neural point at which some form of music processing interacts with autobiographical memories.

5. Genetic Factors

While music processing is common among all human beings, the extent of a person's musical capacity is not simply based on a *tabula rasa* in which everyone learns to be musical from the same blank slate. Although every brain has the same basic anatomy, the complex interaction of nature and nurture (i.e., genetic expressions and environmental experiences) combine to produce the unique neural organization of each human brain (Oerter, 2003). Determining the exact degree of influence from these varying factors is what remains unknown.

To illustrate the challenge of measuring the difference between nature and nurture, consider that while all humans have the capacity to be musical to some degree, it is widely accepted that Mozart probably had a greater genetic potential for music processing than the average person. However, even Mozart's natural disposition for music would not have flourished if he had not been given the opportunity to nurture his brain through musical exposure, training, and practice.

The development of Absolute Pitch (AP) is one example of music processing that seems to be determined by both genetic and environmental influences. Research showing that AP is a hereditary trait (Baharloo et al., 2000; Drayna et al., 2001; Gregersen et al., 2000) is balanced by evidence that explores the effect of musical training on the development of AP (Takeuchi & Hulse, 1993; W. Ward, 1999; Zatorre, 2003). Additionally, research into extreme degrees of congenital amusia (Peretz et al., 2002) and musical savants or prodigies may enhance the understanding of genetic factors for musical development.

CONCLUSION

Neuromusical research—studying musical experiences with direct brain imaging techniques (e.g., PET, fMRI, etc.)—is a rapidly growing field. More and more studies are being published in a wider variety of venues and gaps in the knowledge base are slowly being closed. New techniques, such as diffusion tensor imaging (DTI), are being added to the arsenal available to researchers. Once relegated to the fringe of neuroscience, studying music has gained credibility and perhaps even a little cachet.

Such progress notwithstanding, there are still many topics in need of exploration. Disparities in findings have yet to be reconciled. Technologies still place severe limitations on the kinds of musical experiences that can be studied effectively. A complete description that connects micro (genetic instructions) to macro levels (observable behaviors) in a smooth, comprehensive accounting of musical processes is not yet feasible.

Considering the status to occupy a mid-position between research still in its infancy and a mature, full-blown depiction, how can the current state of knowledge be summarized? The following represent general statements that are supported by data:

- Some degree of musicality is a birthright of all human beings.
- Musical expressiveness and responsiveness appear at birth (even before birth) and, given appropriate learning opportunities and reinforcements, develop at a natural pace throughout childhood and into adulthood.
- Musicality is highly resilient and persists to some degree even in individuals who are afflicted with physical, cognitive, or emotional impairment.
- Genetic instructions and life experiences work together to shape the “musical brain.”
- The brain changes and adapts in response to music learning experiences such that the brains of adult musicians show marked differences when compared to controls.
- Music is subserved by widely-distributed neural networks, with locally-specific nodal points contributing to the overall experience.
- Although some locally-specific neural substrates have been identified, activation sites may change in response to changes in subject, stimuli, or task variables.
- Certain aspects of musical experience are supported by disassociated (i.e., distinctive, non-shared) neural networks.
- The vast majority of neuromusical studies have been conducted with subjects (both trained and untrained) familiar with Western music. Considerably more research is needed with those engaged in non-Western musical experiences. Short of multi-cultural investigations, universal explanations of the musical brain are not possible.

The degree to which this information influences music pedagogy or the teaching/learning of nonmusical subjects (e.g., mathematics) is the subject of the remainder of this book, along with many other relevant topics. This is an exciting time in neuroscience with new findings coming online at a rapid pace. Significant contributions to our understanding of the music teaching/learning process are already being made. While music practitioners may not have all the answers they would like at the moment, they are encouraged to stay current with the literature. The future of music education will undoubtedly be impacted in significant ways by the swift progress of neuromusical research.

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