MENC Handbook of Musical Cognition and Development

Richard Colwell,
Editor

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Preface

The use of research findings is critical to the success of music teaching and learning. There is probably no area of greater importance in the 21st century than research involving music and its impact on the development and use by the human brain. The popular press has reported partial findings of research indicating the importance of music in human development. It is important that teachers and researchers have a full understanding of the findings of valid studies in order that our knowledge not be misused. Andreas Lehmann, a German scholar, assembled an outstanding team that wrote chapters on our knowledge of perception and cognition for the *New Handbook of Research on Music Teaching and Learning* published by Oxford University Press in 2002. In this text, we provide an up-date of that material with the addition of a chapter on Music and Neuroscience by John W. Flohr and Donald A. Hodges.

This up-date is the result of the efforts of Ms. Kim Robinson and Ms. Eve Bachrach of Oxford University Press and Mike Blakeslee of the National Association for Music Education—MENC, believers in the importance of disseminating research findings to the profession. It is our hope that the publication of separate, small, economical, books on specialized research topics will make the material more accessible to users in a variety of fields. Music cognition is a vital topic for scholars in medicine, psychology, in educational psychology, and in music theory, as well as for music educators. One will note that we have selected authors from all of these fields and authors from continental Europe, Great Britain, Canada, and the United States. It has been my pleasure to work through with them with the assistance of Professor Lehmann issues of language, definitions, and concepts to make the material clear to not only English speakers but those who use English as a research tool. Accurate definitions apply to the topic of each chapter although the authors have coordinated their writing to avoid duplication and to cover the material of music perception and cognition as succinctly as possible in only seven chapters. Although the chapters stand alone as a research resource, they have also been organized to be read in the normal textbook fashion, from the introduction to the end of chapter 7.

It has been my pleasure to work with not only the authors but with the National Association for Music Education and Oxford University Press in this exemplary cooperative project. As one who does not normally think about how music works within the human, I have found these chapters enlightening as I'm sure will both sophisticated and those of us who are less sophisticated in brain functioning and its responses.

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Contributors

JANE W. DAVIDSON is professor of performance studies in the Department of Music at the University of Sheffield and specializes in research on performance skills acquisition, expression, and social dynamics. Her recent edited volume, *The Music Practitioner*, explores the uses of research for the practicing musician. A former editor of *Psychology of Music*, she is currently vice-president of the European Society for the Cognitive Sciences of Music. She also holds a visiting professorial post at the University of Western Australia. Besides her academic career, as an ex-professional opera singer, she specializes in directing. She has more than thirty productions in her repertoire, having worked on the wildly contemporary (*Death and the Madman*, for Drama per musica in Portugal) to the pastoral and lyrical, including Mozart's rarely performed *Betulia Liberata*. Over the years, she has worked with the Hong Kong Cultural Centre, London International Opera Festival, the Edinburgh Festival, Wigmore Hall, Extemporary Dance Theatre, Théâtre de Complicité, Opera North, and Drama per Musica on a range of music theatre projects.

JOHN W. FLOHR received his doctorate in music education from the University of Illinois-Urbana. He has performed as a professional musician and taught at the college, public school, and preschool level. He is professor of music at Texas Woman's University–Denton, serves as current president of the Texas Music Educators Conference, and recently was faculty fellow at the national Arts Eduction Partnership. He specializes in early childhood music education and has authored research papers, books, videos, audio recordings, and computer programs in music and music education. His most recent book is *Musical Lives of Young Children*.

HEINER GEMBRIS holds a degree in music education from the Academy of Music Detmold and in musicology from the Technische Universität Berlin. He worked as a music teacher in secondary public schools for several years. In 1985, he earned his doctorate with a study on music listening and relaxation. After an employment at the University of Augsburg, he was appointed professor for systematic musicology at the University of Münster (1991), and later at the University of Halle/Wittenberg (1998). Since 2001 he has been head of music education and Music Psychology at the University of Paderborn and has directed the Institute for Research on Musical Ability (IBFM). Heiner Gembris has occupied numerous leading positions in scientific organisations and is member of the scientific board of national and international journals. His main research interests concern the effects of music listening, music preferences, and the nature and development of music abilities across the lifespan. In 1998, he published a textbook in German on musical talent and development (2nd edition 2002).

WILFRIED GRUHN is professor emeritus of music education at the University of Music (Musikhochschule), Freiburg, Germany. He served as chair of the Music Education Department, and worked as co-editor of several German journals for music education. His research areas include musicology, music education, and psychology. He specialized in the neurobiology of music learning, perception, and cognition and collaborates with neurologists in interdisciplinary projects. Currently he is director of the Gordon-Institute for Early Childhood Music Learning in Freiburg, Germany.

DONALD A. HODGES is Covington Distinguished Professor of Music Education and director of the Music Research Institute at the University of North Carolina at Greensboro. He is contributing editor of the *Handbook of Music Psychology* and the accompanying *Multimedia Companion* (CD-ROMs vols. 1 & 2). Recent research includes a series of brain imaging studies of musicians.

REINHARD KOPIEZ has been professor of music psychology at the School of Music and Drama in Hannover, Germany since 1998. He earned his PhD in 1990 from the Technical University of Berlin. After appointments as assistant professor for musicology at the Technical University of Berlin and later for systematic musicology at the school of music in Wuerzburg. Since 1998 he has been vice president of the German Society for Music Psychology (DGM) and since 2002 its president. He is also a member of the executive council of the European Society for the Cognitive Sciences of Music (ESCOM). Kopiez has written several books and numerous chapters and articles for national and international publications. His main areas of research interest are performance research, rhythm perception, and music in everyday-life. Some recent publications include: (1998) *Fussball-Fangesaenge* [Singing at soccer games], Wuerzburg: Koenigshausen; (2003a) Intonation of harmonic intervals: adaptibility of expert musicians to equal temperament and just intonation, *Music Perception*, 20(4), 383–410; (2003b) Tempo and loudness analysis of a continuous 28-hour performance of Erik Satie's composition "Vexations," *Journal of New Music Research*, 32(3), 243–258; (2003c) Stability of motor programs during a state of meditation: electrocortical activity in a pianist playing 'Vexations' by Erik Satie continuously for 28 hours, *Psychology of Music*, 31(2), 173–186.

ANDREAS C. LEHMANN is currently professor of systematic musicology and music psychology at the *Hochschule für Musik Würzburg*, Germany. He earned a degree in music education and a Ph.D. in musicology, both from the *Hochschule für Musik und Theater* in Hannover, Germany, from 1998 to 2000 he worked as a junior faculty ("Wissenschaftlicher Assistent") with Heiner Gembris in the musicology department at the *Martin-Luther University* in Halle. Between 1993 and 1998 he was a postdoctoral fellow in the Department of Psychology at the *Florida State University*, Tallahassee, Florida, where he worked with K. Anders Ericsson in the area of cognitive psychology. Andreas Lehmann received in 1997 a Young Researcher Merit Award from the *European Society for the Cognitive Sciences of Music (ESCOM)*, and he has co-edited a book on practice and published a number of chapters and journal articles. Currently, Andreas Lehmann is also associate editor of the journal *Musicae Scientiae* and vice-president of the German music education research organization *(AmpF)*. In his research, he is mainly interested in studying the structure and acquisition of high levels of instrumental music performance skills such as those displayed by advanced music students and professional performers. This research on practice and performance has real-life applications for music education and is of theoretical importance for many other domains of expertise.

FRANCES RAUSCHER is an associate professor in the Department of Psychology at the University of Wisconsin Oshkosh. She holds degrees in cello performance and experimental psychology. Her research focuses on the relationship between music exposure and cognitive performance in adults, humans, and rats. She has publications in music cognition, cognitive neuroscience, developmental psychology, and social psychology, and has given presentations in North America, Europe, and Australia.

E. GLENN SCHELLENBERG is a professor in the Department of Psychology at the University of Toronto at Mississauga with a cross-appointment in the graduate faculty in the Department of Human Development and Applied Psychology at the Ontario Institute for Studies in Education at the University in Toronto. He received his doctorate from Cornell University in 1994 in human experimental psychology. His primary research area focuses on cognitive developmental issues in the auditory domain with a special interest in music perception and cognition particularly on reciprocal influences between basic psychological processes and musical structure. He is also interested in the cognitive (nonmusical) consequences of formal music lessons. Ongoing research projects are investigations of how one becomes an enculturated listener, the development of children's memory for familiar songs, effects of aging and musical training on pitch perception, developmental perspectives of absolute pitch, and the impact of music lessons on cognitive development. His extensive record of publications not only in developmental and cognitive psychology but in social psychology has recently earned him the Premier's Research Excellent Award for 2002–2007.

WILLIAM FORDE THOMPSON is director of the CCIT and a professor in the Department of Psychology at the University of Toronto at Mississauga. He is also an associate member of the Unit for the Study of Musical Skill and Development. After receiving his doctorate in psychology from Queen's University, he began an exemplary career in music perception and cognition. He is an accomplished composer, writing music for the theater that has been staged throughout Canada and on CBS Radio. He is an officer in the Society for Music Perception and Cognition and heads Experiment Creator, which tests and teaches concepts related to audio-visual content. His research interests are in decoding speech prosody, acoustic cues and speech, visual influences on perception, and recognition of emotion in cross cultural situations. His most recent book is *Music Thought and Feeling: The Psychology of Music*, Oxford University Press, 2006.

BRUCE TORFF is associate professor of curriculum and teaching at Hofstra University in Hempstead, New York. An educational psychologist, Torff has published numerous books and articles on topics in cognitive-developmental psychology, teacher education, and musical cognition. His books include *Understanding and Teaching the Intuitive Mind* and *Multiple Intelligences and Assessment*. Torff earned a doctorate and two masters degrees at Harvard University, where he worked with Howard Gardner and served as a project director at Project Zero, Gardner's research organization. Torff also held a postdoctoral appointment at Yale University in collaboration with Robert J. Sternberg. Torff is active as a leader of professional-development workshops for educators and is also a jazz pianist and songwriter.

MENC Handbook of Musical Cognition and Development

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Introduction

Music Perception and Cognition

ANDREAS C. LEHMANN

Research in perception and cognition in music has seen tremendous growth over the last two decades (see Levitin, 1999). The reason for this expansion is not that music research has emerged only recently as a new discipline; instead, it appears that whoever had been interested in music years ago but did not dare to do music research can now freely admit to his or her "vice." As a result, the field has become extremely diversified and includes psychologists, sociologists, and anthropologists as well as AI researchers, physiologists, and acousticians. Many of them are active musicians with varying degrees of firsthand experience, while other scientists simply think that music is a convenient domain for their purposes. There are also artists who use their working environment to undertake new types of action research (see J. W. Davidson, 2004, e.g., chapters 11 and 22). Common to all is the desire to find out more about how our brain processes the auditory input we then experience as music. Unfortunately, the issues that entice researchers are not always identical to those that appeal to music educators, who, after successful mastery of the scientific jargon, are often disappointed to discover how difficult it is to apply the findings to the classroom. Admittedly, some research done today might only prove its usefulness many years from now in the context of future research.

In the wake of recent advances in neurobiology, trying to separate perception and cognition has become less appropriate and useful. Where, for example, does music cognition actually begin? Does it start in the cochlea or right after the cochlea, or does it emerge out of the simultaneous firing of neurons in different cortical areas? And how does our individual genetic makeup influence music perception and cognition? Where do our memories and feelings enter into the perception and cognition game? As a result, and in order to be of maximal use for music educators, here we did not adhere to a strong division of perception and cognition but rather understood cognition in its broader sense, namely, how it applies in the context of experience, training, development, and culture.

This book with its seven chapters does not purport to cover the whole range of topics relevant to music perception and cognition. We have tried to capitalize on emergent issues and research done since the publication of the first Handbook (Colwell, 1992). In our experience, music educators as a group are likely to look at the research presented in the following 7 chapters. We should keep in mind, however, there is probably not *the* music educator, as there is not *the* music psychologist. Any choice of issues discussed, references cited, or references omitted (due to space limitations) will have to be the result of subjective decisions. A review of the literature is never objective, because the writer has an agenda, which is to introduce a personal view on a topic. With the help of the many reviewers who made thoughtful suggestions to improve the draft chapters, the printed chapters should now match the needs of aspiring or in-service music educators and music education researchers.

The chapters follow a certain logic in that the first five chapters proceed from the basic neurological and cognitive processes to a panoramic view of musical development and the theories behind research on learning. The last two chapters concentrate on music performance skills, musical expression, and the audience. A chapter that was not originally part of the *Musical Cognition and Development* part of the 2002 Handbook is the one by Flohr and Hodges on Music and Neuroscience. Here the authors circumscribe the research methods and results currently available in the area of neuroscience. It is obvious that we are starting to better understand how music is processed in the brain, and how nature and nurture interact. This chapter in fact provides the necessary backdrop to some of the others presented in this volume. Wilfried Gruhn and Frances Rauscher introduce neuropsychological and neurophysiological research as it relates to learning. They also introduce some learning theories that essentially can be viewed as theories of cognition, and they clarify one hotly debated topic in music education, namely, the question of transfer of learning, which sometimes serves as a justification for music education in schools. William Forde Thompson and E. Glenn Schellenberg are experts in basic music cognition with all its developmental and cultural implications. Their chapter abounds with pointers to current research methodology and brings to our attention the processes in music perception we often take for granted (e.g., melody perception, timbre, rhythm). Heiner Gembris gives a more panoramic survey of topics and issues in developmental psychology. While emphasizing cognitive aspects, he also incorporates sociological and cultural aspects. This chapter is closely tailored to the questions frequently asked by music educators. Bruce Torff comes from the general area of educational psychology. His chapter places research on music perception and cognition into the larger context of research on music learning and development with its changing epistemological facets. The contextualist perspective presented by Torff is today an accepted and important position for music education. Reinhard Kopiez reviews the area of performance research in which great progress has been made internationally. Most interestingly, researchers are no longer interested solely in motor programming and internal clocks (although these topics are still under scrutiny) but also interested in knowing how we communicate and understand musical expression. As a trained musicologist, the author is able to bring modern research into contact with its historical roots. Jane W. Davidson and I sum up some of the research in skill acquisition, which stresses the environmental aspects of music learning, especially in learning to play an instrument. In some ways, this chapter acts as a counterweight to the chapter by Gruhn and Rauscher, which emphasizes the "hardware" aspects of musical learning.

For those readers looking for an update in one of the areas mentioned earlier, each chapter should provide a suitable point of entry. For the novice reader the chapters offer a thorough introduction into the topics of music psychology that are relevant to music educators.

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Music and Neuroscience

1

JOHN W. FLOHR
DONALD A. HODGES

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

1. *Strategies for conducting neuromusical research.* A review of the methodological approaches to conducting neuroscientific research in music. The neuroscience tools reviewed in this section have in many ways revolutionized our ability to examine both the function and structure of the brain. (For a more complete review, see Hodges, 1996b.)
2. *Overall development.* A review of findings relating to overall development, selected topics, and theories and theoretical areas.
3. *Future directions.* A generalized summary of findings and recommendations and considerations for future research directions.

Strategies for Conducting Neuromusical Research

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

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

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

Animal Research

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

Significant insights into human musicality can be gained particularly by investigating sound-making and responding behaviors in such species as birds, whales, dolphins, monkeys, and apes (D'Amato, 1988; Geissman, 2000; Marler, 2000; Payne, 2000; Warren, 1993; Whaling, 2000). Sight (e.g., seen in displays of aggression or mating behavior) or smell (e.g., marking territory) are ways animals can communicate. But sound has certain advantages in that it can travel long distances rapidly, operate during day or night, and encode complex and changing messages (Slater, 2000). Therefore, many species have developed sophisticated sound-making behaviors (not only vocalizations but also other noises, such as chest-thumping among gorillas). To assume that animal sounds have nothing to do with human music would be to ignore a significant amount of information and would be counter to linkages found in other types of behavior (e.g., language and social organization).

The opposite is equally true; one cannot automatically assume that there is a direct correlation between animal sounds and human music. Thus, one of the first issues to be dealt with is whether or not animals actually create music. This is a difficult question and one that may elude a definitive answer. It is tempting to anthropomorphize animal sounds; after all, we call it bird*song* because that is what it sounds like to us. But is it music to the animals? Certainly most animal sounds have to do with territoriality, courtship and mating rituals, and signaling (e.g., alarm calls) (Brody, 1991). Slater (2000) remarks that with more than 4,000 species of songbirds alone, and all the varied forms and patterns of their songs, it would not be difficult to find many seemingly musical characteristics embedded in their songs, but that this would most likely be coincidental. Even where birdsongs are more complex, varied, or elaborate than is strictly necessary for biological function, they may be so to achieve distinctiveness. If the point of sound-making is to communicate, it will do no good if the message is lost in a sonic environment rife with many voices. In a cacophonous habitat where many sounds are competing for "airspace," distinctiveness is an advantage. Krause's (1987) niche hypothesis is that each species produces sounds that occupy a particular bandwidth in the overall acoustic spectrum, along with unique rhythm patterns, tonal qualities, and so on. This ensures that the message will not get lost among all the other sounds. Having said that, however, does not preclude an animal deriving pleasure from the act of making sounds. Until we can gain access to their inner worlds, the most we can do is speculate.

In the meantime, this research strategy informs two concerns of music psychologists: What are the evolutionary antecedents of human musicality? What "extra" cognitive structures and processes do humans possess beyond those of other animals that allow for the degree of musicality expressed in all cultures? In the first instance, the sounds of nature (what Krause [1987] terms "biophony") most likely exerted strong influences on early hominid sound-making. It would be quite natural for us to mimic the sounds around us. Of course, with our sophisticated brains, it would not take long for us to move beyond mere mimicry to elaboration, extension, synthesis, and eventually the creation of novel sounds. In time, we would develop our own niche in the biophony. This line of research is important in developing a theory of an evolutionary basis for music (Hodges 1989, 1996a, 2000; Wallin, Merker, & Brown, 2000).

The second concern feeds more directly into the larger question of neuromusicology. For example, animals rely on absolute frequency analysis (D'Amato, 1988) rather than on relative pitch as we do (Trehub, Bull, & Thorpe, 1984). Thus, while various animals can be trained to choose between two songs, they fail miserably if those songs are transposed. By contrast, our adult musicality is possible, in large part, because we deal with pitch relationships. "Yankee Doodle," for instance, is recognizable to us at any pitch center.

There are other cognitive limitations among animals as well. For example, musical forms ranging from simple verse-chorus alternations to lengthy symphonic movements are possible because of our ability to retain musical information for long periods of time. Yet dolphins represent the best animals can do, and they can only recognize the second A section of a simple ABA form if each section is no more than 2 seconds long (Warren, 1993). Once again, however, it must be recognized that testing animals on their capacity for processing human music seems patently unfair. Nevertheless, this line of research does provide evidence of some of the neural mechanisms humans possess that allow for our musicality.

Fetal and Infant Research

In order to understand how the brain is predisposed to music, it would be ideal to look at the brain in a "pure" state, that is, without the influence of the environment. Since this is impossible, studying fetal and infant responses to music allows us to approach a "pure" state with minimal environmental influence. The limitations and difficulties of using babies as subjects seem apparent, but there is much useful information to be gained from this approach. A growing body of literature is focusing on fetal responses to music because in the last trimester before birth, the fetus is capable of responding to sounds in the womb. Researchers can gauge fetal responses by monitoring heart rate and through bodily movements (Abrams & Gerhardt, 1997; Deliège & Sloboda, 1996; Flohr, 2004a).

Almost immediately after birth, babies can orient toward sounds and soon after that can pick out the sounds of the mother's voice (Trehub, Schellenberg, & Hill, 1997; Trehub & Trainor, 1993). A significant amount of the interactions between a newborn and its caretakers is based on two-way sound manipulations. The caretakers sing lullabies and talk "baby talk," and there are musical crib mobiles and toys. "Motherese," a term psychologists have coined to refer to the type of baby talk typically spoken to infants, emphasizes pitch, timbre, dynamic inflections, and rhythm patterns in order to convey meaning (Dissayanake, 2000). Clearly, the baby cannot interpret the meaning of words but does learn to interpret the emotional content. Likewise, the baby learns early on to communicate by manipulating the same sonic elements to express mood states such as hunger, pain, fear, happiness, love, and so on. From this line of research, it is clear that infant musical behaviors are exhibited primarily because of inherited mechanisms (Imberty, 2000; Trehub, 2004). While learning takes place from the outset, babies do not need systematic, formal instruction in order to respond to music, speech, and other sounds.

Research on Brain-Damaged Individuals

Another approach that has a long history in neuroscience is to look at individuals who suffer from some form of brain damage, either from trauma, genetic defect, or aging. Studying persons who have suffered a tumor, stroke, or lesion indicates that some individuals suffer from aphasia (loss of language) but not amusia (loss of music) or vice versa. This lends support to the notion that music and language are dissociated; that is, that music and language are represented, at least to a large degree, by separate neural systems (Hodges, 1996b; Marin & Perry, 1999). Both are umbrella terms, in that there are many different forms of aphasia (e.g., loss of speech, comprehension, or the ability to read or write) and amusia (e.g., loss of ability to track pitch, or rhythm, or timbre or loss of familiar tune recognition). Because of the complexity and modularity of both systems, it is also possible that many brain regions are implicated in both language and music (Falk, 2000). (For more details on modularity see hereafter.)

A common research paradigm is to ask brain-damaged subjects to do a variety of music-related tasks. Their inability to do a task successfully (when compared to a person with an undamaged brain) is then linked to anatomical lesion sites. Several notes of caution must be inserted. First, a damaged brain is different from a normal brain, and the assumption that it is operating like the normal brain with the exception of the damaged portion is not necessarily warranted. Second, for older studies in the literature, anatomical lesion sites are not given very precisely; sometimes reports are as vague as "damage on the left side." Third, the case with music is somewhat different from the case with language. While one can reasonably assume that an adult has language competency, adult musical skills may vary all the way from minimal (even including "tone deafness") to highly professional. Thus, if, for example, a brain-damaged person cannot do a given musical task—such as match pitches, recognize familiar tunes, or read music—care must be taken to determine whether he or she had such skills prior to the trauma. (For a detailed review of the effects of brain damage on musical behaviors, see Hodges [1996b, pp. 212–216].)

A second class of subjects is those with inherited cognitive limitations. Musical savants are cognitively impaired but capable of amazing musical feats (Miller, 1989). Individuals with Williams syndrome often have cognitive "peaks" and "valleys," and music appears to be something many of them can do quite well (Levitin & Bellugi, 1998). Musical behaviors are only possible in such individuals because of the presence of specific neural structures. Williams syndrome, in particular, is a fertile area for research in that it may ultimately be possible to link research on genetics (Williams syndrome results from a microdeletion on chromosome 7) with neuroscientific and behavioral data. In contrast, some individuals may be born with musical limitations (e.g., deficits in pitch or rhythm processing) in what Peretz (2001) calls congenital amusia.

A third class of subjects involves those suffering from cognitive dementias due to aging (especially Alzheimer's). Individuals with prior musical backgrounds may retain procedural skills (e.g., singing or playing an instrument) in spite of declining linguistic fluency (Crystal, Grober, & Masur, 1989). In at least one case, an Alzheimer's patient was able to sing the words to familiar songs even though she could no longer communicate via language (Johnson & Ulatowska, 1995). Interestingly, music (among other things) is being recommended to elders as a means of staving off the ravages of Alzheimer's (Golden, 1994). The presence of musical skills, in the absence of linguistic and other skills, once again denotes neural structures devoted to musical processing.

Hemispheric Asymmetry Research

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

Dichotic listening tasks have been widely used as a means of comparing one side of the brain's performance with the other. Basically, the technique is to present conflicting signals to the right and left ears via headphones. Approximately 70% of the fibers in the auditory pathway are contralateral, meaning that they go from the inner ear to the auditory cortex in the opposite hemisphere. Thus, although both sides receive all the information from each ear, signals from the right ear are more strongly represented in the left hemisphere, and vice versa (Kimura, 1961; Robinson & Solomon, 1974). Contralateral response times are faster than ipsilateral (from one inner ear to the auditory cortex on the same side) (Majkowski, Bochenek, Bochenek, Knapik-Fijalkowska, & Kopec, 1971) and can occlude impulses arriving along ipsilateral pathways (Kimura, 1967). In a typical experiment, subjects might hear a nonsense syllable such as “bleh” in the right ear and “teh” in the left ear (stimuli must be nonsensical, as real words would be immediately recognized). They are then presented with four foils and asked to identify the one they heard. Over a number of trials, consistency in picking out the right ear signal would indicate processing dominance by the left hemisphere and vice versa.

A major limitation of this technique for music research is that the stimuli can be no longer than 2 seconds. If they are longer, the brain can go back and forth, picking up enough information from each ear to make recognition of both stimuli possible. Obviously, only limited musical meaning can be found in 2-second fragments. Also, stimulus variables (the type of sound/music being used), task variables (whether subjects are asked to make global or local decisions), and subject variables (amount of training, gender, handedness, etc.) can make dramatic differences in the results. Sergent was highly critical of this line of research and felt that all such data could be discarded (Sergent, 1993; for an extended review of this literature and discussion, see Hodges [1996b, pp. 222–232]).

For a period of time, primarily during the 1970s, much was made of music being in the right side of the brain. This oversimplification has since been modified. Music is *not* in the right side of the brain alone; both sides are involved. In fact, sophisticated musical processing most likely involves the front-back, top-bottom, and left and right sides of the brain in widely distributed but locally specialized neural networks. Furthermore, selectively changing the focus of attention radically alters brain activation patterns (Platel et al., 1997). Further implications of this line of research are discussed subsequently.

Brain Imaging Research

Modern neuroscientists have a broad range of highly sophisticated research tools at their disposal. These include electroencephalography (EEG), event-related potentials (ERP) derived from EEG, magnetoencephalography (MEG), superconducting quantum interference device (SQUID), magnetic resonance imaging (MRI), functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and transcranial magnetic stimulation (TMS, discussed in the section on neuromotor responses). Space does not allow for much more than a brief description of each of these technologies (see figure 1.1). Because of limited access to equipment, costs involved, and related issues, typical neuroimaging experiments are conducted with a very small number of subjects.

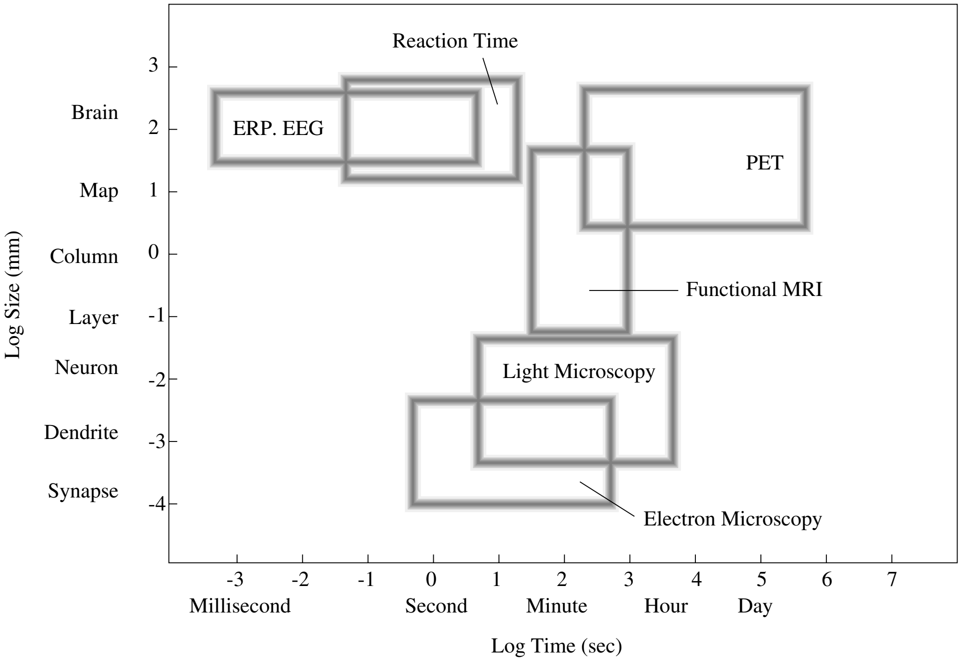

Figure 1.1. Schematic illustration of the spatial (vertical axis) and temporal (horizontal axis) resolution of techniques used to study brain function in humans. The hazy edges of each box suggest that these are approximations and that these techniques may not be limited to these boundaries in the future. This figure emphasizes the different spatial and temporal characteristics of methods used to study the neurobiology of behaviors, none of which alone is sufficient to understand the neural basis of a behavior or its development. (From Janowsky & Carper in Sameroff & Haith, eds., 1996.)

EEG and ERP. Due to neural activity, the brain constantly produces a small amount of electrical current that can be measured; EEG measures the summed activity of millions of brain cells under electrodes placed in various places around the skull (Gur & Gur, 1994). Data are interpreted in terms of frequency (Hz), amplitude (microvolts), form, and distribution (sometimes converted into a brain map). Most often reported are frequency components, including delta (0.5–4.0 Hz), theta (4.5–8.0 Hz), alpha (8.5–12.0 Hz), and beta waves (12.5–32.0 Hz). Electroencephalography has been used for some time to study different levels of arousal and is now being employed to study cognitive processes in general and music processing specifically (Altenmüller, 1993; Barber, 1999; Faita & Besson, 1994).

While EEG tracks the brain's electrical activity over time, ERP examines the brain's immediate response to a stimulus in millisecond (ms) intervals. A computer averages EEG readings following multiple presentations of a stimulus. This allows extraneous aspects of the EEG to be canceled out, while electrical activity occurring in time-locked response to the stimulus is revealed (Brown, Marsh, & Ponsford, 1985). Data are evaluated for directional changes in the wave pattern (either positive or negative), intensity level (amplitude), and latency (time lapse). A P300 wave indicates a positive wave whose maximum amplitude occurred approximately 300 ms after the stimulus, while a N400 wave is a negative wave form occurring approximately 400 ms after the stimulus. The P300 has been more frequently studied in relation to music. It is hypothesized to be an indicator of "working" memory, comparing incoming stimuli to stored memories, and has been linked to the detection of musical events (Cohen & Erez, 1991; Frisina, Walton, & Crummer, 1988; Hantz & Crummer, 1988; Paller, McCarthy, & Wood, 1992; Paulus, 1988; Schwent, Snyder, & Hillyard, 1976).

MEG and SQUID. The brain's electrical activity produces a magnetic field that can be measured just outside the skull through MEG, giving location information about neural activity. SQUID provides refined spatial information, in millimeters, and precise temporal resolution, in milliseconds (Hari, 1990). This approach has been used in only a few studies related to music (Kaufmann, Curtis, Wang, & Williamson, 1991; Williamson & Kaufmann, 1988).

MRI and fMRI. MRI provides very precise information about anatomical structures under the skin but does not provide information about function (Ackerman, 1992). It has been used to show structural features of musician's brains (Amunts et al., 1997; Pantev et al., 1998; Schlaug, Jancke, Huang, & Steinmetz, 1994, 1995). A newer development, fMRI does provide data about both location and function. Currently, there is considerable interest in finding a way to use fMRI to study music. The difficulty is that both MRI and fMRI are very noisy environments for the subjects. The camera's motion within the scanner generates rhythmical noise that competes with musical perception. While it is possible to extract speech or other nonmusical sounds from the ambient noise, it is not so easily done with music. Regular headphones cannot be used, because of the strong magnet. Researchers are attempting to deliver musical stimuli through pneumatic tubes or to develop better antinoise cancellation devices. A recently developed technique causes the cameras to pause for up to 10 seconds, which allows stimuli to be presented during the resulting silent period; staggering the camera start time allows for full acquisition of the hemodynamic response. If these problems are solved, fMRI should prove to be a very valuable approach for studying music cognition.

PET. In PET, radioactively tagged oxygen, water, or glucose is inhaled or injected into the bloodstream; PET scans then detect brain metabolism or regional cerebral blood flow (rCBF) while the subject engages in an assigned task (Raichle, 1994). By means of paired-image subtraction (subtracting the activations of one task from another), areas of the brain most active during a specific task are identified (Posner & Raichle, 1994). Areas of deactivation (i.e., less active than during rest) also provide useful information. Because PET provides information about function but not location, it is mapped onto MRI data. The combination of the two tells neuroscientists "what" is going on "where." PET is a powerful technique that is revealing important information about music processing (Fox et al., 1995; Parsons, Fox, & Hodges, 1998; Zatorre, 1994; Zatorre, Evans, & Myer, 1994).

Taken collectively, these various brain imaging techniques are opening up new understandings about the brain in general and about music cognition specifically. The most rapid advancements are being made in this field, and music psychologists, music educators, and music therapists should be aware of findings as they are reported (see Avanzini et al., 2003, Avanzini, Lopez, Koelsch, & Majno, 2005, and Zatorre & Peretz, 2001, for recent compilations).

Neuromotor Research

Musical responses are both expressive (i.e., performing) and receptive (i.e., listening). Musical performance activates motor control areas in the brain to such a high degree that musicians may be considered small-muscle athletes (Wilson, 1986). A PET study of eight professional pianists confirmed this as motor systems in the brain were strongly activated during performance (Fox et al., 1995; Parsons, 2001). Transcranial magnetic stimulation (TMS), a technique for mapping neuromotor pathways, was used with 15 subjects to show that the motor cortex controlling the fingers increased in response to piano exercises, both actual and imagined (Pascual-Leone et al., 1995). Researchers used magnetic source imaging to compare 9 string players with 6 nonmusicians; the main finding was that the string players had greater neuronal activity and a larger area in the right primary somatosensory cortex that controls the fingers of the left hand than controls (Elbert, Pantev, Wienbruch, Rockstrub, & Taub, 1995). These effects were greater for those who started playing at a young age.

Highly precise and rhythmically coordinated movements are critical for musical performance, and investigators are beginning to identify timing mechanisms in the brain (Freund & Hefter, 1990; Miller, Thaut, & Aunon, 1995; Moore, 1992; Wilson, 1991, 1998). A related issue is focal dystonia, a neuromotor problem in which the brain and hands (or other body parts, such as mouth structures used in embouchure formation) fail to communicate properly (Wilson, 1988, 1992; Wilson & Roehmann, 1992). Several concert pianists have had major careers curtailed by a focal dystonia in one hand. Highly practiced movements seem to be most affected, while other uses of the hand remain functional.

In the receptive mode, Thaut and colleagues have produced an impressive body of work on how Parkinsonian and stroke patients can regain motor function (e.g., walking or grasping) through rhythmic entrainment (McIntosh, Thaut, & Rice, 1996; Thaut, Brown, Benjamin, & Cooke, 1995; Thaut, McIntosh, Prassas, & Rice, 1993). Rhythmic timing embedded in music serves as a cue to motor system timing mechanisms in the brain.