

The Neurobiology of Music Cognition and Learning

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Music Learning and Cognition

The last century has provided a wealth of important data about cognition and learning. However, with the cognitive revolution in developmental psychology and the rise of Piaget's theory within developmental psychology, the emphasis shifted from learning to thinking. Consequently, we now know quite a bit about children's thinking at different ages, but we know little about how they learn. The movement away from studying children's learning reflected more than a shift in interest; it also reflected an assumption that development and learning are fundamentally different processes. However, learning and cognition are two sides of the same coin. What one knows is largely based upon what one has learned, and learning, of course, generates knowledge. Therefore, any theory of development that has little to say about how children learn is a seriously limited theory of development.

Over the past decade, the emergence of the interdisciplinary field of cognitive neuroscience has led to the realization that the neural basis of cognition and learning can be empirically studied. Such investigations commonly lead to fresh insights and theories about a variety of developmental processes. This chapter reviews current research on the neural basis of musical learning and cognition with the view that neuroscientific research is as relevant to musical processes as knowledge and concepts gained from the study of, for example, perception, emotion, and motor function. Where possible, we refer the reader to relevant chapters elsewhere in this Handbook for a greater degree of technical detail.

A brief survey of the literature on learning (and cognition) will provide the framework for our particular neu-

robiological perspective. Four different approaches to investigating learning are reviewed: behaviorism (Watson, 1913), cognitive psychology (Piaget, 1947, 1959), socio-historical theory (Vygotsky, 1934/1962), and connectionism (see McClelland, 1995).

Behaviorism

The behaviorists viewed developmental changes in behavior as relying on several basic principles of learning, particularly classical conditioning (Pavlov, 1927) and operant conditioning (Skinner, 1953), as initially demonstrated by animal experiments. For example, Ivan Pavlov's experiments with dogs revealed that a neutral stimulus (a bell) begins to elicit a response (salivation) after being repeatedly paired with another stimulus (food) that already elicits that response. A stimulus-response chain ($S \rightarrow R$) can be strengthened by repetition and reinforcement, and the response will gradually generalize. Learning, according to the behaviorists, occurs when a behavioral change can be linked to a stimulus presumed to have caused that change and can thus be objectively measured. However, the behaviorists failed to do justice to the organization of human behavior and the complex inner processes that are responsible for generating it. For example, although the neuronal activity of learning in the human brain cannot be observed directly, it clearly plays a major role in behavior. From a behaviorist point of view, however, the mind remains a "black box" about which one can only speculate and which therefore cannot contribute very much to the scientific study of behavior. Any introspection into the processes of learning was seen by the behaviorists as neither reliable nor relevant to the understanding of behavioral

processes. This limitation in the behaviorist view, along with the emergence of computer science, encouraged investigators to attempt to describe the cognitive processes that are necessary to generate and control complex human behavior. This event became known as the "cognitive revolution."

Cognitive Psychology

The cognitive revolution represented a qualitative shift from an emphasis on behavior toward an emphasis on understanding the inner processes involved in cognition and intellectual growth. The *constructivist* perspective emphasizes the active role of the child in constructing advanced forms of cognition that transcend less adequate earlier forms (Baldwin, 1894/1968). Constructivists believe that one should begin the study of children's cognitive development by exploring the foundational concepts with which children come equipped at birth and then go on to document any change that may take place in these concepts with age. Jean Piaget was perhaps the most influential developmental psychologist to carefully observe children's development. Based on his own observations of his three young children, Piaget built a cognitive theory of the awakening of intelligence in children. According to Piaget, children progress through a series of five universal stages of development, which are characterized by "sensori-motor intelligence," "preoperational and symbolic thinking," "intuitive thought," "concrete operations," and "formal operations" (1947, 1959). As they progress through these stages, children develop cognitive schemas through interaction with the environment and other persons. The forms of these schemas are different at different stages of their development, and it is this difference that gives the thought of young children its unique character. Piaget hypothesized that the progression of humans through the four developmental stages is biologically determined. In any given stage, new experiences are "assimilated" to the existing set of schemata. Transition from one form of thought to the next is driven by "accommodation," a process by which existing schemata are broken down and then reorganized into new and more adaptive patterns, in turn leading to a highly differentiated cognitive structure. This model was expanded, elaborated, and modified by others (Aebli, 1980/1981; Case, 1972; Pascual-Leone & Smith, 1969). Thus the term *mental representation* became a key signature of the cognitive revolution. Piaget's theory was applied to musical development by Pflederer Zimmerman (1984; Pflederer Zimmerman & Webster, 1983) and to music learning (slightly modified) by Bamberger (1991).

Piaget and successors to his theory have expanded our understanding of development by revealing substantial domain-specific cognitive capabilities that children possess

from early in life. These theorists emphasize that learning at all ages involves an active interchange between structures in the mind and information from the environment. Mental structures are joined with processes, such as assimilation and accommodation, to actively contribute to cognitive development.

Sociohistorical Theory

Contextual models, sometimes called systems views, emphasize that the transformation from infant to adult takes place via a complex, multidirectional system of influences (Gottlieb, 1991). These theorists are concerned with understanding how the broad range of biological, physical, and sociocultural settings affect learning and development. For example, Lev S. Vygotsky's sociohistorical theory from the 1930s stresses the importance of cultural tools, symbols, and ways of thinking that the child acquires from more knowledgeable members of the community (1934/1962). Development is viewed as a dynamic, never-ending transaction that involves continuing, reciprocal exchanges: People and settings transform the child, who in turn affects the people and settings that surround him or her, which further reshape the child, in an endless progression. According to the sociohistorical view, knowledge does not originate in the environment alone (as the behaviorists claimed) or in the interaction between the individual and the environment (as the constructivists maintained). Rather, knowledge originates in the social, linguistic, and material history of the individual's culture and its tools, concepts, and symbol systems. Children's participation in cultural activities with the guidance of others allows them to "internalize" their community's tools for thinking. Thus efforts to understand individual cognitive development and learning must consider the social roots of both the tools for thinking that children are learning to use and the social interactions that guide children in use of these tools. Vygotsky's concept of the zone of proximal development posits that development proceeds through children's participation in activities slightly beyond their competence with the assistance of adults or more skilled children. These ideas were expanded by other Soviet researchers, most notably Luria (1961) and Leont'ev (1981). The translation of Vygotsky's work into English marked the beginning of widespread use of Vygotskian ideas in the United States and Western Europe.

Connectionism

Connectionism offers a fresh perspective to the understanding of learning by focusing research on the microstructure of cognition. Connectionist theory is extremely rich in terms of its implications for brain development.

Highly sophisticated brain-imaging techniques, such as electro- and magneto-encephalography (EEG and EMG), event-related potential (ERP), magnetic resonance imaging (MRI), computer tomography (CT), and positron emission tomography (PET), permit a new view of the active brain. The topography of brain areas involved in aural perception and learning has been elaborated and transcribed into brain maps. The study of highly complex network structures and interconnections has laid the foundation for a connectionist model of "parallel distributed processing (PDP)" (Rumelhart & McClelland, 1986). The theory behind PDP is bound to the hypothesis of the modularity of mind (Fodor, 1983). Here the input systems refer to different brain areas that are highly specialized in processing particular properties of the incoming auditory stimulation, such as pitch, loudness, location of the sound source, melodic contour, and so forth. The possibility of exactly measuring the neural activation, the intensity and distribution of activation patterns, and the localization and lateralization of domain-specific processing tasks across the cortex have enabled new avenues for the investigation of the physiological foundations of music cognition and music learning (Hodges, 1996).

Along with the development and implementation of the imaging techniques, computer models of artificial "neural" networks have been developed to investigate strategies in problem-solving and decision-making processes (Fiske, 1993; Griffith & Todd, 1999; Todd & Loy, 1991). The connectionist approach can be seen as a neurally inspired model of information processing, in which groupings of neurons are interconnected in input layers (by which signals enter the system), output layers (which represent the outcome of the network), and hidden layers (which compute the more complex nonlinear relationships within the network). (For a more detailed introduction to connectionist ideas, see Bechtel & Abrahamsen, 1991.) Thus connectionist modeling can provide a functional understanding of the sequential structure of decision-making processes that are performed by an activation of units ("nodes") at an input layer, their gradual selection from a hidden layer, which corresponds to their semantic or syntactic weight, and finally their progression to an output layer. Cognition here is the result of a process of propagation and back-propagation within different layers of selection. Learning describes the tracing of paths and connections in that neural network.

In light of the neurobiological exploration of brain activities involved in music cognition and learning, mental representation has become a crucial component of learning. If neural networks function as the neural correlate for musical representations, then learning must be related to physiological conditions in the brain, that is, to the *activity* of neurons, to the *connectivity* among neurons, cell assem-

blies, and brain areas, and to the *neuronal plasticity* of the brain—especially the establishment, growth, and progressive differentiation of genuine musical representations with respect to their strength, localization, and extension in both hemispheres.

Neurobiological Foundations of Cognition and Learning

Cognition can be seen as the result of a pattern-matching process by which mental representations are activated through perceived stimuli. The term *mental representation* covers a broad array of meanings and is often used synonymously with *mental models* (Johnson-Laird, 1983), *scripts* (Schank & Abelson, 1977), *frames* (Minsky, 1980), *schemas* (Aebli, 1980/1981; Piaget, 1959) or *neural networks* (Todd & Loy, 1991). In addition to the debate on the meaning of mental representations, there is also a debate on the nature of mental representations. In one view, representations are seen as veridical images that are stored in the mind and can be retrieved from it; that is, they are *depictive* in nature (Kosslyn, 1994), whereas another perspective holds that representations result from formal processes and accumulated experiences that are *propositional* in nature (Pylyshyn, 1973). In music, depictive representation of a chord shows, for example, the real image of the position of fingers on a keyboard or the picture of the notation, whereas propositional representation results from knowledge in terms of statements about that chord as a sum of many experiences.

In this section, we will only refer to the neural cortical substrates for sensory representations. We ask the following questions: How are musical (sound) representations characterized, and how, if possible, can we begin to understand the developmental processes of neural connections? Methodologically, four strategies are commonly employed to investigate the learning brain: (1) the observation of persons with brain lesions that cause particular deficits; (2) animal experiments that study neuronal brain reactions; (3) the measurement of infants' information processing, especially sensory and auditory temporal processing; and (4) the implementation of brain-imaging techniques for a clear and precise identification and localization of changes in brain activation.

Neurons are highly specialized to respond to particular qualities of stimuli, for example, to a section of a band of frequencies (pitch), to a movement of sounds up and down (direction), to the intensity of sound (loudness), and so forth. Neurons of a particular brain area represent different features. Unfortunately, little research exists on the auditory sensory mapping of the associative cortex. In cognition, distributed processing of sensory information must

be coordinated for the creation of what is eventually perceived by the conscious mind. As M. E. Martinez (1999) has put it:

The human mind is not a video camera. We do not process and store countless sensory bits; rather, we construct our inner and outer worlds according to the organizing principle of meaning. The fact that knowledge can be represented in different ways implies that knowledge is not a sensory transcription of the external world into the inner world of the mind. (p. 21)

Single cortical neurons with similar "interests" tend to be vertically arrayed in cortical columns like thin cylinders (Calvin, 1995). The best-known columns are the visual cortex's orientation columns, but little is known about aural orientation columns and representations. The data available, however, suggest the existence of complex musical structures that are processed in distributed areas and are connected in coherent networks or cell assemblies. What we perceive as music originates from distributed processing but combines into one conscious feature that forms a robust mental representation.

Experimental programs have demonstrated that formal training and informal experience in varied environmental situations cause measurable changes in the neurochemistry and even in the neuroanatomy of the brain (Black & Greenough, 1998). Even the cortical maps of adult primates can be radically altered through environmental input (Kempermann et al., 1997). This neuronal plasticity is crucial for the neurobiology of learning. As Ramon y Cajal stressed at the end of the 19th century, learning is deeply involved in, if not biologically based upon, the formation of new synaptic connections. Since Donald O. Hebb (1949) theorized that chemical changes in a cell's dendrites increase the likelihood that it will activate neighboring cells, remarkable empirical progress has been made in the investigation of synaptic connectivity and its impact on the electrochemical transmission between neurons. "This basic concept of a cooperative set of modifiable connections as the basis of learning and memory, along with the Hebb synapse, continues to have substantial influence on neural network theory" (Black & Greenough, 1998, p. 56).

If learning is associated with synaptic growth, the investigation of the formation of synaptic contacts in the human cerebral cortex becomes enormously important. It has been documented for animal and human brains that the synaptic density—the number of synapses per neuron or per unit volume of cortical tissue—changes over life spans and defines the limits of the processing capacity (Huttenlocher, 1979, 1984). In human beings, synaptogenesis takes place prenatally and in early infancy. By the age of 1 year it reaches a plateau stage, followed by a progressive synapse decline, which happens most rapidly dur-

ing preschool years (Huttenlocher, 1984). However, there are regional differences in synaptogenesis in human brains. Huttenlocher (Huttenlocher & Dabholkar, 1997) compared the development in two cortical areas: the auditory and prefrontal cortex. He found that synaptic density increases more rapidly in the auditory cortex (maximum at age 3 months) than in middle frontal gyrus (peak after age 15 months). Here synaptic growth occurs concurrently with growth of dendrites and axons and with myelination of the subcortical white matter. The following phase of synapse elimination also starts earlier in the auditory cortex, where it reaches a mature level by age 12 years, than in the prefrontal cortex (Huttenlocher & Dabholkar, 1997). The exuberant overproduction of neuronal connections during infancy may be seen as an anatomical substrate for neural plasticity (Huttenlocher, 1990) that has a tremendous impact on the unique structure of early learning. The discovery of an inverted U-shaped structure in brain development is confirmed by the development of glucose metabolism. Cerebral glucose consumption rises from birth until about 4 years of age, maintains from 4 to about 9–10 years, and then gradually declines (Chugani, 1998). These findings have important implications for our understanding of brain plasticity and critical periods for learning.

Recently neuroscientists at Geneva University (Müller, Toni, & Buchs, 2000) have investigated the chemical changes that influence synaptic strength. The researchers stimulated rat brain slices to produce long-term potentiation (LTP). If a receiving neuron has been activated, the incoming neurotransmitter induces LTP by flooding calcium ions into the spine. An hour after treatment, 20% of the synapses had developed double spines, forming a second spine adjacent to the active one. Müller concludes that LTP triggers "a duplication of the active synapse" (Barinaga, 1999, p. 1661). Presumably this causes an increase in synaptic strength.

The neurobiological foundations for learning are derived from studies that suggest that experience or learning induces changes in the brain that relate to cortical thickness (Diamond et al., 1964), the size of cell bodies (Diamond, 1967), the size of synaptic contact areas (West & Greenough, 1972), an increase in dendritic spines (Globus et al., 1973), a parallel increase in the number of synapses per neuron (Turner & Greenough, 1985), the thickness of the corpus callosum (Schlaug, Jäncke, Huang, Stalger, & Steinmetz, 1995), an increase in hippocampal neurons (Kempermann et al., 1997), the size of the left planum temporale (Pantev et al., 1998), and the doubling of spines through LTP (Müller et al., 2000). These research findings relate either to the growth of number or size of new synaptic connections by formal training or enriched environmental experience or to the growth of stronger and bigger already-existing synapses. In any case, the ev-

idence of neurochemical and neuroanatomical plasticity is basic for the neurobiology of learning, that is, for the formation and modification of mental representations. In particular for young children, it is evident—despite Bruer's reluctance (see "Discussions and Conclusions")—that early music training leads to an expansion of the representation of sound in the auditory cortex (Rauschecker, 1999).

For cognition and learning experiments, the localization of task-specific cortical areas has been empirically investigated (see "Brain Research on Music Cognition and Learning"). Even the specialization within the auditory cortex has been clarified by its subdivision into four distinct territories (Gaschler-Markefski, Baumgart, Tempelmann, Woldorff, & Scheich, 1998). The contribution of different cortical areas to music processing still remains a major focus of research in neuroscience. From patients with surgical lesions we know about different strategies of musical-information processing. They demonstrate, for example, that a right temporal cortectomy impairs the use of both contour and interval information, whereas a left temporal cortectomy interferes with interval information only (Liegeois-Chauvel, Peretz, Babai, Leguitton, & Chauvel, 1998). In general, the acquisition of implicit knowledge through neuronal self-organization that results from mere exposure to music (Peretz, Gaudreau, & Bonnel, 1998) should not be underestimated, as Tillmann, Bharucha, and Bigand have shown by experiments that dealt with tone, chord, and key relationships, including memory judgments, and expectancies (2000). Furthermore, the learning context plays an important role in memory retrieval, especially for infants who displayed a 7-day retention only when the music played during the retention test matched the training music (Fagen et al., 1997). However, all that knowledge about functional cortical areas cannot suffice as the only explanation for the neurobiological processes involved in music learning. In this section, learning is, therefore, exclusively defined as the process of incrementally developing and altering the structure of mental representations.

Following the experimental brain studies on learning primarily conducted with animals, researchers have recently conducted EEG studies on music learning of children (aged 12–14) and adults (aged 17–39) (Altenmüller & Gruhn, 1997; Altenmüller, Gruhn, Parlitz, & Liebert, 2000; Gruhn, 1997; Gruhn, Altenmüller, & Babler, 1997; Liebert et al., 1999). These studies reveal that significant changes in auditory activation patterns are induced by different types of learning that correspond to formal instruction and informal musical exposure. Subjects who received informal instruction by singing and playing supported the efficiency of the phonological loop at the aural-oral level and, by this, developed procedural knowledge. This learning strategy evidenced increased activation patterns at the

right frontal and bilateral parieto-occipital lobes, which may be ascribed to a global way of processing through the integration of visuo-spatial associations). However, music processing of subjects who received formal verbal instruction evidenced an increased activation of left fronto-temporal brain regions, which might refer to a more local strategy (Altenmüller & Gruhn, 1997).

In another long-term learning experiment, subjects displayed different activation patterns depending upon how successfully they performed a task. Those who succeeded in the task, regardless of the type of learning (declarative versus procedural), demonstrated a shift to the *right* fronto-temporal lobes, whereas brain activation in those subjects who did not succeed focused in the *left* fronto-temporal regions. Therefore, it appears that a simple right-left dichotomy with music in the right hemisphere is an oversimplification. Any music processing involves both hemispheres equally but in an asymmetric specialization that depends upon many intra- and interpersonal factors. Perhaps different types of processing (global versus local processing; Peretz, 1990; see "Brain Research on Music Cognition and Learning") produce a lateralization effect because different cognitive strategies are applied individually.

Brain activation patterns can also differentiate long-term from short-term learning. In a short-term ear-training experiment (Liebert et al., 1999), researchers found an overall increase of brain activation, whereas experiments with long-term learning demonstrated a general decrease of brain activation. These findings seem to support that long-term learning causes a structural change within mental representation, which may be called formal (Bamberger, 1991; Gruhn, 1998). Formal representations produce a more distributed, widely spread neuronal network and may therefore need only a reduced cortical brain potential, presumably due to the involvement of subcortical regions in the representation of genuine musical qualities. (This must be shown by functional fMRI studies.) There is good reason to assume that, biologically, learning is accomplished by a move from one type of cortical representation (which might be called figural, according to Bamberger, 1991) to a different type of cortical representation that involves subcortical layers. The essence of this model is based upon different encodings of the processing and storing of musical information and knowledge. Learning, therefore, effects the transformation from cortical to integral cortical-subcortical representations.

In instrumental training, motor skills and auditory skills collaborate. The activation of representation in one area is linked to that of a corresponding area that is not directly stimulated. This process has been described as coactivation. Bangert, Parlitz, et al. (1999) demonstrated that subjects exhibit a slight coactivation of the sensorimotor cortex in a passive auditory task even 20 minutes after

a keyboard-training session. Likewise, fronto-temporal regions were activated in pianists during a mute motor task. This clearly suggests that cortical activation patterns, even during a strictly limited task, display a widely distributed network far beyond a simple image of the involved activity. Learning, in a neurobiological sense, is due to the establishment of those networks.

Neurobiological Research on Music and Learning

Overview

A comprehensive review of brain development is beyond the scope of this chapter. However, M. H. Johnson (1998) has identified four factors that we believe are important to any understanding of the neurobiology of music learning and cognition.

First, there are neural structures in the brain that are common to both humans and other mammals, both primate and nonprimate. Differences between humans and other animals primarily concern the extent of the cerebral cortex. Subcortical structures, such as the hippocampus and cerebellum, are structurally similar across mammalian species.

Second, the cerebral cortex, hippocampus, and cerebellum continue to develop throughout childhood. Although the vast majority of neurons are present at birth (Rakic, 1995), synapses, dendrites, and fiber bundles continue to develop postnatally, perhaps as a function of experience. Myelin, the fatty sheath that surrounds neuronal pathways (and is thought to increase the efficiency of information transmission), also increases dramatically after birth. The immaturity of the human brain at birth may explain some of the limitations on learning and cognition present in infants and children. Similarly, the dynamic postnatal development of the cortex allows more intentional, purposeful behavior.

Third, different areas of the cerebral cortex develop at different rates. For example, Conel's (1939/1967) study of cortical development in the human infant led him to conclude that the cortex develops in an "inside-out" fashion, with outer brain layers developing in advance of inner layers. Differential development *between* cortical regions (i.e., visual cortex and frontal cortex) has also been documented (Huttenlocher, 1990). These patterns of development may influence information processing.

Finally, studies on cortical plasticity suggest that cortical specialization is heavily influenced by experience. Although primary cortices are genetically predetermined, there is a high degree of modulation with respect to the extension and connectivity of functional brain areas according to experience and learning. Therefore, brain plasticity can be

seen as fundamental for the development of mental representations.

Empirical Methods

The recent explosion of knowledge of brain development makes the task of relating it to cognitive changes considerably more viable. Consequently, efforts to correlate neural changes to cognitive changes have increased dramatically over the past two decades. However, because a multitude of neuroanatomical variables change over the first decade of life, it is unwise to make causal inferences that regard the relationship between changes in specific brain areas to specific cognitive changes. Evidence of temporal correlation can, however, be supported by empirical methods. A variety of techniques are now available to developmentalists interested in the biological basis of cognitive development. Some of these methods, such as PET, require the injection of a radioactive dye and are therefore of limited use for studying the cognitive functioning of healthy children and adults. Others, such as EEG, ERP, and functional MRI (fMRI), are currently being employed. These imaging techniques are described by Hodges and Flohr in this volume (chap. 52).

While the new functional brain-imaging techniques promise to provide researchers with important information that regards the relationship of brain structure and function to learning and cognition, somewhat similar questions can be explored through the use of animals as subjects. Research on animals (mostly rodents) has contributed a great deal to our understanding of the relation between brain and behavior. The field of molecular genetics, for example, has opened up new possibilities for investigating this relationship. In particular, mice that undergo lesions in the alpha-calcium-calmodulin kinase II gene are unable to perform certain learning tasks in adulthood (Silva, Paylor, Wehner, & Tonegawa, 1992). These types of techniques, in which certain genes from the genome of an animal are either removed or lesioned, permit the investigator to answer questions that regard genetic contributions to learning and behavior and are particularly well suited when applied to established animal models of development.

Further insight into the relations between brain and behavior can be found in studies in which the brain is removed in order to examine it at the cellular level. For example, studies that used this technique suggest that rats reared in an "enriched" environment after weaning show a wealth of enduring neurobiological and behavioral changes. Rats raised with stimulus objects such as running wheels, rubber tubes, nibble bars, and such in their cages show morphological and biochemical alterations in cortical and hippocampal formation and perform better on learning and memory-dependent tasks than animals raised

in normal laboratory conditions (see Renner & Rosenzweig, 1987, for review). Similar effects have been found for rats raised in socially enriched conditions, in which animals are housed with several siblings rather than in pairs or isolation (Pacteau, Einon, & Sindon, 1989). Furthermore, recent research has demonstrated that rats exposed to complex music learned a spatial maze faster and with fewer errors than rats exposed to minimalist music, white noise, or silence (Rauscher, Robinson, & Jens, 1998), results that appear to be a function of increased hippocampal dendritic density in the animals exposed to the complex music (Rauscher & Koch, 2000). Taken together, these studies strongly suggest a morphological change in mammalian cortex as a function of environmental stimulation.

Marker tasks, behavioral tasks that have been linked to particular brain regions by neuroimaging studies, provide another useful approach to understanding brain development and learning. By testing individuals of varying ages with different versions of these tasks researchers can relate levels of task performance to the functional development of different brain regions. A number of marker tasks have recently been developed for the functioning of structures involved in oculomotor control and visual attention shifts (M. H. Johnson, 1998).

Brain Research on Music Cognition and Learning

There may be no other area of music psychology that has seen as much recent advancement as research on music-induced plasticity of the brain. For example, Gottfried Schlaug and his colleagues found that a small neural structure in the cerebral cortex that processes sound signals, the planum temporale, was larger in the left hemisphere and smaller in the right in the brains of musicians than of nonmusicians (Schlaug, Jäncke, Huang, & Steinmetz, 1994), an effect that was later found to be due to musicians who possessed perfect pitch and who began their musical training before the age of 7 (Schlaug et al., 1995). Schlaug and his colleagues also reported that musicians, particularly those who had begun their training before age 7, had thicker corpus callosi (the band of nerve tissue that connects the left and right hemispheres) than nonmusicians (Schlaug et al., 1994).

Other correlational studies also suggest that instrumental instruction affects brain development. Elbert, Pantev, Wienbruch, Rockstroh, and Taub (1995) asked string players and nonmusicians to move the fingers of their left hands while magnetoencephalography (MEG) measurements were taken. The researchers found that magnetic response from the right primary somatosensory cortex—a brain region that controls the left-hand fingers—was larger for the string players than it was for the nonmusicians. Furthermore, the magnitude of the response was related to

the age at which the string players began instruction, with those who began lessons earlier evidencing the largest response. Finally, a recent paper by Pantev and his colleagues reported that auditory cortical representation was 25% larger in musicians than in nonmusicians, regardless of the instrument played and the presence of perfect pitch (Pantev et al., 1998). The younger the instrumental training began, the larger the cortical reorganization. Effects were found for subjects who began to practice before age 9.

Many studies have compared cortical processing of aural imagery tasks with perception tasks (Reisberg, 1992; Zatorre & Halpern, 1993; Zatorre, Halpern, et al., 1996). Zatorre and Halpern (1993) hypothesized that similar neuronal mechanisms may underlie both imaginal and perceptual processing. A PET study demonstrated that although many of the same regions appear to be involved in imagined and perceived tonal-pattern processing, two inferior frontopolar regions showed significant increase of blood flow only for the imagery task (Zatorre et al., 1996). This may refer to different aspects of the generation of auditory information from memory. However, in an experiment on the effects of unilateral temporal-lobe excision on perception and imagery Zatorre and Halpern (1993) found that patients with right temporal-lobe excision showed a significant decrease in both perceptual and imagery tasks. The interaction of aural imagery and music perception plays an important role in music learning because aural imagery depends on already-established mental representations that are a prerequisite for any type of discrimination learning.

Correspondingly, different processing strategies influence lateralization effects and particular musical properties call for different activation areas. In a study with unilateral brain-damaged patients, Peretz (1990) found two types of musical-information processing that she called local and global processing. If, on the one hand, the processing is interval-based, focusing on local properties as single tones and distances, the left hemisphere is dominant; if, on the other hand, the processing is contour-based, focusing on the more global aspects of a tune, then the right hemisphere is dominant. Similar results support these findings. In an EEG study, Breitling, Guenther, and Rondot (1987) found different bilateral involvement for different stimulus conditions (single tone, scale, melody). Only in the melody condition (global processing) was the right hemisphere more activated.

In general, it can be stated that lateralization effects mirror the asymmetric specialization of brain functions, depending on acoustic aspects of stimuli as well as individual cognitive processing strategies.

Discussion and Conclusions

Until recently, the majority of the research on the neurobiology of learning in general and music learning in par-

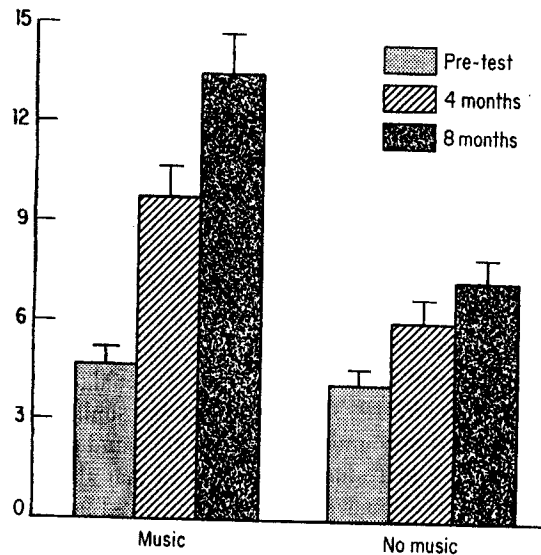


Figure 25.1. Spatial-temporal scores of kindergarten children (School District of Kettle Moraine) before and after music or no training: correct joins/minute.

ticular was descriptive and focused mainly on cerebral localization of function. (See Hodges and Flohr in this Handbook, chap. 52, for a review of these studies.) However, neuropsychologists are now beginning to approach music learning from a more “cognitive” or “information-processing” position. Simply knowing that left unilateral neglect follows posterior right hemisphere lesions does not tell us anything about the specific mechanism(s) responsible, nor how these mechanisms operate to produce the symptom. Thus the goal today is to identify the particular processes that are enhanced, maintained, or disrupted after intervention or cerebral damage and determine how these processes relate to specific neural substrates or neural systems.

The purpose of the research cited earlier was to discover how developmental processes affect brain and cognition, particularly in the early years. These studies suggest that early instrumental instruction may actually physically shape and mold the young brain. However, Bruer (1999) cautions us against drawing excessive conclusions from these data. Although there may indeed exist a relationship between music cognition and brain development, our knowledge of this relationship is far from complete, and alternative explanations for the data should be considered. For example, Elbert et al.’s (1995) research with string players measured the brain’s response to an overlearned skill—fingering a keyboard. It stands to reason that any overlearned motor activity, for example, typing, would produce similar brain reorganization. This study, therefore, was not directly about music. Furthermore, although Schlaug, Jäncke, Huang, and Steinmetz (1994, 1995) and

Pantey, Oostenveld, Engellen, Ross, Roberts, and Hoke’s (1998) findings suggest that early music engagement affects the brain’s pitch/auditory processing regions, it is not clear that the age at which subjects began instruction, rather than how long they had been playing, produced the effects. In other words, the larger brain response may be the result of longer time on task, rather than age of task onset.

It is also not clear in these studies whether the morphological effects were caused by the music instruction. Studies that compare musicians to nonmusicians are correlational, not causal. They therefore do not address whether differences in brain structure between these two groups of subjects are a function of the music exposure or of inborn atypicalities in the brains of musicians that may attract them to music making in the first place. Clearly, longitudinal causal studies are needed to investigate the maturation of cognitive abilities and brain regions before and during early versus later onset music instruction. It is important to note that no scientific studies have directly investigated the effects of music instruction on the adult brain. We must be careful not to ignore the fact that brain development continues until death.

Transfer Effects

According to conventional opinion, music has an effect on cognitive achievement. Therefore, experimental findings that actually confirm transfer effects would have an important impact on educational policies with respect to school music curriculum. Consequently, there is an increasing interest in inquiries on whether music can really improve the mind (Overy, 1998). Thus several longitudinal observations of schoolchildren who received extra music lessons within their regular school curriculum were performed in Europe (Bastian, 2000; Spychiger, 1995). Here effects of music on social behavior and school achievement appeared.

In an experimental memory study, Chan, Ho, and Cheung (1998) found that music training improved verbal memory because verbal memory is mediated mainly by the left temporal lobe, which is larger in musicians than in nonmusicians. Although Chan used subjects from Hong Kong whose native language was tonal (a language in which verbal memory includes pitch memory), the greater effect on verbal than on visual memory tasks in musicians possibly indicates a general transfer effect.

Just recently, a meta-analysis of studies on the relationship between music and academic achievement (Winner & Hetland, 2000) has examined the outcome of studies on music and reading skills, music and mathematics, and music and spatial-temporal reasoning. Twenty-four correlational studies and six experimental studies on the impact of music on the development of reading skills were ex-

amined (Butzlaff, 2000). Whereas correlational studies showed that students who studied music scored significantly higher on standardized reading tests, there was no reliable effect supported by the experimental studies. With respect to an impact of music instruction on mathematics, a total of 25 correlational and experimental studies were examined. The analysis revealed a small but evident association between music and mathematics achievement: Individuals who voluntarily chose to study music privately and those who were exposed to a music curriculum in school produced higher mathematical scores than those who did not (Vaughn, 2000). However, a positive relationship is not sufficient to establish a causal link. Furthermore, listening to background music had no notable effect.

The explosion of studies that explore the transfer of musical processing to spatial processing compels us to examine these data from a neurophysiological perspective. Two lines of behavioral research have been pursued: the effects of *listening* to music on *adult* spatial abilities and the effects of *instrumental instruction* on *children's* spatial abilities. Two recent meta-analyses (Hetland, 2000a, 2000b) have examined the studies relevant to these inquiries. The first analysis explored the so-called Mozart effect, the finding that college students who listened to 10 minutes of Mozart's piano sonata K. 448 scored higher on spatial-temporal tasks than students who listened to taped relaxation instructions or silence (Rauscher, Shaw, & Ky, 1993). Hetland's (2000b) meta-analysis of 36 studies that involved approximately 2,500 subjects revealed a moderate, robust effect that "is limited, however, to a specific type of spatial task that requires mental rotation in the absence of a physical model" (p. 33). Despite Hetland's conclusion, it must be noted that attempts to reproduce Rauscher, Shaw, and Ky's (1993) findings have been inconsistent. For example, in a series of experiments designed to replicate the Mozart effect through use of the same musical composition as well as similar control conditions and dependent measures, Steele and his colleagues achieved negative results (e.g., Steele et al., 1999).

The second meta-analytic review, also undertaken by Hetland (2000a), examined studies on the effects of instrumental instruction on children's spatial abilities (see, for example, Rauscher et al., 1997). Figure 25.1 portrays the effect for kindergarten children. The results of this analysis revealed an overall effect size of $r = .37$, an effect that was deemed "remarkably consistent" and could be "generalized to similar populations of preschool- and elementary-school-aged children, while they are engaged in similar kinds of active music programs, with or without keyboard instruments, taught in groups or individual lessons. The effect cannot be explained away by a Hawthorne effect, nonequivalence of experimental groups, experimenter bias, or study quality. It is a solid finding" (Hetland, 2000a, pp. 41-42).

We will not attempt to undertake a critical analysis of these studies, but instead, as per the focus of this chapter, we will comment on their possible neurophysiological implications. The motivation for research on the transfer of music listening or instruction to spatial task performance came from a neural connectionist model of the mammalian brain proposed by Xiaodan Leng and Gordon Shaw (Leng & Shaw, 1991). Based on Mountcastle's columnar principle of cortex, the model proposed that families of neural networks respond to and compare spatial features of objects. By mathematically deriving their firing probabilities the researchers determined that the networks evolved according to symmetries modified by Hebb learning rules. These neural network patterns (lasting tens of seconds over large cortical areas) corresponded to spatial-temporal task performance (requiring the transformation of mental images over time). Leng and Shaw therefore predicted that certain musical forms and instruction might stimulate these firing patterns, thereby enhancing spatial-temporal performance.

Although it is impossible to "prove" a neural model of brain function, Leng and Shaw's (1991) hypothesis is supported by data. For example, Alzheimer patients who listened to the Mozart sonata or silence demonstrated improved spatial-temporal performance following Mozart (J. K. Johnson, Cotman, Tasaki, & Shaw, 1998; J. K. Johnson, Shaw, Vuong, Vuong, & Cotman, 1999). Neuroscientists have investigated the effect through the use of EEG and fMRI. EEGs of subjects who performed a spatial-temporal task after listening to the Mozart sonata revealed a carry-over effect in parietal and frontal cortex; no carryover was found when reading a story was substituted for the task (Sarnthein et al., 1997). EEGs of epilepsy patients, some comatose, showed decreased seizure activity during exposure to the sonata rather than silence or control music (Hughes, Daaboul, Fino, & Shaw, 1998; Hughes, Fino, & Melyn, 1999). The compositions differentially activated the prefrontal, occipital, and cerebellar regions—all regions associated with spatial-temporal reasoning. These findings, although specific to music listening, may also have neurophysiological implications for the effects of music instruction on certain spatial abilities.

Parsons, Hodges, and Fox (1998) have proposed an alternative theory. These researchers suggest that the rhythmic elements of music, processed in the cerebellum, are responsible for the enhancement of spatial tasks (such as mental rotation tasks) that also require cerebellar function. A recent experiment by Parsons and his colleagues (cited in Hetland, 2000a) supports this hypothesis. Subjects performed two spatial-temporal tasks following one of five conditions: auditory exposure to rhythm without melody (a popular song bass line), auditory exposure to melody without rhythm (a melody presented in a steady beat), visual exposure to rhythm (a pulsating square on a computer

screen), auditory exposure to a continuous tone, or silence. Enhanced performance of the spatial-temporal tasks was found following only the auditory and visual rhythmic conditions. This suggests that the enhancement of spatial-temporal tasks is due to rhythm, regardless of the modality of presentation.

Other explanations for these transfer effects can be found in the cognitive literature. For example, Rauscher (1999) has proposed that several of the elements of music cognition described by Serafine (1988)—temporal succession and simultaneity, nontemporal closure, transformation, and abstraction—may be musically analogous to the cognitive processes required to solve certain visuo-spatial tasks. Perhaps some of the skills involved in learning music transfer to the performance of particular spatial skills.

The importance of studying the transfer of musical learning to spatial learning becomes evident when one considers the overall significance of spatial abilities to cognitive function. High levels of spatial ability have frequently been linked to creativity, not only in the arts but in science and mathematics as well (Shepard, 1978; West, 1991). Physicists (Albert Einstein, James Clerk Maxwell, Michael Faraday, and Hermann von Helmholtz), inventors (such as Nikola Tesla and James Watt), and other scientists displayed high levels of spatial abilities and reported that these abilities played an important role in their most creative accomplishments. In psychology, Shepard (1978) has given particularly lucid accounts of the role of spatial imagery in his own thinking. Involuntary dream images were the source of many of his most creative and influential contributions, including the idea for his research on mental rotation, the first method of nonmetric multidimensional scaling, and the computer algorithm that underlies additive nonhierarchical cluster analysis. Given the prominent role of spatial abilities both in models of human abilities and in models of cognition, studies that demonstrate that music instruction may influence spatial reasoning have important educational implications. However, due to the fact that there is as yet no commonly accepted theoretical approach that adequately accounts for these transfer effects, we recommend discretion in both the interpretation of research results and their application.

Music Learning by Individuals with Brain Disorders

Patients with Mental Disorders

The study of brain-damaged populations has always been a major area of research for investigating cognitive functioning of the human brain. Unfortunately, results of studies of brain-damaged patients are neither consistent nor easy to interpret, because the loss of a particular ability may not necessarily be attributed to a damaged brain area

or specific module of information processing. Rather, loss of ability may instead be due to an interruption of important connections between collaborating cell assemblies. However, the effect on musical skills can be observed in musicians with brain injuries who suffer from music alexia and agraphia (Brust, 1980). Namely, developmental musical dyslexia in children who have difficulties reading music has been studied (N. Gordon, 2000), just as general dyslexia, which has significant effects on children's musical abilities to recognize musical tone sequences and differentiate tone colors and sound intensities, has been (Kurth & Heinrichs, 1976). Therefore, investigations of the development of musical abilities in populations with brain disorders, as well as those with genetic abnormalities, offer valuable research. In particular, individuals with Williams syndrome, Down's syndrome, Alzheimer's and Huntington's disease, and musicogenic epilepsy are rather informative with respect to particular musical abilities.

There is an extended body of research that investigated Alzheimer's disease and its impact on musical abilities. It is well documented that previously acquired musical skills (e.g., singing and playing an instrument) remain accessible despite otherwise severe cognitive impairment. A case study of an 82-year-old musician reports relatively spared anterograde and retrograde procedural memory for music making (Crystal, Grober, & Masur, 1989). Similarly, J. Johnson and Ulatowska (1995) studied the progression of deterioration of Alzheimer's patients in music and language. They found that song texts in connection with the tunes persisted while speech was profoundly disturbed. This supports Gardner's (1983/1985) theory of unique multiple intelligences, that is, that music as a manifestation of intelligence constitutes a faculty per se and is to a large degree uncorrelated with other cognitive abilities.

A notable affinity for music is documented for children with Down's and Williams syndromes. Quantitative studies of brain morphology demonstrate a distinctive dysmorphology unlike that of other forms of mental retardation (Lenhoff et al., 1997). A highly selective effect of brain development appears to accompany Williams syndrome: Patients demonstrate a reduced cerebral size and a significant increase of neocerebellar vermal lobules, whereas individuals with Down's syndrome evidence a reduction in both cerebellar components (Jernigan & Bellugi, 1990; Levitin & Bellugi, 1998). These individuals often possess relatively intact verbal working memory but are more impaired in spatial working memory (Levitin & Bellugi, 1995, p. 375). Therefore, they demonstrate deficient spatial coordination on the motoric level but perform general musical tasks sufficiently. Moreover, subjects with Williams syndrome have a striking independence of rhythmic abilities and show a propensity for creative rhythmic productions. The obvious evidence for this quality is called rhythmicity or rhythmic musicality by Levitin and Bellugi

(1998). Although children with Williams syndrome fail in Piagetian conservation tasks, they demonstrate a clear conservation of musical time and rhythm. This may be linked with a general predominance of local over global processing strategies, especially in the processing of visual stimuli (Bellugi, Lai, & Wang, 1997). In a rhythm repetition task, children with Williams syndrome often do not repeat correctly the global structure but use local variations for creative completions (Levitin & Bellugi, 1998). A similar affinity for music and musical rhythm is reported for children with Down's syndrome. In a comparative study with other mentally challenged and normal children, children with Down's syndrome exhibited the same level of rhythm discrimination as normal children but did differ from other mentally challenged children (Stratford & Ching, 1983).

These findings with subjects with Down's and Williams syndrome suggest that musical abilities and other cognitive functioning may develop independently, perhaps due to neuroanatomical differences in the brain disorders of these patients. This suggests that music may not only serve a therapeutic goal, especially in Alzheimer's patients (Aldridge, 1994; Glynn, 1992; Lord & Garner, 1993), but it may also serve as a special tool for learning due to the evident interaction between *rhythmicity* and brain function (Thaut, Kenyon, et al., 1999) as well as movement and vocal sound production (Gruhn, 2001). This explanation also relates to the striking effect of music on the motor control of patients with Parkinson's disease. Also, researchers have shown that patients with Huntington's disease could significantly modulate their gait velocity during self-paced and rhythmic metronome cueing, but velocity adaptations did not fit with an exact synchronization of steps and metric impulses (Thaut, Miltner, et al., 1999). Effects are also reported from patients with epilepsy where brain-wave abnormalities occur during music-induced seizures (Crichtley, 1977). Just recently, fewer clinical seizures and fewer generalized bilateral spike and wave complexes were reported from a patient with Lennox-Gastaut syndrome after regular exposure to Mozart's piano sonata K. 448 (Hughes et al., 1999).

Deaf Children with Cochlear Implants

During the last two decades, advanced technology has been applied to the treatment of deaf (or severely hearing-impaired) children who still have an active hearing nerve. An artificial cochlea can be implanted to stimulate the hair cells of the cochlea by electrodes that are activated through electric impulses from an outside microphone. Cochlear implant (CI) surgeries have become routine in Europe, Australia, and the United States since the 1980s, and younger and younger prelingually deaf children can now be treated. The most appropriate time window for an ef-

ficient surgery is between age 2 and 4, that is, before the development of prosody has already been stabilized. Although there is only limited access to music transmitted by the available technology of today (Fujita & Ito, 1999), further generations of speech processors (such as Nucleus, Clarion, and Med-el) will expand the range of formats by developing different strategies through use of either time resolution (CIS = continuous interleaved sampling strategy), spectral peak resolution (SPEAK strategy), or a combined strategy (ACE = advanced combined encoder).

There is an enormous amount of research on speech development and aural processing in CI patients and an increasing interest in music perception as well (Gfeller et al., 1997; Ito et al., 1995; Pijl, 1997). Here we discuss the neurobiological development of primary and secondary auditory cortices of deaf patients. Up to now, very little has been known about the cortical development of CI patients after they recover auditory cortex areas. These areas, like the visual cortices of children born blind, are underdeveloped and utilized by other sensory representations. Perception of different sounds evoked through electrical stimulation must be learned with respect to sound discrimination and the gradual attribution of meaning to discernible sounds. A clear understanding of the neurobiological development of mental representation can facilitate this learning process, the goal of which relates to speech acquisition. As we know from neurolinguistics, even the semantics of a language are carried out through sequential structures in time. Therefore, music, especially rhythm patterns, may function as a cortex trainer for CI patients to gain or regain perceptive and expressive competence. Only EEG measurements (because MEG and MRI cannot be applied to the highly sensitive cochlear electrodes) can demonstrate whether sound stimulation actually arrives at the brain stem and how auditory and associative cortices develop during listening training and sound exposure. The aforementioned interaction of movement and brain function (Thaut, Kenyon, et al., 1999) plays an important role in the learning process here, because the motor system responds so sensitively to the auditory priming and, vice versa, rhythmic auditory stimulation corresponds with motor activation.

Applications to Music Education

Results from brain research and neurobiological findings alone can hardly lead to immediate applications and recommendations for music education. These data cannot be directly transferred to educational practice because scientific descriptions are essentially different from educational prescriptions. Empirical data are based upon objective facts and verifiable procedures; scientific research is committed to objectivity, reliability, and validity. Judgments in

education, however, are value judgments to a large degree. Normative decisions on values can never be deduced objectively from empirical descriptions. As Gardner (1999) puts it: "We could know what every neuron does and we would not be one step closer to knowing how to educate our children," because "the chasm between 'is' and 'ought' is unbridgeable" (pp. 60, 79).

Mental representation has become the key notion of the cognitive revolution during the decade of the brain (Gardner, 1999). Therefore, one possible application to music education may involve the fostering of mental representations (see chap. 30, by Andreas C. Lehmann and Jane W. Davidson in this volume). As already mentioned, education is based on decisions that are grounded in value judgments that deal with the "what" and "why" of teaching, but findings in neurobiology may indicate new ways of "how" to teach. Teaching interacts with the disposition and potential of each individual. Although neurobiological findings cannot tell us why to teach music of a particular culture and what to select from the broad variety of musical traditions, empirical findings can advise us on how and when to teach so that mind, memory, perception, and cognition can be developed most effectively. From that perspective, the neurobiology of cognition and learning allows us to draw the following tentative conclusions:

1. Learning is the process by which one develops and incrementally differentiates mental representations. Therefore, music learning focuses on the development of genuine musical representations that are characterized by different forms of encoding.
2. Procedural knowledge (knowing how) is more appropriate in music cognition than formal declarative knowledge (knowing about). Immanent musical properties (pulse, meter, tonality, intervals, motifs, contours, etc.) are represented by neuronal connections that can only be recognized when activated through aural stimulation. Conversely, these musical entities can only be articulated in singing or playing if developed as mental representations. Conscious activation may be called *audiation* (E. E. Gordon, 1980/1997). It takes place when neuronal representations are activated in thinking, listening, or music making.
3. This calls for the idea of teaching music *musically* (Gruhn, 1997; Swanwick, 1999), that is, advancing those teaching strategies and learning modes that promote the development of genuine musical representations by priming an aural-oral loop.
4. There is increasing evidence that music learning may transfer to other areas of learning (e.g., spatial learning). The possible mechanisms of this transfer, either cognitive or neurophysiological, are still unknown. Much more work is needed before applications to educational practice can be derived from these studies.
5. The same caution should also be applied to studies on the lateralization effects in music. Music is processed in

both hemispheres, but there exists an asymmetric predominance that depends on the applied cognitive strategy (global versus local; verbal versus procedural). Therefore, music teaching and learning should take into consideration that different strategies engage different brain areas. The more interconnected these areas are, the more stable the developed representations will become.

6. Research on individuals with mental disorders has clearly demonstrated that musical abilities develop independently of other domains of cognition. Therefore, these studies suggest that each person forms his or her individual intelligence profile. Music education should take advantage of the individual's potential within the musical domain rather than hoping for possible extra-musical transfer effects. Music education must develop the individual's unique musical aptitude to its highest possible level.

Further research questions that regard the development of appropriate methods for teaching and learning remain, such as:

- How do motor, aural, and visual representations interact?
- What role does memory play in "formal" representation?
- How is global versus local processing in music localized?
- What is the neuronal substrate of different types of representation (figural versus formal)?
- What kinds of subcortical representations are engaged in music processing?
- How do cortical and subcortical representations interact in music learning?
- Are there culture-specific types of brain processing and formation of mental representation and, if so, what are the optimal ways of teaching music within and between cultures?

The ongoing dramatic progress in brain research has spawned the investigation of many aspects of music learning in a more sophisticated way than was ever thought possible. This research may in the long run open new insights into the learning and understanding of music, with far-reaching applications for music education.

REFERENCES

- Aebli, H. (1980/81). *Denken—das Ordnen des Tuns*, 2 vols. Stuttgart, Germany: Klett-Cotta.
- Aldridge, D. (1994). Alzheimer's disease: Rhythm, timing and music as therapy. *Biomedicine and Pharmacotherapy*, 48(7), 275-281.
- Altenmüller, E., & Gruhn, W. (1997). *Music, the brain, and music learning. Mental representation and changing activation patterns through learning* (GIML series vol. 2). Chicago: G.I.A.

- Altenmüller, E., Gruhn, W., Parlitz, D., & Liebert, G. (2000). The impact of music education on brain networks. Evidence from EEG studies. *International Journal for Music Education*, 35, 47–53.
- Baldwin, J. M. (1968). *The development of the child and of the race*. New York: Augustus M. Kelly. (Original work published 1894)
- Bamberger, J. (1991). *The mind behind the musical ear: How children develop musical intelligence*. Cambridge, MA: Harvard University Press.
- Bangert M. W., Parlitz, D., & Altenmüller, E. (1999). Neuronal correlates of the pianists' "inner ear." *International Conference on Musical Imagery*, Oslo, Norway.
- Barinaga, M. (1999). Learning visualized, on the double. *Science* 286, 1661.
- Bastian, H. G. (2000). *Musik(erziehung) und ihre Wirkung: Eine Langzeitstudie an Berliner Grundschulen* [Music education and its effects]. Mainz, Germany: Schott.
- Bechtel, W., & Abrahamsen, A. (1991). *Connectionism and the mind: An introduction to parallel processing networks*. Cambridge, MA: Blackwell.
- Bellugi, U., Lai, Z., & Wang, P. (1997). Language, communication and neural systems in Williams syndrome [Special issue: *Communication processes in children with developmental disabilities*]. *Mental Retardation and Developmental Disabilities Research Review*, 3, 334–342.
- Black, J. E., & Greenough, W. T. (1998). Developmental approaches to the memory process. In J. Martinez & R. Kesner (Eds.), *Neurobiology of learning and memory* (pp. 55–88). San Diego, CA: Academic Press.
- Breitling, D., Guenther, W., & Rondot, P. (1987). Auditory perception of music measured by brain electrical activity mapping. *Neurophysiologia*, 25, 765–774.
- Bruer, J. T. (1999). *The myth of the first three years*. New York: Free Press.
- Brust, J. C. (1980). Music and language: Musical alexia and agraphia. *Brain*, 103(2), 357–392.
- Butzlaff, R. (2000). Can music be used to teach reading? *Journal of Aesthetic Education*, 34(3–4), 167–178.
- Calvin, W. H. (1996). *How brains think*. New York: Basic Books.
- Case, R. (1972). Learning and development: A neo-Piagetian interpretation. *Human Development*, 15, 339–358.
- Chan, A. S., Ho, Y. C., & Cheung, M. C. (1998). Music training improves verbal memory. *Nature*, 396, 128.
- Chugani, H. T. (1998). A critical period of brain development: Studies of cerebral glucose utilization with PET. *Preventive Medicine*, 27(2), 184–188.
- Conel, J. L. (1967). *The postnatal development of the human cerebral cortex* (Vols. 1–8). Cambridge, MA: Harvard University Press. (Original work published 1939)
- Critchley, M. (1977). Musicogenic epilepsy. In M. Critchley & R. Hensen (Eds.), *Music and the brain* (pp. 344–353). Springfield, IL: Charles C. Thomas.
- Crystal, H. A., Grober, E., & Masur, D. (1989). Preservation of musical memory in Alzheimer's disease. *Journal of Neurology, Neurosurgery, and Psychiatry*, 52(12), 1415–1416.
- Diamond, M. C. (1967). Extensive cortical depth measurements and neuron size increases in the cortex of environmentally enriched rats. *Journal of Comparative Neurology*, 131, 357–364.
- Diamond, M. C., Krech, D., & Rosenzweig, M. R. (1964). The effects of an enriched environment on the histology of the rat cerebral cortex. *Journal of Comparative Neurology*, 123, 111–119.
- Elbert, T., Pantev, C., Wienbruch, C., Rockstrub, B., & Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science*, 270, 305–307.
- Fagen, J., Prigot, J., Carroll, M., Pioli, M., Stein, A., & Franco, A. (1997). Auditory context and memory retrieval in young infants. *Child Development*, 68(6), 1057–1066.
- Fiske, H. E. (1993). *Music cognition and aesthetic attitudes*. Lewiston: Edwin Mellen.
- Fodor, J. A. (1983). *The modularity of mind*. Cambridge, MA: MIT Press.
- Fujita, S., & Ito, J. (1999). Ability of nucleus cochlear implantees to recognize music. *Annals of Otology, Rhinology, and Laryngology*, 108, 634–640.
- Gardner, H. (1985). *Frames of mind: The theory of multiple intelligences*. New York: Basic Books. (Original work published 1983)
- Gardner, H. (1999). *The disciplined mind*. New York: Simon & Schuster.
- Gaschler-Markefski, B., Baumgart, F., Tempelmann, C., Woldorff, M. G., & Scheich, H. (1998). Activation of human auditory cortex in retrieval experiments: An fMRI study. *Neural Plasticity*, 6(3), 69–75.
- Gfeller, K., Woodworth, G., Rubin, D., Wih, S., & Knutson, J. (1997). Perception of rhythmic and sequential pitch patterns by normally hearing adults and adult cochlear implant users. *Ear and Hearing*, 18(3), 252–260.
- Globus, A., Rosenzweig, M. R., Bennett, E. L., & Diamond, M. C. (1973). Effects of differential experience on dendritic spine counts in rat cerebral cortex. *Journal of Comparative and Physiological Psychology*, 82, 175–181.
- Glynn, N. J. (1992). The music therapy assessment tool in Alzheimer's patients. *Journal of Gerontological Nursing*, 18(1), 3–9.
- Gordon, E. E. (1997). *Learning sequences in music. A music learning theory* (5th ed.). Chicago: G.I.A. (Originally published 1980).
- Gordon, N. (2000). Developmental dysmusia (developmental musical dyslexia). *Developmental Medicine and Child Neurology*, 42(3), 214–215.
- Gottlieb, G. (1991). Experimental canalization of behavioral development: Theory. *Developmental Psychology*, 27, 4–13.
- Griffith, N., & Todd, P. M. (Eds.). (1999). *Musical networks: Parallel distributed perception and performance*. Cambridge, MA: MIT Press.
- Gruhn, W. (1997). Music learning: Neurobiological foundations and educational implications. *Research Studies in Music Education*, 9, 36–47.
- Gruhn, W., Altenmüller, E., & Babler, R. (1997). The influence of learning on cortical activation patterns. *Bulletin of the Council for Research in Music Education*, 133, 25–30.
- Gruhn, W. (1998). *Der Musikverstand: Neurobiologische Grundlagen des musikalischen Denkens, Hörens und Ler-*

- nens [The music brain: neurobiological basis of musical thinking, listening, and learning]. Hildesheim, Germany: Olms.
- Gruhn, W. (2001). Musikalische Lernstadien und Entwicklungsphasen beim Kleinkind. Eine Langzeituntersuchung zum Aufbau musikalischer Repräsentationen bei Kindern bis zum 4. Lebensjahr. *Diskussion Musikpädagogik*, 9, 4–33.
- Hebb, D. O. (1949). *Organization of behavior*. New York: Wiley.
- Hetland, L. (2000a). Learning to make music enhances spatial reasoning. *Journal of Aesthetic Education*, 34, 179–238.
- Hetland, L. (2000b). Listening to music enhances spatial-temporal reasoning: Evidence for the “Mozart effect.” *Journal of Aesthetic Education*, 34, 105–148.
- Hodges, D. A. (Ed.). (1996). *Handbook of music psychology* (2nd ed.). San Antonio, TX: IMR Press.
- Hughes, J. R., Daaboul, Y., Fino, J. J., & Shaw, G. L. (1998). The “Mozart effect” in epileptiform activity. *Clinical Electroencephalography*, 29, 109–119.
- Hughes, J. R., Fino, J. J., & Melyn, M. A. (1999). Is there a chronic change of the “Mozart effect” on epileptiform activity? A case study. *Clinical Electroencephalography*, 30(2), 44–45.
- Huttenlocher, P. R. (1979). Synaptic density in human frontal cortex—Developmental changes and effects of aging. *Brain Research*, 163(2), 195–205.
- Huttenlocher, P. R. (1984). Synapse elimination and plasticity in developing human cerebral cortex. *American Journal of Mental Deficiency*, 88(5), 488–496.
- Huttenlocher, P. R. (1990). Morphometric study of human cerebral cortex development. *Neuropsychologia*, 28, 517–527.
- Huttenlocher, P. R., & Dabholkar, A. S. (1997). Regional differences in synaptogenesis in human cerebral cortex. *Journal of Comparative Neurology*, 387(2), 167–178.
- Ito, J., Takagi, A., Kauno, M., & Honjo, I. (1995). Results with the currently used cochlear implant. *Annals of Otolaryngology, Rhinology, and Laryngology Supplement*, 166, 298–300.
- Jernigan, T. L., & Bellugi, U. (1990). Anomalous brain morphology on magnetic resonance images in Williams syndrome and Down syndrome. *Archives of Neurology*, 47(5), 529–533.
- Johnson, J. K., Cortman, C. W., Tasaki, C. S., & Shaw, G. L. (1998). Enhancement in spatial-temporal reasoning after a Mozart listening condition in Alzheimer's disease: A case study. *Neurological Research*, 20, 666–672.
- Johnson, J. K., Shaw, G. L., Vuong, M., Vuong, S., & Cortman, C. W. (1999). *Spatial-temporal reasoning in Alzheimer's disease: A group study*. Unpublished manuscript submitted for publication.
- Johnson, J., & Ulatowska, H. (1995). The nature of the tune and text in the production of songs. *Music Medicine* 2. St. Louis: MMB Music.
- Johnson, M. H. (1998). The neural basis of cognitive development. In W. Damon (Ed.), *Handbook of child psychology: Vol. 2. Cognition, perception, and language* (5th ed.) (pp. 1–49). New York: Wiley.
- Johnson-Laird, P. N. (1983). *Mental models: Toward a cognitive science of language, inference, and consciousness*. Cambridge, MA: Harvard University Press.
- Kempermann, G., Kuhn, H., & Gage, F. (1997). More hippocampal neurons in adult mice living in an enriched environment. *Nature*, 386, 493–495.
- Kosslyn, S. M. (1994). *Image and brain: The resolution of the imagery debate*. Cambridge, MA: MIT Press.
- Kurth, E., & Heinrichs, M. (1976). Musical-rhythmic discrimination ability and recall in children with reading and spelling disorders. *Psychiatrie, Neurologie und Medizinische Psychologie (Leipzig)*, 28, 559–564.
- Leng, X., & Shaw, G. L. (1991). Toward a neural theory of higher brain function using music as a window. *Concepts in Neuroscience*, 2, 229–258.
- Lenhoff, H. M., Wang, P. P., & Greenberg, F. (1997). Williams syndrome and the brain. *Scientific American*, 277(6), 68–73.
- Leont'ev, A. N. (1981). The problem of activity in psychology. In J. V. Wertsch (Ed.), *The concept of activity in Soviet psychology* (pp. 37–71). Armonk, NY: Sharpe.
- Levitin, D., & Bellugi, U. (1998). Musical abilities in individuals with Williams syndrome. *Music Perception*, 15(4), 357–389.
- Liebert, G., Gruhn, W., Parltitz, D., Trappe, W., Bangert, M., & Altenmüller, E. (1999). Kurzzeit-Lerneffekte musikalischer Gehörbildung spiegeln sich in kortikalen Aktivierungsmustern wider. In *Proceedings of the 1999 Annual Meeting of the German Society for Music Psychology* (pp. 32–33). Karlsruhe, Germany.
- Liegeois-Chauvel, C., Peretz, I., Babai, M., Laguitton, V., & Chauvel, P. (1998). Contribution of different cortical areas in the temporal lobes to music processing. *Brain*, 121(10), 1853–1867.
- Lord, T. R., & Garner, J. E. (1993). Effects of music on Alzheimer patients. *Perception and Motor Skills*, 76(2), 451–455.
- Luria, A. R. (1961). *The role of speech in the regulation of normal and abnormal behavior*. New York: Liveright.
- Martinez, M. E. (1999). Cognitive representations: Distinctions, implications, and elaborations. In I. E. Sigel (Ed.), *Development of mental representation* (pp. 13–31). Mahwah, NJ: Erlbaum.
- McClelland, J. L. (1995). A connectionist perspective on knowledge and development. In T. J. Simon & G. S. Halford (Eds.), *Developing cognitive competence: New approaches to process modeling* (pp. 157–204). Hillsdale, NJ: Erlbaum.
- Minsky, M. (1980). K-lines: A theory of memory. *Cognitive Science*, 4, 117–133.
- Muller, D., Toni, N., & Buchs, P. A. (2000). Spine changes associated with long-term potentiation. *Hippocampus*, 10(5), 595–604.
- Overy, K. (1998). Discussion note: Can music really “improve” the mind? *Psychology of Music* 26(1), 97–99. [See also responses to Overy's paper, next issue, 26(2), 197–210.]
- Pacteau, C., Einon, D., & Sindén, J. (1989). Early rearing environment and dorsal hippocampal ibotenic acid lesions:

- Long-term influences on spatial learning and alternation in the rat. *Behavioural Brain Research*, 34, 79–96.
- Pantev, C., Oostenveld, R., Engellen, A., Ross, B., Roberts, L. E., & Hoke, M. (1998). Increased auditory cortical representation in musicians. *Nature*, 392, 811–814.
- Parkinson, A. J., & Parkinson, W. S. (1998). Speech perception performance in experienced cochlear-implant patients receiving the SPEAK processing strategy in the Nucleus Spectra-22 cochlear implant. *Journal of Speech, Language, and Hearing Research*, 41(5), 1073–1087.
- Parsons, L., Hodges, D., & Fox, P. T. (1998). Neural basis of the comprehension of musical harmony, melody, and rhythm. *Proceedings of the Cognitive Neuroscience Society Meeting*, San Francisco.
- Pascual-Leone, J., & Smith, J. (1969). The encoding and decoding of symbols by children. A new experimental paradigm and a neo-Piagetian theory. *Journal of Experimental Child Psychology*, 8, 328–355.
- Pavlov, I. P. (1927). *Conditioned reflexes* (G. V. Anrep, Trans.). New York: Oxford University Press.
- Peretz, I. (1990). Processing of local and global musical information by unilateral brain damaged patients. *Brain*, 113, 1185–1205.
- Peretz, I., Gaudreau, D., & Bonnel, A. M. (1998). Exposure effects on music preference and recognition. *Memory and Cognition*, 26(5), 884–902.
- Pflederer Zimmerman, M. (1984). The relevance of Piagetian theory for music education. *International Journal of Music Education*, 3, 31–34.
- Pflederer Zimmerman, M., & Webster, P. (1983). Conservation of rhythmic and tonal patterns of second through six grade children. *Bulletin of the Council for Research in Music Education*, 73, 28–49.
- Piaget, J. (1947). *La psychologie de l'intelligence*. Paris: Librairie Armand Colin.
- Piaget, J. (1959). *La naissance de l'intelligence chez l'enfant*. Neuchâtel: Delachaux & Niestlé.
- Pijl, S. (1997). Labeling of musical interval size by cochlear implant patients and normally hearing subjects. *Ear and Hearing*, 18(5), 364–372.
- Pylyshyn, Z. W. (1973). What the mind's eye tells the mind's brain: A critique of mental imagery. *Psychological Bulletin*, 80, 314–329.
- Rakic, P. (1995). Corticogenesis in human and nonhuman primates. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 127–145). Cambridge, MA: MIT Press.
- Rauschecker, J. P. (1999). Auditory cortical plasticity: A comparison with other sensory systems. *Trends in Neurosciences*, 22(2), 74–80.
- Rauscher, F. H. (1999). Music exposure and the development of spatial intelligence in children. *Bulletin of the Council for Research in Music Education*, 142, 35–47.
- Rauscher, F. H., & Koch, J. E. (2000). *The effects of exposure to music on spatial processing sites*. Unpublished raw data.
- Rauscher, F. H., Robinson, K. D., & Jens, J. J. (1998). Improved maze learning through early music exposure in rats. *Neurological Research*, 20, 427–432.
- Rauscher, F. H., Shaw, G. L., & Ky, K. N. (1993). Music and spatial task performance. *Nature*, 365, 611.
- Rauscher, F. H., Shaw, G. L., Levine, L. J., Wright, E. L., Dennis, W. R., & Newcomb, R. L. (1997). Music training causes long-term enhancement of preschool children's spatial-temporal reasoning. *Neurological Research*, 19, 1–8.
- Reisberg, D. (Ed.). (1992). *Auditory imagery*. Hillsdale, NJ: Erlbaum.
- Renner, M. J., & Rosenzweig, M. R. (1987). *Enrichment and impoverished environments: Effects on brain and behavior*. New York: Springer.
- Rumelhart, D. E., & McClelland, J. L. (1986). *Parallel distributed processing: Explorations in the microstructure of cognition*. Cambridge, MA: MIT Press.
- Sarnthein, J., von Stein, A., Rappelsberger, P., Petsche, H., Rauscher, F. H., & Shaw, G. L. (1997). Persistent patterns of brain activity: An EEG coherence study of the positive effect of music on spatial-temporal reasoning. *Neurological Research*, 19, 107–116.
- Schank, R. C., & Abelson, R. P. (1977). *Scripts, plans, goals, and understanding: An inquiry into human knowledge structure*. New York: Wiley.
- Schlaug, G., Jäncke, L., Huang, Y., & Steinmetz, H. (1994). In vivo morphometry of interhemispheric asymmetry and connectivity in musicians. In I. Deliège (Ed.), *Proceedings of the 3d International Conference for Music Perception and Cognition* (pp. 417–418). Liège, Belgium: ESOM (Centre de Recherches et de Formation Musicales de Walbnie).
- Schlaug, G., Jäncke, L., Huang, Y., Staiger, J. F., & Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia*, 33(8), 1047–1055.
- Serafine, M. L. (1988). *Music as cognition: The development of thought in sound*. New York: Columbia University Press.
- Shepard, R. N. (1978). The mental image. *American Psychologist*, 33, 125–137.
- Silva, A. J., Paylor, R., Wehner, J. M., & Tonegawa, S. (1992). Impaired spatial learning in a-calcium-calmodulin kinase II mutant mice. *Science*, 257, 206–211.
- Skinner, B. F. (1953). *Science and human behavior*. New York: Macmillan.
- Spychiger, M. (1995). *Mehr Musikunterricht an den öffentlichen Schulen?* Hamburg, Germany: Kovac.
- Steele, K. M., Dalla Bella, S., Peretz, I., Dunlop, T., Dawe, L. A., Humphrey, G. K., Shannon, R. Z., Kirby, J. L., & Olmstead, C. G. (1999). Prelude or requiem for the Mozart effect? *Nature*, 400, 827.
- Stratford, B., & Ching, E. Y. (1983). Rhythm and time in the perception of Down's syndrome children. *Journal of Mental Deficiency Research*, 27, 23–38.
- Swanwick, K. (1999). *Teaching music musically*. London: Routledge & Kegan Paul.
- Thaut, M. H., Kenyon, G. P., Schauer, M., & McIntosh, G. (1999). The connection between rhythmicity and brain function. *IEEE Engineering in Medicine and Biology Magazine*, 18(2), 101–108.
- Thaut, M. H., Miltner, R. Lange, H. W., Hurt, C., & Hoemberg, V. (1999). Velocity modulation and rhythmic synchronization of gait in Huntington's disease. *Movement Disorders*, 14(5), 808–819.

- Tillmann, B., Bharucha, J. J., & Bigand, E. (2000). Implicit learning of tonality: A self-organizing approach. *Psychological Review*, 107(4), 885-913.
- Todd, P. M., & Loy, D. G. (Eds.). (1991). *Music and connectionism*. Cambridge, MA: MIT Press.
- Turner, A. M., & Greenough, W. T. (1985). Differential rearing effects on rats' visual cortex synapses. 1. Synaptic and neuronal density and synapses per neuron. *Brain Research*, 329, 195-203.
- Vaughn, K. (2000). Music and mathematics: Modest support for the oft-claimed relationship. *Journal of Aesthetic Education*, 34(3/4), 149-166.
- Vygotsky, L. S. (1962). *Thought and language* (E. Hanfmann & G. Vaker, Trans.). Cambridge, MA: MIT Press. (Original work published 1934)
- Watson, J. B. (1913). Psychology as the behaviorist views it. *Psychological Review*, 20, 158-177.
- West, T. (1991). *In the mind's eye: Visual thinkers, gifted people with learning difficulties, computer images, and the ironies of creativity*. Amhurst, NY: Prometheus Books.
- West, R. W., & Greenough, W. T. (1972). Effect of environmental complexity on cortical synapses of rats: Preliminary results. *Behavioral Biology*, 7, 278-284.
- Winner, E., & Hetland, L. (2000). The arts in education: Evaluating the evidence for a causal link. *Journal of Aesthetic Education*, 34(3/4), 3-10.
- Zatorre, R., & Halpern, A. (1993). Effect of unilateral temporal-lobe excision on perception and imagery of songs. *Neuropsychologia*, 31(3), 221-232.
- Zatorre, R., Halpern, A., Perry, D., Meyer, E., & Evans, A. (1996). Hearing in the mind's ear: A PET investigation of musical imagery and perception. *Journal of Cognitive Neuroscience*, 8, 29-46.