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# Vocal and instrumental musicians: Electrophysiologic and psychoacoustic analysis of pitch discrimination and production

Dee Adams Nikjeh  
*University of South Florida*

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Vocal and Instrumental Musicians: Electrophysiologic and Psychoacoustic Analysis of  
Pitch Discrimination and Production

by

Dee Adams Nikjeh

A dissertation submitted in partial fulfillment  
of the requirements for the degree of  
Doctor of Philosophy  
Department of Communication Sciences and Disorders  
College of Arts and Sciences  
University of South Florida

Co-Major Professor: Stefan A. Frisch, Ph.D.  
Co-Major Professor: Jennifer J. Lister, Ph.D.  
Lynne Gackle, Ph.D.  
Arthur M. Guilford, Ph.D.  
Jane Scheuerle, Ed.D.

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discrimination, mismatch negativity (MMN), vocal pitch matching

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## Dedication

This great adventure is dedicated to my husband and best friend, Mr.-Dr. Nikjeh, who challenged and encouraged me to take my dream and make it an achievement.

And

In memory of my dad, Ronald H. Adams, who taught me by word and example, 'To learn is to live, and to live is to learn.'

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# Vocal and Instrumental Musicians: Electrophysiologic and Psychoacoustic Analysis of Pitch Discrimination and Production

Dee Adams Nikjeh

## ABSTRACT

Neurological evidence indicates that instrumental musicians experience changes in the auditory system following skill acquisition and sensory training; yet, little is known about auditory neural plasticity in formally trained vocal musicians. Furthermore, auditory pitch discrimination and laryngeal control are recognized as essential skills for vocal musicians; however, the relationship between physiological variables, perceptual abilities, and vocal production is unclear.

Electrophysiologic and psychoacoustic measures were used to examine pitch production accuracy as well as pre-attentive and active pitch discrimination between nonmusicians and two classes of musicians. Participants included 40 formally trained musicians (19 vocalists/21 instrumentalists) and 21 nonmusician controls. All were right-handed young adult females with normal hearing. Stimuli were harmonic tone complexes approximating the physical characteristics of piano tones and represented the mid-frequency range of the untrained female vocal register extending from C4 to G4 ( $F_0 = 261.63\text{-}392\text{ Hz}$ ). Vocal pitch recordings were spectrally analyzed to determine pitch production accuracy. Difference limens for frequency (DLFs) were obtained by an adaptive psychophysical paradigm. Pre-attentive auditory discrimination was assessed by

auditory evoked potentials (AEPs), including the mismatch negativity (MMN). A standard tone (G4 = 392 Hz) and three deviants differing in frequency (1.5%, 3%, and 6% below) were presented in a multi-deviant paradigm.

All musicians demonstrated superior pitch perception and vocal production compared to nonmusicians. Pitch perception and production accuracy did not significantly differ between vocalists and instrumentalists; however, pitch production accuracy was most consistent within the vocalist group. Music training appears to facilitate both auditory perception and vocal production regardless of music specialty. Pitch perception and production were correlated skills only for instrumental musicians. Vocalists demonstrated minimal variability for both skills so that perception and production were not correlated. These two skills may be independent abilities between which a relationship develops with training. AEP analysis revealed an influence of musical expertise on neural responses as early as 50 ms after onset of musically relevant stimuli. MMN responses indicate that vocal musicians as well as instrumental musicians have superior sensory memory representations for acoustic parameters of harmonic stimuli and imply that auditory neural sensitivity is developed by intense music training.

## Chapter One

### Introduction

Music is a universal occurrence in all human cultures. Throughout history, on every part of the earth, in every past and present culture, individuals have enjoyed music. Examination of the neural basis of music production and investigations of neural changes related to music training provide opportunities for researchers to study the interaction between brain development and environmental influences. It is argued that because of the intense training and skill acquisition that a musician receives from an early age, the musician's brain serves as an excellent model for the study of neuroplasticity (Gaser & Schlaug, 2003; Münte, Nager, Beiss, Schroeder, & Altenmüller, 2003; Pascual-Leone, 2001; Schlaug, 2001; Zatorre, 2003). Current research indicates that trained instrumental musicians have superior auditory pitch discrimination ability relative to nonmusicians (Kishon-Rabin, Amir, Vexler, & Zaltz, 2001; Spiegel & Watson, 1984). Pitch is the auditory perception of a tone's frequency. Electrophysiological data have shown that long-term music training modifies neural processing of acoustic input. In addition, it has been found that instrumental musicians have faster neural responses for pitch changes than nonmusicians (Koelsch, Schmidt, & Kansok, 2002; Shahin, Bosnyak, Trainor, & Roberts, 2003).



It is questioned whether the neurological and anatomical differences between musicians and nonmusicians are inherent neurophysiological distinctions or secondary to training-induced neurological changes. While the literature contains comprehensive evidence for neural plasticity in trained instrumental musicians, little is known about formally trained vocal musicians. Vocal musicians receive intense music training comparable to instrumental musicians. The vocalist's musical instrument is the larynx, the biological organ within the human body responsible for voice production. Auditory pitch discrimination (perception) and vocal pitch control (production) have been identified as related abilities and essential skills for successful vocal musicians. Vocal pitch control requires the integration of the body's motor and sensory systems. The interactions and relationships between the auditory system and the laryngeal system necessary for instant and exact vocal pitch productions are areas of interests for researchers and educators (Amir, Amir, & Kishon-Rabin, 2003; Mürbe, Pabst, Hofman, & Sundberg, 2004; Wyke, 1974).

### *Music and Neural Plasticity*

The presence of neurological and anatomical differences between musicians and nonmusicians supports the premise of functional and structural experience-dependent plasticity in the auditory system (Pantev, Engelien, Candia, & Elbert, 2001; Pascual-Leone, 2001; Schlaug, 2001; Schön, Magne, & Besson, 2004; Trainor, Shahin & Roberts, 2003). Electrophysiological studies of auditory responses reveal differences between musicians and nonmusicians and parallel anatomic studies show cortical enlargement of

auditory areas important for music perception (Elbert et al., 1998; Pantev et al., 2003; Trainor et al., 2003). Taken together, these studies provide evidence of enhanced pre-attentive auditory processing in musicians compared to nonmusicians, suggesting that fundamental auditory abilities to process pitch and temporal features can be facilitated by music training and supporting the theory of training-induced cortical plasticity. Specifically, electroencephalography (EEG) and magnetoencephalography (MEG) data suggest that musical expertise influences pitch processing by refining the neural frequency-processing network (Koelsch, Schröger, & Tervaniemi, 1999; Pantev et al., 2001; Schön et al., 2004; Shahin et al., 2003; Tervaniemi, 1993; Trainor et al., 2003).

### *Vocal Pitch Control*

The vocal production of music requires the integration of multiple brain systems including the sensorimotor, auditory, limbic, and executive systems (Münste et al., 2003). There are those within our population who express an exceptional ability to produce musical modulations of the voice for singing. The ability to sing with accurate pitch control is considered the most basic feature that distinguishes singers from nonsingers (Murry, 1990; Titze, 1994; Watts, Barnes-Burroughs, Adrianopoulos, & Carr, 2003). Physiologically, the act of singing involves control and coordination of several neuromuscular systems. In addition to respiration, resonance, and articulation, vocal pitch precision relies on pre-phonatory tuning of the laryngeal musculature, laryngeal reflex modulation, and an auditory governance system (Elman, 1981; Jürgens, 2002; Kirchner & Wyke, 1965; Sundberg, 1987; Wyke, 1967; Wyke, 1974).

Auditory input, neuromuscular pitch memory, and kinesthetic feedback of the laryngeal system contribute to pitch control (Amir et al., 2003; DiCarlo, 1994; Jones & Munhall, 2000; Mürbe et al., 2004; Titze, 1994; Ward & Burns, 1978). It has been suggested that the development of kinesthetic feedback or ‘internal models’ of pitch control assists trained singers in controlling fundamental frequency and maintaining targeted pitches more accurately than non-trained singers (Murry, 1990; Sapir, McClean, & Larson, 1983; Ward & Burns, 1978; Watts, Murphy, & Barnes-Burroughs, 2003). DiCarlo (1994) writes that vocal instruction and reflex conditioning train the professional singer to associate an auditory image with an internal sensation. Similarly, an ‘internal model’ for the control of pitch has been proposed by Jones and Munhall (2000). This model corresponds to a neural representation of the spatial, dynamic, and/or proprioceptive characteristics that provide an internal pitch reference to the nervous system to predict and plan for vocal frequency control. In other words, singers match the perceived pitch to a reference pitch in the brain. Longitudinal studies of vocalists in training indicate that accuracy for the absolute neuromuscular memory of pitch increases with music education (Mürbe, Pabst, Hofman, & Sundberg, 2003, 2004).

#### *Auditory Pitch Perception*

Speigel and Watson (1984) describe a ‘relative acuteness of the ears’ and a ‘mystique’ associated with the listening abilities of performers, conductors, and composers of classical music (p. 1690). A physical characteristic important for the perception of speech and music is a change in fundamental frequency; that is, a change in

pitch (Novitski, Tervaniemi, Huotilainen, & Näätänen, 2004). Pitch extraction is basic to the perception of speech intonation, but precise pitch perception is crucial to the processing of music. Musical melodies use much smaller pitch intervals than speech intonation contours (Ayotte, Peretz, & Hyde, 2002). The ability to perceive and discriminate pitch differences is regarded by music educators as a fundamental capacity for musical talent and an implicit skill of a successful performer (Bentley, 1966; Geringer, 1983; Seashore, 1919). Psychoacoustic studies comparing frequency discrimination thresholds, also known as difference limens for frequency (DLFs), for musicians and nonmusicians report significantly smaller discrimination thresholds for musicians (Kishon-Rabin et al., 2001).

Researchers have also investigated processes of auditory pitch perception for music through neuropsychological studies, neural imaging and, more recently, electrophysiology. EEG studies of pre-attentive pitch discrimination indicate superior pre-attentive discrimination by musicians as compared to nonmusicians suggesting training induced modification of pre-attentive auditory neural processing (Koelsch et al., 1999; Shahin et al., 2003).

#### *Relationship between Pitch Discrimination and Pitch Control*

Auditory pitch discrimination and vocal pitch control reflect abilities necessary for accurate integration of sensory perception, motor planning, and execution of vocal production. Intuitively, it seems these two abilities are directly related. A positive relationship between auditory pitch discrimination and vocal pitch matching skills is

reported for instrumentalists (Amir et al., 2003). Amir and colleagues (2003) postulate that intense music training fine-tunes the coordination between auditory perception and motor-production skills. The authors stated that musicians are more perceptive to acoustic parameters in vocal productions compared to nonmusicians despite the fact that the musicians in the study were instrumental musicians and had no previous vocal training.

Although many researchers acknowledge a relationship between auditory pitch discrimination and vocal pitch control, research is sparse and the nature and development of this relationship is uncertain (Amir et al., 2003; Geringer, 1983; Goetze, Cooper, & Brown, 1990; Watts et al., 2003; Yarbrough, Green, Benson, & Bowers, 1991). Amir and colleagues (2003) and Goetze and colleagues (1990) suggest a plausible relationship between auditory pitch discrimination and vocal pitch matching abilities; however, the relationship does not appear to be reciprocal. Physiological, perceptual, and production variables may be independent abilities between which relationships form as a result of training-induced neural changes in the auditory system.

#### *Statement of the Problem*

Neuroplasticity of the human brain reflects dynamic neural changes and re-organization as an effect of training and experience (Merzenich et al., 1996; Pantev et al., 2003; Teter & Ashford, 2002). Investigations comparing the brains of musicians and nonmusicians have identified anatomical and physiological differences in the cortex and cerebellum ( Schlaug, 2001). Data from established neurophysiological techniques,

including EEG and MEG, suggest that experience-dependent functional and structural plasticity occurs in the auditory system of musicians. These differences support the premise that neural changes occur in the human brain following skill acquisition and sensory stimulation. Although ‘musician’ includes instrumentalists and vocalists, there is a paucity of comparative research including formally trained vocal musicians. Previous neurophysiological research has focused predominantly on instrumental musicians (e.g., violinists, keyboard players) rather than vocal musicians (Münste et al., 2003; Schlaug, 2001; Zatorre, 2003). Vocal musicians adhere to the same rigorous training as other musicians; however, the auditory system of vocal musicians has been studied to a much lesser extent. The overall objective of this study is to take an initial step to contribute to the body of basic research regarding the perception and production abilities of formally trained vocal musicians.

A review of the available literature indicates an inadequate understanding of the relationship between physiological variables, perceptual abilities, and pitch production of formally trained vocal musicians. Investigators and educators have identified auditory pitch discrimination (perception) and vocal pitch control (production) as related abilities and essential skills for vocal musicians. Auditory pitch discrimination and vocal pitch control contribute to the professional singer’s laryngeal neuromotor performance; however, the strength and nature of this relationship is unclear. Evidence suggests that long-term vocal training influences auditory abilities for pitch perception and discrimination. Previous studies have examined these skills separately using a variety of tasks in the musically trained population; however, no previous investigation has

attempted to relate pre-attentive auditory neural responses to active auditory pitch perception and vocal pitch matching abilities in the population of formally trained vocal musicians. What is the relationship among these abilities in this population as compared to formally trained instrumental musicians and musically untrained subjects? Do the vocal musicians have an identifiable pattern of abilities? Does skill in one area precede ability in another?

Specifically, objective information regarding the relationship between auditory pitch discrimination and vocal pitch control, as well as the effects of long-term vocal training on the neurophysiology of the auditory system is needed. This study is designed to contribute to a growing body of research identifying relationships that may have implications for vocal performers and music educators.

#### *Potential Application*

A consideration of human differences in any domain invariably leads to the issue of ‘nature’ versus ‘nurture.’ Reliable neuroimaging techniques reveal anatomical and neurological differences between musicians and nonmusicians. Electrophysiological data provide evidence of enhanced pre-attentive auditory processing in musicians compared to nonmusicians. Existing evidence indicates that formally trained professional singers control fundamental frequency and maintain accurate pitch better than untrained singers (Dejonckere, 1995; Jones & Mundall, 2000; Leydon, Bauer, & Larson, 2003; Wyke, 1974). Whether these differences and superior abilities are inherent and/or dependent on training and neural plasticity is a controversial issue.

Are these differences determined by a genetic code whose expressions guide the decision to seek musical training and become a professional musician; or alternatively, do these attributes arise from modifications of synaptic connections or neural growth influenced by sensory input from music training at an early age (Buonomano & Merzenich, 1998; Monaghan, Metcalfe, & Ruxton, 1998; Shahin, et al., 2003)? Investigating neural changes associated with the acquisition and mastery of new skills represents one experimental model used to determine whether or not functional and anatomical markers of exceptional skills exist or develop (Gaser & Schlaug, 2003). Similar to an athletic scout who searches for certain indicative qualities such as height, speed, and balance, identification of predictive variables of musical skill may assist music educators in the early identification of children with potential musical ability.

Investigating the relationship between the components of our physiological mechanisms which discriminate and control fundamental frequency may expand existing data on the function of auditory feedback and vocal production in those individuals who lack these abilities. For those who can sing easily and accurately, the failure of others to do the same is baffling. Much of the existing research in music education has focused on children who cannot match pitch (Apfelstadt, 1984; Geringer, 1983; Goetze, Cooper, & Brown, 1990; Green, 1990; Howle, 1992; Joyner 1969; Moore, 1994; Pedersen & Pedersen, 1970; Porter, 1977; Yarbrough et al., 1991). The possibility that some children may not learn to sing accurately is considered a major problem for music educators (Yarbrough et al., 1991).



There is a growing body of evidence suggesting that music training of children promotes cognitive development including reading and math achievement, as well as critical thinking abilities, motor skills, and social abilities (Weinberger, 1994). Music lessons require focused attention and daily practice. Music training involves a multiplicity of experiences including comprehension of musical notation and structures (e.g., musical symbols for notes and timing, chords, scales, clefs), memorization of musical passages, progressive mastery of fine-motor skills and emotional expression during performance (Schellenberg, 2004). Compared with groups of children engaged in nonmusical activities, those children who received music training demonstrated greater increases in full-scale intelligence quotients (Schellenberg, 2004).

Music and language are intimately related and share similar neural substrates (Friederici, Pfeifer, & Hahne, 1993; Koelsch et al., 2000; Tervaniemi & Brattico, 2004). Acoustically, signals of music and language consist of variations of intensity and frequency as a function of time which are perceived by the brain as sound. Cognitively, both have rules of syntax and are dependent on memory (Tervaniemi & Brattico, 2004). Neural imaging data from EEG and functional magnetic resonance imaging (fMRI) imply there is considerable overlap of neural structures and processes underlying the auditory perception of music and language (Friederici et al., 1993; Koelsch et al., 2000). EEG data comparing formally trained musicians to nonmusicians indicate that extensive music training facilitates pitch analysis by refining the auditory frequency-processing network not only for music, but also for language. If music training stimulates neuroanatomical changes in the cerebral cortex, then further identification and differentiation of the neural

substrates for music processing and vocal pitch control may have implications for treatment strategies for individuals who have neurological, language, and vocal impairments, such as dyslexia, aphasia, Parkinson's disease, and hearing impairment (Ayotte et al., 2003; Overly, 2003; Ramig, Yoshiyuki, & Bonitati, 1991).

While no single investigative technique is sufficient to provide more than a small piece of the puzzle, converging evidence from a variety of methods is needed to provide a comprehensive and robust understanding of the relationship between music training and neurological structures. The global picture that emerges from studies of music and its neural substrate is far from complete; however, each piece of information contributes to our overall comprehension of the complex structure and function of the human brain.

#### *Purpose of the Study*

The purpose of this study was to assess, compare and correlate three identified variables of perception and production that contribute to the performance of the singing voice. This study proposed a causal-comparative (ex post facto) design to assess and compare the assigned variables of active auditory pitch discrimination, pre-attentive auditory pitch discrimination, and vocal pitch matching accuracy within and between the following groups: formally trained vocal musicians, formally trained instrumental musicians, and a matched untrained control group.

This investigation sought to determine whether a significant difference exists between formally trained vocal musicians, formally trained instrumental musicians, and nonmusicians for the abilities of vocal pitch control, active auditory pitch discrimination,

and pre-attentive auditory pitch discrimination. Furthermore, by examining these abilities across populations, it is possible to assess what, if any, relationships exist among these abilities. It was also questioned whether formally trained vocal musicians, similar to instrumental musicians, experience training-induced neural plasticity in the auditory system. This study was a beginning step of inquiry into the effects of intensive music training on the auditory neural function of vocal musicians.

There was one independent variable, *subject group*, which was sub-divided into formally trained vocal musicians, formally trained instrumental musicians, and a matched control group of musically untrained subjects. Three dependent variables were measured and reported as: (1) *relative* accuracy for vocal pitch production accuracy in percentage (*rel PPA%*), (2) *relative* difference limen for frequency in percentage (*rel DLF%*), and (3) latency and amplitude of the mismatch negativity (MMN); that is, an auditory evoked potential (AEP) associated with pre-attentive auditory neural responses.

### *Research Questions*

The relationship between physiological, perceptual, and production abilities for musical stimuli between formally trained musicians and musically untrained subjects was examined. Specifically, relationships between vocal pitch matching accuracy, active auditory pitch discrimination, and pre-attentive auditory pitch discrimination among formally trained vocal musicians, formally trained instrumental musicians, and a matched

control group of musically untrained participants were investigated. This study was designed to answer the following questions:

1. Is there a difference in vocal pitch matching accuracy between musicians and the control subjects and furthermore, is there a difference between the instrumental and vocal musician groups?
2. Is there a difference in active auditory frequency discrimination ability between musicians and the control subjects? Moreover, is there a difference between the instrumental and vocal musician groups?
3. Is there a difference in pre-attentive auditory neural responses to pitch change (i.e., pre-attentive auditory pitch discrimination for musical stimuli) between musicians and the control subjects and particularly between the instrumental and vocal musician groups?
4. Is there an overall correlation between perception and production variables across the groups?
5. Is there a correlation between perception and production variables within each subject group (i.e., controls, instrumental musicians, and vocal musicians)?

## Chapter Two

### Review of the Literature

#### *Music and Neural Plasticity*

##### *Knowledge of Music*

*Innate or learned.* What is the interaction between genetics and the environment that produces distinct musical abilities? Music is recognized as a universal characteristic occurring in all human societies, both past and present. Cross-cultural evidence supports the innateness of music and indicates that certain features of music, such as interval scales, are universal regardless of the musical genre or style (Hauser & McDermott, 2003; Tillman, Bharucha, & Bigand, 2000). An interval, as it relates to music, refers to the distance between sounds played simultaneously or successively and is crucial for scales and harmony (Pantev et al., 2003; Tervaniemi & Brattico, 2004). Certain acoustic stimuli are recognized as music by most members of a given culture, even if these sounds have never been heard before; and conversely, there are acoustic stimuli that humans recognize as nonmusical or dissonant (Hauser & McDermott, 2003). Therefore, even if a particular melody has never been heard, a dissonant tone may be detected based on an internal musical representation (Tervaniemi & Brattico, 2004). This representation may correspond to a neural template *hardwired in the brain* or may become automatic

secondary to implicit neuronal models that *develop from exposure* to music in the environment (Tervaniemi & Brattico, 2004).

Studies of infant auditory perception demonstrate seemingly innate traits. Young infants prefer consonant musical intervals rather than dissonant intervals (Schellenberg & Trehub, 1996; Trainor & Heinmiller, 1998; Trehub, 2001) and they are capable of detecting the smallest differences that are musically meaningful in any culture (Trehub, Schneider, & Henderson, 1995). However, the fetus can hear a filtered version of sounds in the external environment by the third trimester of pregnancy (DeCaspar & Fifer, 1980). Learning occurs during the fetal period and the nature of this learning with respect to music depends on the musical sound environment before birth (Tervaniemi & Huotilainen, 2003). Thus, it is possible that seemingly *innate* traits are actually the result of early exposure to music.

*Musical meaning.* Musical meaning is understood within the context of an arrangement of acoustic events, such as a scale or melody. The melody, referred to as the musical structure, has two components, rhythm and pitch (Pantev et al., 2003). Rhythm refers to timing and/or beat. Pitch is perceived as a tone's highness or lowness. It is the perceptual correlate of frequency which pertains to the sound's physical structure (i.e., the number of cycles per second) (Patel & Balaban, 2001). The pitch produced by a person's voice is measured as the fundamental frequency (F0).

Pitch structure has contour and an interval code. Contour refers to the up and down pattern of pitch changes common to speech prosody and music. Interval code is the distance between two sounds on a musical scale. The perception of pitch along musical

scales is central to pitch organization. A musical scale refers to the use of a small subset of pitches in a given musical piece. Scale tones are not equivalent and are organized around a central tone, called the tonic. This tonic hierarchy of pitch facilitates perception, memory and performance of music by creating expectancies (Peretz & Coltheart, 2003).

Although the commonly used scales differ from culture to culture, most musical scales use pitches of unequal intervals organized around five to seven focal pitches (Tillman et al., 2000). The seven tones above or below a given tone in a scale form an octave. In Western culture, speech intonation contours use variations in pitch that are larger than  $\frac{1}{2}$  an octave to convey relevant information. In contrast, musical melodies of Western culture use smaller pitch intervals approximately  $\frac{1}{6}^{\text{th}}$  to  $\frac{1}{12}^{\text{th}}$  of an octave (Ayotte, Peretz, & Hyde, 2002). In other cultures, such as Arabic, Indian, and Chinese, the musical pitch intervals are even smaller (Tervaniemi & Brattico, 2004). Thus, the auditory processing of pitch for music is necessarily more sensitive than for speech.

*Musical syntax.* Like language, music is rule-governed. Each musical style has a relatively small set of rules to generate an infinite variety of musical compositions (Trehub, 2003). The rules that govern musical structure are referred to as musical syntax. Musical syntax does not imply that it is a linguistic syntax in musical terms; rather, it reflects that music is structured according to complex regularities similar to language (Koelsch & Friederici, 2003). The ability of listeners to expect specific musical events according to complex musical regularities and to detect violations of harmonic

expectancies within a musical sequence is an example of musical syntax (Bharucha & Krumhansl, 1983; Koelsch, Schmidt, & Kansok, 2002; Tillman et al., 2000).

When a person sings, plays an instrument or speaks a sentence, a succession of acoustic events constitutes a context which is understood by others. To understand a musical context, listeners extract a tonal center by perceiving the musical relations between notes; that is, the interval (Krumhansl & Kessler, 1982). The mental representation of tonality and musical context is quickly established by the listener; thus, there is an expectancy of what tone comes next. The dominant tonic progression at the end of a harmonic sequence is considered a basic syntactic structure for major-minor tonal music. For listeners, the sound of a chord that violates musical regularities of major-minor tonal music is perceived as unexpected (Bharucha & Krumhansl, 1983; Koelsch, Schmidt, & Kansok, 2002; Tillman et al., 2000).

Similar to language, culturally specific aspects of music are dependent on knowledge acquired through prior experience. Music perception is molded by implicit and/or explicit experience and is founded on early automatic functions of the auditory system that dynamically organize and store separated sounds (Tervaniemi & Brattico, 2004). Thus, in theory, 'knowledge of music,' including musical meaning and syntax, may be acquired through normal exposure to music within a culture without training just as linguistic knowledge is acquired through exposure independent of education.



### *Music and Neural Correlates*

The structural and functional organization of the human auditory system for the processing of music has been an issue of research dating back to the beginning of the 19<sup>th</sup> century. Franz Joseph Gall (1758-1828), a physician from the University of Vienna, established the idea that the brain was the organ of the mind and as such, it was comprised of multiple *organs* so that the different functions of the brain were situated in specific sites (Bentivoglio, 2003). In Gall's classification, the organ of music was responsible for the relationships between sounds, musical memory, and emotions of melody and harmony. This organ was located laterally in the 'supraorbital' region, at the border between the inferior frontal and superior temporal regions. Gall identified this organ by palpation of the head of several musically talented individuals and first recognized it in Mozart's head (Bentivoglio, 2003). Gall's concept of localization of mental function has had a lasting impact. Even in the 21<sup>st</sup> century, the issue of localizing musical structures and functions in the human brain is still debated.

During the 1960s, brain lesion research by experimental psychologists supported the distinction between music and language by locating each of these functions in a different hemisphere (Platel, 2002). A widely held view attributes linguistic function to the left cerebral cortex and other non-verbal auditory functions, such as those involving music and environmental sounds, to the right cerebral cortex (Liégeois-Chauvel, Peretz, Babaï, Laguitton, & Chauvel, 1998). However, subsequent research suggests music processing is complex, bi-hemispheric, and interactive.

The primary auditory cortical areas responsible for auditory processing are located in the left and right temporal lobes in the middle and superior temporal gyri, including the associative areas which expand to the posterior sites of the temporal lobes (Tervaniemi & Hugdahl, 2003). The primary auditory cortex is mainly engaged in the early stages of processing for pitch, duration, intensity, and spatial location; whereas, more complex features involving temporal patterns are processed via neurons within the associative areas.

In a truly linear system, resolution of time and pitch has an inverse relationship so that as one is enhanced, the other is impeded (Zatorre, 2001). In theory, the auditory nervous system is a highly nonlinear and distributed system. Music is acoustically complex and requires neurophysiological processing of multiple components including fundamental frequency, pitch contour, intensity, timbre and rhythm. Evidence supports functional asymmetry of the auditory cortices suggesting that temporal resolution occurs more rapidly in the left auditory cortical areas and spectral resolution is stronger in the right auditory areas (Dalla Bella & Peretz, 1999; Tervaniemi & Hugdahl, 2003; Zatorre, Belin, & Penhune, 2002). Zatorre and Belin (2001) speculate that neurons in the right auditory cortex compared with those in the left have increased synaptic densities, more closely spaced cortical columns, and comparatively less myelination which may reflect a specialization of these neurons for processing spectral information.

*Temporal processing.* Liégèois-Chauvel and colleagues examined the human auditory cortex by means of intracerebrally recorded auditory evoked potentials in both hemispheres (Liégèois-Chauvel, Giraud, Badier, Marquis, & Chauvel, 2001). Findings

indicated that neurons in the right auditory cortex were more sharply tuned to pitch than neurons in the homologous regions of the left hemisphere revealing a functional asymmetry of the auditory cortex and suggesting a preference for frequency (spectral) processing in the right Heschl's gyrus. Anatomically, magnetic resonance imaging (MRI) shows the volume of white matter underlying Heschl's gyrus to be significantly greater on the left than on the right in two independent samples of right-handed subjects (Penhune, Zatorre, MacDonald, & Evans, 1996). If white matter volume is indicative of myelination and thus greater speed of processing, then these findings suggest faster transmission of acoustically relevant information occurs on the left which supports the theory of rapid temporal processing in the left auditory cortex.

*Pitch processing.* Whereas the analysis of speech requires good temporal resolution to process rapidly changing formants, it can be argued that music processing requires good pitch resolution (Zatorre et al., 2002). Pitch variation is an essential element of all music compositions, and as a result of this variation, structures such as melodies are created. Pitch processing is a central feature of music and is amenable to study because the physical parameters are easily manipulated.

Pitch can be neurologically disassociated from the other perceptual functions and broken into a hierarchy of levels (Foxton, Dean, Gee, Peretz, & Griffiths, 2004; Peretz, 1990; Zatorre, 2001). Low-level pitch processing includes basic tasks such as the discrimination between two sounds or detection of pattern change. The discrimination of pitch sequence patterns and the organization of sounds into melodies and harmony

require higher levels of processing and may include interaction with other cortical areas (Foxton et al., 2004; Zatorre, 2001).

The nature of the neural processes underlying basic pitch processing and the manner in which pitch is perceived is debatable (Gelfand, 1998; Zatorre et al., 2002). The precise interaction of frequency and temporal coding is speculative. Traditionally, pitch processing has been dominated by two main theories: (a) the place theory, and (b) the temporal or rate coding theory (Liégeois-Chauvel, Giraud, Badier, Marquis, & Chauvel, 2001).

The place theory postulates exclusively tonotopic coding throughout the pathways of the auditory system. A complex sound is broken down into its frequency components. These frequencies excite different places along the basilar membrane of the cochlea which resonate in response to a particular frequency (Gelfand, 1998). The place theory assumes that the pitch of a sound is directly related to this excitation pattern (Moore, 1997). Thus, an incoming stimulus results in the vibration of those parts of the basilar membrane whose natural frequencies correspond to the components of the stimulus.

The temporal coding theory assumes "...that the pitch of a sound is related to the time pattern of the neural impulses evoked by that sound" (Moore, 1997, p. 143). The temporal theory proposes that the hair cells of the cochlea transmit all parameters of the signal to the central auditory nervous system for processing. This is accomplished by the volley principle which states that groups of neurons work together so that the single response of the group is a spike corresponding to each cycle of the stimulus. It is believed that the rate at which a neuron fires correlates to the frequency of the stimuli; that is, the

impulses are *phase-locked* to the frequency. Neurons can only respond in an all-or-none manner. The absolute refractory period of the neuron corresponds to a maximum firing rate of 1000 times per second. Physiologic data from auditory nerve fibers indicate that the maximum pure tone frequency for which the nerve fibers can preserve the period via phase locking is approximately 5000 Hz. Thus, temporal coding alone cannot account for the perception of pitch for pure tones having frequencies greater than 5000 Hz (Gelfand, 1998; Moore, 1997).

Moore (1997) speculates that both coding processes may occur depending on the task and proposes a combination theory called the spectral-temporal theory that accounts for most of the existing data on the pitch perception of complex tones. This combination theory assumes that information from both low and high harmonics contributes to the determination of pitch. The place theory has been shown to work best for the processing of higher frequencies and the temporal coding mechanism is best for coding frequencies in the lower frequencies; however, there is no agreement to the exact borderline between these registers (Gelfand, 1998; Novitski, Tervaniemi, Huotilainen, & Näätänen, 2004; Moore, 1997; Zeng, 2002).

Novitski and colleagues (2004) examined auditory frequency discrimination as indexed by electrophysiological measures. Data indicated that pre-attentive, auditory change-related responses; that is, the mismatch negativity responses (MMN), recorded at lower frequencies (250 and 500 Hz) differed significantly from those responses recorded at higher frequencies (2000 Hz and 4000 Hz). They found a glaring discrepancy in the MMN amplitudes and latencies as a function of frequency. From 250 to 1000 Hz, the

amplitude of the MMN was higher and the latency decreased indicating stronger and faster neural responses; however, as frequency increased beyond 1000 Hz, the amplitude of response continued to grow while the latency increased, implying a stronger but slower neural response. Novitski et al. (2004) speculated that this changing point at 1000 Hz may indicate a transition between the place and temporal mechanisms of pitch discrimination supporting a theory that the border between these two mechanisms is approximately 500 to 1000 Hz.

Beyond basic pitch perception, neural correlates for low level pitch tasks (e.g., discrimination of two sounds or detection of pattern change) have also been examined. Data from electrophysiology and neural imaging techniques support earlier brain lesion studies. Thus, although music processing engages components lateralized in both hemispheres, it is the posterior portion of the superior temporal gyrus (STG) in the right hemisphere that is especially important for low-level pitch processing tasks (Johnsrude, Penhune, & Zatorre, 2000; Liégeois-Chauvel et al., 1998; Peretz, 1990; Zatorre, Evans, & Meyer, 1994). Perry et al. (1999) were the first to use positron emission tomography (PET) scans to examine regional cerebral blood flow (rCBF) during rudimentary singing of a single pitch and vowel. In contrast to a pitch perception baseline, singing resulted in greater activation of the right primary auditory cortical regions (Heschl's gyrus).

For higher level pitch processing tasks involving melodies and pitch sequencing, neural imaging reveals multiple areas of activation including bilateral activation of the superior parietal areas near the angular gyrus and activation of the occipital lobe. This implies integration with visual associative functions in the brain and frontal lobe

activation supporting the interactive roles of memory and attention (Gaab & Schlaug, 2003; Schmithorst & Holland, 2003; Zatorre et al., 1994).

*Summary.* Based on reviewed evidence, the following is a summary of generally accepted neural correlates for speech and music (Alho et al., 1998; Anderson, Brown, & Tallal, 1993; Dalla Bella & Peretz, 1999; Gelfand, 1998; Liégeois-Chauvel et al., 2001; Steinmetz et al., 1989; Tervaniemi & Brattico, 2004; Zatorre et al., 2002; Zatorre et al., 1994):

1. The exact neural processes underlying basic pitch perception and the precise interaction of frequency and temporal coding are uncertain.
2. The left auditory hemisphere is implicated for speech processing, while the right auditory hemisphere is implicated for music.
3. The left auditory hemisphere is responsible for processing fast temporal information intrinsic to speech, while the right auditory hemisphere is responsible for processing minute changes in pitch (spectral information) intrinsic to music.
4. The right auditory hemisphere is dominant for directing spatial attention.
5. The superior temporal and inferior frontal cortices in the right hemisphere interact for the active retention of pitch.
6. This pattern of hemispheric functional asymmetry is consistent for both attentive and pre-attentive levels of musical cognition.

### *Music Training and Neural Plasticity*

The ability of a sensory or motor system to adjust or adapt to environmental stimuli, or a compensation of a cerebral structure for another impaired area due to injury is referred to as neuroplasticity ( Schlaug, 2001). Synaptic changes at a cellular level refer to microstructural plasticity. Neuroplasticity at the cellular level is described as “a continuous process in reaction to neuronal activity...” (Teter & Ashford, 2002, p. 405).

Long-term cortical modification is known as macrostructural plasticity. Continuous neuroplasticity at the cellular level may underlie functional and structural cortical re-organization. Neural representations are dynamic and continuously modified by experiences including intense auditory and peripheral sensory stimulation generated by music training and performance (Merzenich et al., 1996; Pantev et al., 2003; Pantev, Engelen, Candia, & Elbert, 2001). Thus, neurophysiological research comparing musicians and nonmusicians serves as an excellent tool for the study of neuroplasticity (Münte et al., 2003; Schlaug, 2001; Zatorre, 2003).

*Microstructural plasticity.* Microstructural plasticity is observed when there is a change in the efficiency of transmission at a cellular level; that is, changes in the firing probabilities, changes in activation strength between synapses or structural adjustments in the connections between groups of neurons (Calford, 2002; Robertson & Murre, 1999). Functional systems in the brain retain flexibility at the cellular level throughout life (Edelman, 1987; Plante, 2000). New variations of synapses continue to occur between interacting neural networks and within hierarchies of networks.



Neurophysiological studies of musicians who play instruments support microstructural changes in the brain as a result of music training ( Schlaug, 2001). Pascual-Leone et al. (1995) showed that as subjects learned a five-finger exercise on the piano over the course of five days, the cortical representation on the sensorimotor area targeting the long finger flexor and extensor muscles enlarged. Thus, training-induced microstructural plasticity can occur within a short time period (Pantev et al., 2001; Pascual-Leone et al., 1995; Trainor, Shahin, & Roberts, 2003). Rauschecker (2001) views training-induced neural change as a common occurrence. He states, “Of course, even the ability to learn and memorize a simple tune is an expression of the brain’s ability to change with musical experience” (p.330).

*Microstructural effects of auditory training.* Whether musical abilities of and neural differences in musicians are due exclusively to learning, or whether these differences reflect innate capacities enhanced by early music training is unknown (Gaser & Schlaug, 2003; Pantev et al., 1998; Schlaug, 2001; Trainor et al., 2003; Zatorre, 2003). To examine the neuroplastic effect of auditory experience independent of innate abilities that may be present in musicians, researchers have studied auditory training in nonmusicians (Brattico, Tervaniemi, & Picton, 2003; Menning, Roberts, & Pantev, 2000; Trainor et al., 2003).

Electroencephalography (EEG) has been used to compare the effects of musical context and musical syntax on neural responses of pitch perception in musicians and nonmusicians (Brattico, Näätänen, & Tervaniemi, 2001; Koelsch, Schmidt, & Kansok, 2002; Lopez et al., 2003). EEG is a non-invasive method of recording electrical activity

and changes to real-time cognitive processing. Event-related potentials (ERPs) reflect this electrical activity in waveforms with positive and negative peaks. An ERP is a sequence of voltage changes that are time-locked to a stimulus event (Koelsch & Friederici, 2003; Mody, 2004).

Trainor, Shahin and Roberts (2003) compared seven 4-year old children taking Suzuki music lessons with 6 age-matched control children who were not studying music. ERPs were recorded when subjects just began Suzuki lessons and one year later. The children listened to three different tones matched in loudness: violin, piano, and pure tones. The P1-N1-P2 complex was examined.

The P1 occurs approximately 50 – 100 ms after the onset of an auditory stimulus and is interpreted as an indicator of preferential attention (Key, Dove, & Maguire, 2005). It is frequently associated with auditory inhibition and suppression of unattended information (Key et al., 2005). The N1 is a negative wave peak typically recorded at about 100 ms after the stimulus onset. It reflects activation of the large neuronal population in regions of the auditory cortex on the superior surface of the temporal lobe. The N1 is sensitive to attention and may be augmented by plasticity occurring either cortically or at subcortical sites projecting to the auditory cortex (Menning et al., 2000). The P2 occurs between 150-275 ms after stimulus onset and is sensitive to physical parameters of the stimulus, such as pitch and loudness (Key et al., 2005). The P2 has been found to differ between musicians and nonmusicians and has been enhanced in nonmusician adults with auditory training (Bosnyak, Eaton, & Roberts, 2002 as cited in Trainor et al., 2003).

In the Trainor et al. study, there were no significant differences between the two groups of children prior to music training. For all children, ERP responses were most robust to piano tones with clear P1, N1, and P2 components suggesting an increased cortical response to sounds rich in harmonics. Responses to pure tones were least robust and only clear P1 components were present. ERP responses were measured again when the students were 5 years of age (i.e., after one year of training for the Suzuki students). ERP responses differed between the groups only for the piano tones. The P2 response was stronger and the N1 component emerged earlier in the Suzuki-trained children. Thus, auditory cortical responses can be differentiated between groups of children as young as 4 or 5 years old. ERP differences between the children lend strong support for cortical changes as a result of music training; however, the authors caution that the influence of genetic factors cannot be dismissed (Trainor et al., 2003).

Menning, Roberts, and Pantev (2000) investigated plasticity of the auditory cortex in nonmusicians through intensive frequency discrimination training. Ten right-handed volunteers were trained for 15 days to detect progressively smaller deviant stimuli. Frequency discrimination diminished to about 30% of its initial value and thresholds stabilized in about 10 sessions near 2 Hz. Data from magnetic electroencephalography (MEG) indicate increased strength of pre-attentive auditory neural responses during training and three weeks after training compared to pre-training data. Thus, results support training-induced neuroplasticity of the auditory system and suggest that the neural processes responsible for detection of pitch irregularities may be enhanced by auditory discrimination training.

Brattico, Tervaniemi, and Picton (2003) examined whether the pre-attentive auditory neural response to different tone frequencies can be affected by brief discrimination training at one specific frequency. Eighteen volunteers of mixed gender and mixed handedness received a one-hour training session. Immediate post-training EEG data indicated that the cortical response to the learned tone (1062 Hz) and repeated tone (1000 Hz) was as large in amplitude as before training; however, the auditory neural responses to the *other* test tones were diminished suggesting a counteraction of the sensitization effect by activation of neurons that previously did not respond. The authors conclude that these plastic changes may underlie the long-term modification of cortical representation observed in musicians (Pantev et al., 2003).

*Macrostructural plasticity.* A common finding across most skill acquisition studies is the functional enlargement of the cortical representation area underlying a particular skill (Gaser & Schlaug, 2003). Also known as ‘map extension,’ cortical representation demonstrates the flexibility of a functional brain region to enlarge on the basis of skilled practice or frequent exposure to a stimulus (Grafman, 2000).

Elbert and colleagues (1995) found altered representation for the fingers in the somatosensory cortex for professional musicians who play stringed instruments. Specifically, neural imaging revealed increased cortical representation of the fingers of the left hand in skilled violinists. These researchers also noted that functional enlargement of cortical representation was inversely correlated with the age at which musicians begin to practice suggesting microstructural adaptation evolving to macrostructural changes. Thus, consistent and intense practice of bimanual finger

sequences has been shown to alter the structure of a musician's primary motor cortex and somatosensory cortex, especially when training occurs during a critical period of brain development.

Using magnetoencephalography (MEG), Pantev et al. (1998) compared the location and strength of the electrical source for neural representation of piano tones and pure tones between musicians and nonmusicians. Supporting earlier research (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995), musicians demonstrated an increase in the size of cortical representation for the processing of piano tones. Once again, beginning age of music training was inversely correlated with neuronal representation. That is, the earlier the initiation of musical practice, the stronger the neuronal response was to the piano tones.

#### *The Musician's Brain – Anatomical Differences*

The lifelong ability to adapt to environmental demands and sensory stimulation is grounded in the dynamic capacity of the human brain to modify its structure and function. A musician's brain provides opportunities for researchers to study the interactions between inherent neurophysiological distinctions and the impact of music training on structural adaptation and development.

*Corpus callosum.* The corpus callosum is the main interhemispheric fiber tract responsible for interhemispheric integration and communication. Structural and functional maturation of the corpus callosum extends into late childhood and early

adolescence. Maturation coincides with the termination of the corpus callosum myelination cycle (Yakovlev & Lecours, 1967).

The anterior portion of the corpus callosum is the last subregion to mature. This portion contains fibers mainly from frontal motor-related regions and pre-frontal related regions. Functional magnetic resonance imaging (fMRI) reveals that the anterior half of the corpus callosum is significantly larger in musicians compared to nonmusicians (Schlaug, 2001). This difference in callosal size may be due to (a) an increase in the number of fibers, (b) a larger proportion of thicker myelinated fibers with fast interhemispheric transfer, or (c) fibers with thicker axons or more axon collaterals (Schlaug, 2001). During music training for an instrument requiring the use of both hands, such as a violin or a piano, intense interhemispheric communication is necessary for management of complex bimanual motor sequences. Thus, music training is implicated in the determination of callosal fiber size and composition. Furthermore, the anterior corpus callosum is significantly larger in musicians who begin training prior to age 7 compared to musicians who begin later or to nonmusician controls (Schlaug, 2001).

*Cerebral cortex.* Neural imaging studies examining the primary motor cortex, somatosensory cortex and auditory cortex provide evidence of macrostructural differences between instrumental musicians (violin and keyboard players) and control subjects (Elbert et al., 1995; Pantev et al., 1998; Schlaug, 2001). All studies found a strong negative relationship between the age that music training begins and the degree of neural alteration; that is, the earlier in life that practice begins, the greater the structural change.

These differences support the concept that intensive music training influences neural changes.

Schlaug and colleagues (2001) examined the intrasulcal length of the posterior bank of the precentral gyrus (ILPG) as a gross anatomical marker of the primary motor cortex. Data from functional magnetic resonance images indicated a significantly greater intrasulcal length in the *right* hemisphere for musicians. There was no significant between-group difference in the left ILPG. Schlaug suggests that the longer right ILPG in musicians is a training-induced adaptation of the motor area for greater control of the nondominant hand. Correlation analyses support a strong relationship between mean intrasulcal length and age of commencement of music training.

*Gray matter volume.* Gaser and Schlaug (2003) compared the brain structures of professional musicians, amateur musicians, and nonmusicians using voxel-based morphometry (VBM). VBM is a fully automatic technique for computational analysis of differences in local gray matter volume. Voxel clusters are overlaid on a rendered cortex surface of a selected single subject. VBM provides high resolution anatomical images of the whole brain using a magnetization prepared rapid acquisition gradient echo sequence (Gaser & Schlaug, 2003).

A significant positive correlation between musician status and increase in gray matter volume were found in the peri-rolandic regions including the primary motor and somatosensory areas, pre-motor areas, anterior superior parietal area, and the inferior temporal gyrus bilaterally. A positive correlation indicates volume was highest in professional musicians; that is, those with the most training, intermediate in the amateur

musicians, and lowest in those with no previous music training. Positive correlations between gray matter volume and musician status were found in the left cerebellum, left Heschl's gyrus, and left inferior frontal gyrus. No significant correlation between white matter volume and musician status was indicated. It was suggested that either the VBM is insensitive to white matter difference or that most of the presumed plastic changes occur in the cerebral gray matter (Gaser & Schlaug, 2003).

*Cerebellum.* The cerebellum comprises only 1/10<sup>th</sup> of the brain's total volume; however, the number of cells in the human cerebellum exceeds the total number of cells in the cerebral cortex by four times (Anderson, Korbo, & Pakkenberg, 1992). Because of its role in motor learning, movement coordination, and timing of sequential movements, it was questioned whether the cerebellum is structurally different between musicians and nonmusicians (Schlaug, 2001). Functional magnetic resonance imaging data revealed a significantly higher mean relative cerebellar volume (5%) for male musicians (strings and keyboard players) compared to male nonmusicians. A positive trend was noted between intensity of music training (practice time per day and across a lifetime) and relative cerebellar volume.

### *Summary*

Music is a rule-governed, universal characteristic of human culture acquired through implicit and explicit experience. The study of music and its neural correlates for perception and performance has yielded insights into the structural organization of the human brain. Neurological and anatomical differences between musicians and



nonmusicians have been reliably measured with established neurophysiological techniques (Elbert et al., 1998; Pantev et al., 2003; Schlaug, 2001). These distinctions serve as indicators of possible genetic factors or training-induced changes in neural structure indicative of neural plasticity (Zatorre, 2003).

Because of the concentrated training and skill acquisition that a musician pursues from an early age, it is argued that neural development occurs differentially in response to performance demands; that is, macrostructural changes take place as a result of widespread microstructural adaptations (Gaser & Schlaug, 2003; Pantev et al., 1998; Pascual-Leone, 2001; Schlaug, 2001; Zatorre, 2003). The strong association between beginning age of music training and degree of cortical adaptation further supports the argument that these changes evolve over time as a consequence of training. It is yet unknown whether these musical abilities and neurological/anatomical differences of musicians are due exclusively to learning, or whether these distinctions reflect innate abilities and capacities that are advanced by early exposure to music (Gaser & Schlaug, 2003; Pantev et al., 1998; Schlaug, 2001; Zatorre, 2003).

While a review of the literature reveals comprehensive evidence supporting neural plasticity in trained instrumental musicians, little is known regarding trained vocal musicians. Trained vocal musicians present with exceptional abilities to perceive and perform music and adhere to the same rigorous training as other musicians; however, there is a paucity of comparative research and an insufficient understanding of physiological variables in this population.

### *Auditory Pitch Perception*

Auditory perceptual abilities for music and speech emerge from neurophysiological structures and functions. The abilities to perceive and discriminate the components of music are regarded by many music educators as fundamental abilities and implicit skills of a successful performer (Bentley, 1966; Geringer, 1983). Carl Seashore (1919), psychologist and author, argued that the capacity to hear pitch differences “is a fundamental capacity in musical talent, and upon it rests most of the powers of appreciation and expression in music...one must be guided by such hearing in playing and singing” (p. 42, as cited in Pedersen & Pedersen, 1970).

### *Acoustical Perception of Music*

Acoustical perception of music includes the basic perceptual qualities of timbre, loudness, and pitch as a function of time (Sundberg, 1994). Timbre, also referred to as resonance, adds ‘richness’ to a tone (Sundberg, 1994; Watts, Barnes-Burroughs, Adrianopoulos, & Carr, 2003). While there is no clear-cut definition of timbre, Sundberg writes, “Two tones differ in timbre if they are similar in pitch and loudness and still do not sound similar” (p. 107). For example, tones perceived from a trumpet and a piano may have the same pitch and loudness, yet they are perceived as two different sounds. This ‘difference’ is the timbre and depends on the length and shape of the resonating tract.

Loudness is the perceptual correlate of the intensity or magnitude of the acoustic stimulus (Gelfand, 1998; Sundberg, 1994). Sounds with low intensity are perceived as

‘soft’ and sounds with high intensity are perceived as ‘loud’; however, there is not a one-to-one correlation between loudness and intensity. Perceived loudness of complex tones depends on the critical bands of hearing (Scharf, 1970). Tones of similar amplitudes fall into the same critical band so that the tones cannot be heard individually; however, as adjacent bandwidths are stimulated, perceived loudness increases (Gelfand, 1998; Sundberg, 1994). Perceived loudness is the summed loudness of all the critical bands activated by a particular tone.

Pitch is the perception related to frequency and corresponds to the fundamental frequency of the lowest frequency partial (Gelfand, 1998; Sundberg, 1994). Perceived pitch gets higher as frequency increases; however like loudness, there is not a simple one-to-one correlation between pitch and frequency. The pitch perception of complex sounds relies on the processing of the fundamental frequency and its components or harmonics.

Accurate auditory pitch discrimination across a distributed frequency range is a prerequisite for the perception of speech and music (Novitski, Tervaniemi, Huottilainen, & Näätänen, 2004). For the perception of music, pitch differences are said to be perceived categorically. In other words, slight variations in frequency do not affect the perceived tone or note, or the musical interval (Sundberg, 1994). Within a small range of variation, a change of frequency has no effect on our perception or classification of pitch; however, at the border of a frequency range, a minor shift radically changes the perception from one category to another. This phenomenon is known as categorical perception. In other words, not all changes in frequency are perceived. In order for sounds to be detected as differing in pitch, the frequency difference must be at least equal

to the subject's difference limen; that is, frequency discrimination threshold (Gelfand, 1998).

The perception of pitch is fundamentally different when we listen to speech or music. In music, pitch changes are perceived categorically into a limited number of musical intervals. Most melodies written in Western culture are generally written with small pitch intervals approximately  $1/6^{\text{th}}$  to  $1/12^{\text{th}}$  of an octave (Ayotte, Peretz, & Hyde, 2002). In speech, the quantity of pitch change is perceived in a continuous fashion and the variations are larger than one-half an octave to convey relevant information (Ayotte et al., 2002; Sundberg, 1994). This perhaps explains why Seashore (1919) thought that the auditory perception of minute pitch differences “is a fundamental capacity in musical talent, and upon it rests most of the powers of appreciation and expression in music” (p. 42, as cited in Pedersen & Pedersen, 1970). Despite its obvious importance, frequency discrimination is one of the least investigated psychoacoustic abilities in musicians, (Kishon-Rabin, Amir, Vexler, & Zaltz, 2001).

### *Cortical Models of Pitch Perception*

*Modular theory.* Researchers have proposed that speech and music may be processed by two distinct systems and refer to this as the theory of modularity (Peretz & Coltheart, 2003; Tervaniemi & Brattico, 2004) or specific domain (Leiberman & Whalen, 2000). According to Fodor (1983, 2001), mental modules have the following characteristic properties: (a) speed of operation, (b) automaticity, (c) domain-specificity, (d) information encapsulation, (e) neural specificity, and (f) innateness. Each property is

typical, but not a required feature of a modular system. Information encapsulation (Fodor, 1983) and domain-specificity (Peretz & Coltheart, 2003) are considered two of the more important characteristics. Information encapsulation means that processing within a mental module is immune from influence of the central system (Fodor, 1983). Domain specificity implies that the specific operation of a module is restricted to a limited domain of input and output (Peretz & Coltheart, 2003).

Peretz & Coltheart (2003) propose a module that is specific to the processing of music. This module may contain smaller systems specific to different aspects of music, but not necessarily restricted to music. The model is based on the premise that music is an evolutionary and unique cognitive function with dedicated and separate neural substrates (Peretz & Coltheart, 2003; Tervaniemi & Brattico, 2004). Selective impairment and sparing of musical abilities have been found in neurologically impaired individuals. For example, there are individuals who can no longer recognize musical melodies, but for whom the ability to recognize spoken words and environmental sounds are normal; or conversely, spoken words are not recognized, but musical melodies are easily identified (Ayotte, Peretz, & Hyde, 2002; Peretz & Coltheart, 2003). The evidence of a double dissociation supports the modularity theory and points to the existence of separate and dedicated neural circuitry for music and speech processing.

Peretz and Coltheart (2003) propose that all auditory stimuli are first processed in an acoustic analysis module. Within this module, all information is received by all submodules and processed in parallel. It is assumed that activation of the music or the language processing modules is determined by the aspect of the input to which a module

is tuned. Thus, speech and music depend on specific and dedicated neural circuitry (Lieberman & Whalen, 2000). The music input modules are thought to be organized in two parallel and independent subsystems: (a) analysis of pitch content, including contour and intervals; and (b) analysis of temporal content, including rhythm and duration. These modules may process in parallel with language processing modules and may be connected by information pathways to other modules outside of the auditory cortex, such as memory modules and/or perceptual modules.

*Parameter theory.* The domain-specific theory may be challenged by the concept of a parameter-specific lateralization model. This model actually overlaps with the domain-specific paradigm. It proposes neural specializations for processing the acoustic parameters of speech and music based on the premise that auditory hemispheric asymmetries for temporal and spectral processing have evolved as a consequence of functional specialization and not domain-specificity (Zatorre et al., 2002). Speech and music stimuli differ in their acoustic structure and thus in their processing requirements. Whereas the analysis of speech requires good temporal resolution to process rapidly changing formants, it can be argued that music processing requires good pitch resolution (Zatorre et al., 2002). Neuroimaging and electrophysiological data support neural specialization and indicate processing distinctions between the left and right auditory cortices; that is, the left hemisphere is favored to process fast temporal information, while the right hemisphere is more active for spectral resolution (Dalla Bella & Peretz, 1999; Tervaniemi & Hugdahl, 2003; Zatorre et al., 2002).

### *Neural Specialization for Pitch Processing*

Evidence from neural imaging is accumulating to establish structural differences in brain organization between musicians and nonmusicians ( Schlaug, 2001) and functional differences such as increased cortical representation (Elbert et al., 1998; Pantev et al., 2003). Electrophysiological studies (EEG, MEG) indicate that temporally and spectrally complex sounds are automatically processed by the human auditory cortex and this processing differs between sounds of speech and music and between the cerebral hemispheres (Koelsch, Schröger, & Tervaniemi, 1999; Tervaniemi, 2001). Pitch processing may also be broken into a hierarchy of auditory neural functions from low-level activities including the discrimination of two sounds or detection of pattern change to high-level activities including discrimination of pitch contours and organization of tones into melodies and harmony.

*High-level pitch processing.* Earlier neuropsychological studies of music processing investigated subjects with brain lesions and reported that neural pitch processing can be dissociated into different lateralization patterns and selectively disrupted by cortical lesions. Research designed to assess the contribution of each hemisphere to high-level pitch processing found that auditory discrimination of melodic pitch patterns is generally more affected by damage to the right superior temporal area than to the left superior temporal area (Peretz, 1990; Zatorre, 1988). Thus, although there was a substantial contribution of the left hemisphere, results indicated overall right hemisphere superiority for melodic pitch processing.

More recent studies have examined high-level pitch processing using functional magnetic resonance imaging (fMRI). Gaab and Schlaug (2003) examined whether differences in perceptual and/or cognitive strategies alone can explain functional brain difference between musicians and nonmusicians. The nonmusicians were selected from a larger sample group and matched with musicians based on their performance on a pitch memory task. Subjects listened to a sequence of 6-7 tones and were asked to decide whether or not the last or second to last tone was the same or different from the first tone. For both groups, fMRI images indicated bilateral activation of the superior temporal gyrus, supramarginal gyrus, inferior frontal gyrus, and superior parietal lobe. Despite matching the two groups on a performance score of pitch memory, musicians had greater bilateral activation of superior parietal areas, more activation of the supramarginal gyrus (SMG), and greater activity in the right inferior frontal lobe. These results concur with previous PET scan data (Zatorre, Evans, & Meyer, 1994) that also support the hypothesis of frontal lobe activation for the analysis of higher order pitch processing. Gaab and Schlaug (2003) conclude, “Musicians activate a network that includes auditory short-term memory regions (e.g. SMG) and regions implicated in visual-spatial process (e.g. superior parietal cortex). Nonmusicians seem to rely more on a network that includes brain regions important for pitch discrimination (e.g. Heschl’s gyrus) and traditional memory regions (e.g. hippocampal gyrus)” (p. 2294).

Schmithorst and Holland (2003) compared the neural correlates of auditory processing for melody and harmony between musicians and nonmusicians on a passive listening paradigm. On the melody processing task, musicians had significantly greater



activation of the inferior parietal lobes and superior frontal gyrus bilaterally, and in contrast to the above findings, the *left* inferior frontal and superior temporal gyri. This variation in hemispheric activation of the inferior frontal lobe may be due to the differences among the tasks. In the study by Schmithorst and Holland, subjects listened passively to a popular melody which may have activated semantic memory in the left frontal hemisphere; whereas, Gaab and Schlaug required subjects to make active choices after listening to an unfamiliar sequence of tones. Concurring with earlier reports, Schmithorst and Holland found that bilateral activation in the anterior portion of the superior temporal gyrus was robust for both musicians and nonmusicians, supporting a contribution of working memory for melodic processing. For harmonic processing, both subject groups had activation of the occipital lobe suggesting that exposure to harmonic progressions integrates with visual associative functions in the brain. In addition to activation of the occipital lobe, musicians had activation of the parietal-temporal regions near the angular gyrus. Schmithorst and Holland (2003) conclude that extensive music training promotes the recruitment of different neural networks to process harmony and melody.

Brattico, Näätänen, and Tervaniemi (2001) used electroencephalography (EEG) to investigate context effects on pitch perception in musicians and nonmusicians by measuring the mismatch negativity (MMN) response. The mismatch negativity is a component of ERPs and reflects an auditory change detection process based on neural representations of acoustic repetitions or regularities independent of active attention to the task. While quietly reading, subjects were presented with a large pitch change in three

contexts: isolated sounds, a sequential pattern with familiar tones from Western culture, and a sequential pattern with intervals unfamiliar to the subjects. For both groups, the MMN amplitude was greater when the pitch change occurred among sequential patterns within a familiar scale than within an unfamiliar scale and greater when the pitch change occurred within an unfamiliar scale than among single tones. Musicians had a faster neural response for pitch changes than the nonmusicians; that is, a shorter latency for the MMN response.

Koelsch, Schmidt, and Kansok (2002) investigated the influence of long-term musical experience on the processing of chords presented within a complex musical context by examining the early right anterior negativity (ERAN) component of ERPs. The ERAN response is triggered by violations of complex musical regularities and is maximal around 200 ms following stimulus onset (Koelsch, Gunter, Friederici, & Schröger, 2000). Musicians and nonmusicians listened to harmonically appropriate and inappropriate chords. That is, the succession of chord functions and harmonic relations followed expected patterns of music syntax in classic Western tonal music or did not follow these patterns. ERP data revealed that harmonically inappropriate chords elicited an ERAN in both subject groups; however, a significantly larger ERAN was elicited in the trained musicians. Koelsch, Schmidt, and Kansok conclude that because of their music training, musicians have more explicit memory representations of harmonic relatedness and therefore, are more sensitive to violations of music syntax.

Lopez et al. (2003) compared ERP responses of musicians and nonmusicians on five tasks of increasing complexity of musical sequences. Stimulus tasks included five

oddball paradigms, including single tones in a sequence, 3 simultaneous tones (chord), 3 consecutive tones (arpeggio), a familiar song without words, and a sung song. In a basic oddball paradigm, sometimes referred to as a change-detection paradigm, infrequent and unpredictable deviant stimuli are presented among frequent standard stimuli. The proportion of stimuli is typically 80% standard and 20% deviant (Sams, Paavilainen, Alho, & Näätänen, 1985). All odd-ball paradigms elicited (a) a response of the primary auditory cortex, N1; (b) a frontotemporal negativity at 200 ms, the mismatch negativity to the deviant stimuli (MMN); and (c) a late positive component between 350-450 ms of latency, P3. The P3, also referred to as the P300, reflects an involuntary attention switch towards the deviant or novel sound in 'an ignore and attend' condition (Novitski et al., 2004). It is typically elicited by an odd-ball paradigm and relies on active participation of the subject. The P3 is thought to be an indicator of memory maintenance or updating (Donchin & Coles, 1988).

The N1 peak measurements were distinct for all paradigms but not significantly different between the groups. There were clear MMN responses for both groups in all paradigms; however, those with musical ability responded with significantly greater amplitudes and shorter latencies. Similarly, this subject group had the strongest P3 for the arpeggio task (3 consecutive tones) and the complex melody task, suggesting an influence of musical skill, since the P3 responses for the subject groups did not significantly differ on the simpler paradigms of sinusoidal tones and familiar melody.

These studies agree that auditory pitch perception for high-level activities, including discrimination of pitch contours and organization of tones into melodies and

harmonies, is influenced by musical context and syntax (Brattico et al., 2001; Koelsch et al., 2002). Data from ERP research indicate that even nonmusicians have an innate knowledge of musical regularities; that is, listeners expect specific musical events to occur (Koelsch et al., 2000). However, musicians consistently have greater sensitivity to violations of musical syntax secondary to extensive music training. Years of music lessons and practice create a larger number of explicit memory representations, implying that neural mechanisms responsible for processing musical syntax can be influenced by experience and training.

*Low-level pitch processing.* Low-level auditory pitch processing, such as the discrimination of two sounds or the detection of pattern change, have been investigated by a variety of approaches including psychoacoustics, behavioral lesion studies, and electroencephalography (EEG). Spiegel and Watson (1984) compared the performances of orchestral musicians and nonmusicians on tasks of auditory frequency discrimination in an attempt to relate performance to musical background. Surprisingly, on a task of frequency discrimination for single tones, one-half of the nonmusicians attained thresholds almost as low as the musicians. The researchers suggested that innate auditory processing advantages may be present in some persons who have not had music training. This finding is questionable, however, since the subjects in the control group were *not* screened for previous musical experience or familiarity with psychoacoustic procedures.

Kishon-Rabin, Amir, Vexler, and Zaltz (2001) compared frequency discrimination thresholds, also referred to as the difference limen for frequency (DLF) between instrumental musicians and nonmusicians. The nonmusicians had no previous

music training or experience with psychoacoustic studies. Although normative values for DLF in the general population have not been established, average DLF thresholds for pure tones between 500 Hz and 2k Hz using an adaptive two-interval forced choice paradigm (2IFC) have approached 1 – 1.5% ( Moore, 1989). Kishon-Rabin and colleagues compared DLF thresholds using two threshold estimation procedures: two-interval forced-choice method (2IFC) and three-interval forced-choice paradigm (3IFC). Stimuli consisted of three sets of digitally generated pure tones. Each set contained one reference tone and 20 different comparison tones. The comparison tones varied in 0.5 Hz steps for a reference tone of 250 Hz and in 1 Hz steps for 1000 and 1500 Hz. The minimal detectable changes in frequency ( $\Delta f$ ) were transformed to *relative* DLF thresholds in *percent* ( $rel\ DLF\ \% = \Delta f / f \times 100$ ). Findings indicated that both groups had significantly smaller DLFs in the 2IFC paradigm compared to the 3IFC. Consequently, it was suggested that auditory memory plays a role in frequency discrimination tasks. Musicians had significantly smaller values of *rel/DLF %* than nonmusicians. The mean DLF for musicians was approximately half the value of the nonmusicians suggesting that auditory pitch discrimination is influenced by years of music training.

Neuropsychological research has examined the specificity of pitch and temporal discrimination, assuming that damage to a specific area of the brain leads to a specific change in behavior which yields clues to the function of the damaged area (Johnsrude, Penhune, & Zatorre; 2000, Liégeois-Chauvel, Peretz, Babai, Laguitton, & Chauvel, 1998; Zatorre, 2003). Liégeois-Chauvel et al. (1998) compared 65 right-handed patients who had unilateral temporal cortectomies secondary to intractable epilepsy with a control

group. Sequences of simple musical phrases with variations in either pitch or temporal dimensions were presented. Participants judged whether two phrases were ‘same’ or ‘different.’ Results indicated that removal of the posterior superior temporal gyrus (STG) resulted in the greatest deficit in the pitch-based tasks, implying that the posterior regions of the STG may be specialized to compute certain specific aspects of pitch patterns. The authors could not suggest *which* STG is specialized since they combined all left- and right-sided cases in their analysis.

Johnsrude, Penhune and Zatorre (2000) paralleled the above study. Magnetic resonance imaging (MRI) identified lesions as extending or not extending into Heschl’s gyrus. Heschl’s gyrus is the primary auditory cortex and a subdivision of the superior temporal gyrus (STG). All participants performed a simple pitch discrimination task, for which the subject decided if two pure tones were the same or different, and a pitch direction judgment task, for which the subject decided whether the first tone was higher or lower than the second. On the simple pitch discrimination task, there were no significant threshold differences between the control subjects and patients with either a left or right temporal lobe excision that encroached upon the superior temporal gyrus (STG). However, thresholds for a pitch direction judgment task were significantly higher for patients with excision of the right temporal lobe that encroached upon the lateral portion of the STG. Conversely, normal subjects and patients with lesions in the left temporal lobe regardless of the extension into the STG were unimpaired on the tasks. Patients with lesions in the right temporal lobe, but *excluding* the STG, were also unimpaired on the pitch direction task, thus demonstrating a specialization of pitch

function linked to the right auditory cortical areas and specifically to the right superior temporal gyrus.

Using electroencephalography (EEG), neural sound processing can be probed within a millisecond of accuracy by recording the event related potential (ERP). Event related potentials of the auditory cortex are also referred to as auditory evoked potentials (AEPs). EEG studies on automatic neural encoding of music prior to conscious attention often examine the following AEP components: P1, N1, P2, or MMN.

Shahin, Bosnyak, Trainor, and Roberts (2003) compared auditory evoked potentials, N1 and P2, between musicians and nonmusicians as they passively listened to the presentation of violin tones, piano tones, and pure tones matched in fundamental frequency and loudness. Effects of group (violinists, pianists, and control) and stimulus (violin, piano, pure tones) were evaluated. Compared to the nonmusician control group, the musicians had larger N1 and P2 amplitudes to all three types of tonal stimuli indicating stronger pre-attentive auditory responses. There were no response differences between the violin and piano musicians. Piano tones evoked larger N1 responses for musicians and nonmusicians compared to pure tones and violin tones.

As reported previously in this chapter, Trainor, Shahin and Roberts (2003) examined the P1-N1-P2 complex in musically trained and untrained 4- and 5-year old children. AEPs were compared in response to violin tones, piano tones and pure tones. For all children, ERP responses were most robust to piano tones with clear P1, N1, and P2 components suggesting an increased cortical response to sounds rich in harmonics. In the child musicians, the P2 response was stronger and the N1 component emerged earlier

lending strong support for cortical plasticity as a result of music training; however, the authors cautioned that the influence of genetic factors cannot be dismissed (Trainor et al., 2003).

Tervaniemi (1993) compared the pitch discrimination accuracy of musicians with and without absolute pitch (AP) using a mismatch negativity (MMN) paradigm. An MMN response is elicited when a sound is encountered that doesn't match memory representations; that is, it is evoked by a different or deviant stimulus which occurs infrequently among standard or frequent stimuli. It is termed 'pre-attentive,' as it detects aspects of acoustic information that are encoded without the conscious attention of the listener, such as pitch, duration, etc. (Tervaniemi, 2001). A 'strong' MMN refers to large amplitude and short latency. Absolute pitch is characterized as the ability to identify by verbal label (musical note name) the pitch of any sound without reference to another sound, or by producing a musical tone when given the musical note name (Zatorre, Perry, Beckett, Westbury, & Evans, 1998). Stimuli consisted of pure tones and synthesized piano sounds familiar in Western culture. The deviant stimuli were off-scale (i.e., dissonant). Contrary to expectations, the MMN responses did not differ significantly between the musician groups, or between on- or off-scale tones. Interestingly, both groups had greater amplitudes and earlier latency to piano sounds compared to sinusoidal tones suggesting that pitch discrimination is facilitated by the presence of the harmonic partials.

Tervaniemi, Ilvonen, Sinkkonen et al. (2000) in a series of MMN studies, systematically investigated the facilitating effects of overtones on the accuracy of pitch



discrimination. Initially, they found that subjects' pitch-MMN was stronger for complex sounds rather than the pure tones. The next study's objective was to determine if adding harmonic partials would further enhance the MMN response (Tervaniemi, Schröger, Saher, & Näätänen, 2000). ERP data revealed that the MMN amplitude was enhanced for complex sounds when compared to pure tones, but there were no significant differences between spectrally rich tones having 3 to 5 partials. This suggests that few harmonic partials are needed to retrieve the neural representation underlying pitch discrimination.

Subsequent to the previous studies, Novitski, Tervaniemi, Huotilainen, and Näätänen (2004) systematically compared the neural and behavioral accuracy of frequency discrimination across a wider range from 250-4000 Hz. The sound structure (pure versus harmonic tones) and magnitude of frequency change were varied. The harmonic tones elicited stronger MMN responses than did pure sinusoidal tones in all frequency bands. The addition of only two partials to the pure tones caused an increase of MMN amplitude. In the behavioral study, the same subjects indicated whether tones presented in pairs differed in pitch. ERP latencies and amplitudes correlated with the reaction time and hit rate with the highest correlation occurring between MMN amplitude and hit rate ( $r = 0.8$ ).

Since the MMN detects aspects of acoustic information that are encoded without the conscious attention of the listener. It may be used as a means to examine training-induced changes in auditory neural response (Mody, 2004; Tervaniemi, 2001; Trainor, McDonald, & Alain, 2002). Koelsch, Schröger, and Tervaniemi (1999) compared pre-

attentive auditory responses of musicians and nonmusicians to investigate the influence of musical expertise on the brain's automatic pitch change-detection (MMN). Major chords and single tones were presented to musicians and nonmusicians under ignore and attend conditions. Slightly disharmonic chords, presented among perfect major chords elicited a distinct MMN in professional musicians, but not in nonmusicians. Thus, the musicians automatically detected differences in auditory information that was undetectable for nonmusicians.

Consensus among published research suggests that low-level auditory pitch processing, such as the discrimination of two sounds or the detection of pattern change, are linked to the right auditory cortical areas and specifically to the right superior temporal gyrus. Pitch discrimination is facilitated by the presence of the harmonic partials; however, only a few harmonic partials are necessary for retrieval of neural representations. While innate auditory processing advantages may be present in some persons who have not had music training, current research indicates superior pre-attentive auditory skills for musicians and supports the implication that long-term music training modifies pre-attentive neural processing of acoustic input.

### *Vocal Pitch Control*

#### *Evolution of Singing*

The evolutionary origin of singing in the human species appears to be an intriguing occurrence since there is no clear-cut adaptive function for singing (Hauser &

McDermott, 2003). Unlike language, which allows us to communicate our thoughts to others, music has no obvious functional outcome. Charles Darwin wrote,

As neither the enjoyment nor the capacity of producing musical notes are faculties of the least use to man in reference to his daily habits of life, they must be ranked among the most mysterious with which he is endowed. (1871, p. 878 as cited in Hauser & McDermott, 2003)

Darwin and others propose that music evolved as a sexually selected system, designed to attract mates and signal mate quality (Darwin, 1871 as cited in Hauser & McDermott, 2003; Miller, 2000). Thus, shaping human emotions may be a possible adaptive function of music and a basis for the evolution of singing.

### *Laryngeal Anatomy for Pitch Control*

The biological organ for phonation is the larynx. The larynx is only one part of an anatomical network responsible for voice production. This network also includes the respiratory system which is comprised of the bronchi, lungs, and trachea, and the supralaryngeal vocal tract which includes the pharynx and the oral and nasal cavities. Tradition holds that the larynx is innervated by two major branches of the vagus nerve; that is, the superior laryngeal nerve and the recurrent laryngeal nerve. However, evidence suggests that cranial nerve XI, spinal accessory, may also contribute to laryngeal innervation (Webster, 1999; Zemlin, 1999). Additionally, the muscles that suspend the larynx in the cervical region, including the extrinsic laryngeal muscles, are innervated by several cranial nerves (V trigeminal, VII facial, and XII hypoglossal). The coordination

of these muscles tends to enhance the ability of the larynx to manipulate its internal structures. Regardless, the presence of lower motor neuron synaptic connections of both spinal accessory and vagus nerves in the jugular nucleus and the nucleus ambiguus indicate that the pure or single-nerve innervation theory of the intrinsic laryngeal muscles may need to be reviewed. Gross dissection reveals that all the intrinsic laryngeal muscles are innervated by the recurrent laryngeal branch, *except* the cricothyroid muscle which is innervated by the superior laryngeal nerve.

Most of the laryngeal framework is in the form of cartilage which allows for mobility of the larynx (Titze, 1994). The larynx is comprised of the following cartilages: thyroid, cricoid, a pair of arytenoid cartilages, and the epiglottis (Fink & Demarest, 1978). One bone, the hyoid, is a horseshoe shaped structure that floats above the larynx and anchors a number of extrinsic laryngeal and lingual muscles. The hyoid bone is attached to the thyroid cartilage by the thyrohyoid membrane and to the epiglottis via the hyoepiglottic ligament (Titze, 1994).

*Laryngeal cartilages.* The thyroid cartilage consists of two parts or lamina joined anteriorly at the midline, forming a 90° to 120° angle on the top (Titze, 1994). Adult males usually have a smaller angle which forms a laryngeal prominence often referred to as the Adam's apple. The posterior third of this horizontal arch is open. There are four projections from the posterior borders; one on each end projecting down (inferior cornus) and one on each end projecting up (superior cornus). Each inferior cornu articulates in a true joint with the lower side of the posterior portion of the cricoid cartilage and each superior cornu is connected to the posterior extreme of the hyoid bone via the lateral

thyro-hyoid ligament. The thyroid cartilage forms a frontal shield for the airway and a site for attachment of intrinsic laryngeal muscles.

The cricoid cartilage lies directly below the thyroid cartilage and forms the only complete laryngeal ring surrounding the top of the tracheal airway (Titze, 1994; Zemlin, 1999). This ring is wider and taller posteriorly, resembling a signet ring (Fink & Demarest, 1978). The inferior thyroid cornua attach on either side of the cricoid signet to form the cricothyroid joint. Through action of the intrinsic laryngeal muscles, this joint allows the front of the cricoid to rotate upward toward the thyroid cartilage.

The paired arytenoid cartilages are shaped like tetrahedrons (pyramids) with four triangular surfaces. One of the surfaces acts as the base and is attached to the top, posterior portion (the signet) of the cricoid cartilage forming the cricoarytenoid joint. This joint is very flexible and allows for rotation and gliding of the arytenoid cartilages on top of the cricoid cartilage. The movement of the arytenoid cartilages is responsible for the adduction-abduction of the vocal folds (Sawashima & Hirose, 1983; Webster, 1999; Zemlin, 1999).

The epiglottis is a cartilage that resembles the tongue of a shoe. It is attached by connective tissue to the inner surface of the thyroid cartilage just below the thyroid notch and “forms the anterior wall of a chamber” (Titze, 1994, p. 10), the laryngeal vestibule above the glottis. Superiorly, the epiglottis is attached to the hyoid bone that also serves as the base of the tongue. During swallowing, the epiglottis retroflexes over the opening of the larynx to effectively close off and protect the airway.

*Laryngeal muscles.* The muscles of the larynx are divided into two groups, extrinsic muscles and intrinsic muscles. The *extrinsic* laryngeal muscles connect the larynx to other structures in the head, neck, and chest (hyoid bone, sternum, and pharynx). Although there are five extrinsic laryngeal muscles, only the following three significantly contribute to phonation: thyrohyoid muscle, sternothyroid muscle, and sternohyoid muscle. These muscles are responsible for the basic laryngeal positioning including: (1) suspension and stabilization of the thyroid cartilage within the neck, (2) vertical movement as in elevation or depression of the larynx as a whole, and (3) imposition of laryngeal stress/tension/rigidity through cervical and pectoral tension (Jürgens, 2002; Webster, 1999; Zemlin, 1999). During singing, the external laryngeal muscles proportionally increase their activity as the fundamental frequency increases or decreases from the value of a normal, relaxed speaking voice (Roubeau, Chevri-Muller, & Saint Guily, 1997).

The *intrinsic* laryngeal muscles consist of a pair of thyroarytenoid muscles, a pair of cricothyroid muscles, a pair of lateral cricoarytenoid muscles, a pair of posterior cricoarytenoid muscles and a single interarytenoid muscle. Action of these muscles on the cartilages and joints result in (1) abduction-adduction of the vocal folds, (2) constriction of the supraglottic laryngeal structures, (3) changes in the length and tension of the vocal folds, and (4) vertical movements of the larynx (Sawashima & Hirose, 1983; Webster, 1999; Zemlin, 1999). The intrinsic muscles connect the cartilages within the larynx and are primarily responsible for sustaining or changing pitch by controlling the movements of the cricothyroid and cricoarytenoid joints (Sawashima & Hirose, 1983).

The bulk of the vocal fold is made up of the thyroarytenoid muscle. Each muscle extends from the posterior surface of the anterior arch of the thyroid cartilage, below the thyroid notch, and inserts into the anterior/vocal angle of the arytenoid cartilage (Sundberg, 1987; Zemlin, 1999). Isotonic contraction of the thyroarytenoid muscles glides the arytenoid cartilages forward, thereby shortening, thickening and stiffening the vocal folds (Titze, 1994). The vocal fold may be described in three layers: (1) the mucosa, which acts as a cover and consists of the epithelium and the superficial layer of the lamina propria; (2) the ligament, which consists of the intermediate and deep layers of the lamina propria, and (3) the thyroarytenoid muscle, which is lateral to the ligament (Hirano & Sato, 1993). The vocal folds are approximately 3 mm long in the newborn infant and grow to about 9 to 13 mm in females and 15 to 20 mm in adult males (Sundberg, 1987). The longer the vocal fold, the lower the pitch range (Sawashima et al., 1983).

The pair of cricothyroid muscles is the primary muscle for pitch control and the *only* intrinsic laryngeal muscle to be innervated by the superior laryngeal branch of the vagus nerve. This unique innervation pattern allows this one muscle pair to be activated while the others are deactivated. Titze remarks that this special designation "...makes the function of the cricothyroid muscle (raising pitch by vocal fold elongation) very select" (p. 19, 1994).

The cricothyroid muscle consists of two parts that originate on the anterior arch of the cricoid. One part courses vertically and inserts into the lower border of the thyroid cartilage lamina while the other section runs up and back to insert in the inferior cornu of

the thyroid cartilage (Titze, 1994). EMG (electromyography) measurements provide evidence that the contraction of the cricothyroid muscle elongates the vocal folds (Sundberg, 1987). When the cricothyroid muscle contracts, it pulls the cricoid arch upward, depresses the thyroid lamina which shortens the cricothyroid space, and results in lengthening the thyroarytenoid muscle, elongating the vocal fold. Deactivation of the cricothyroid muscle prevents the production of high pitch tones (Jürgens, 2002).

The actions of the thyroarytenoid and the cricothyroid muscles oppose each other; that is, the thyroarytenoid muscles shorten and thicken the vocal folds and the cricothyroid muscles lengthen and thin the vocal folds. Together, these two muscle pairs are responsible for most of the changes in vocal fold length and mass. Muscles that oppose each other comprise an agonist-antagonist pair. It is theorized that because these two muscle pairs are innervated by two separate nerve branches, the effective stiffness of the vocal fold has a wide range of variability.

The lateral and posterior cricoarytenoid muscles form bilateral agonist-antagonist pairs. Each lateral cricoarytenoid muscle originates from the superior borders of the cricoid arch and courses upward and posteriorly to insert laterally into the corresponding arytenoid. They adduct (close) the vocal folds by rotating the arytenoids forward and medially toward midline on the cricoarytenoid joint. This action is opposed by the action of the posterior cricoarytenoid muscles which originate on the posterior surface of cricoid cartilage and course upward and laterally to insert into the arytenoid cartilages. Their function is to abduct (open) the vocal folds by rotating the vocal processes away from the midline.



The interarytenoid muscle is the only single muscle in the larynx and connects the two arytenoid cartilages posteriorly. This muscle serves as an adductor of the arytenoid cartilages and functions to tightly close the posterior portion of the glottis (Titze, 1994). The interarytenoid cartilage's reflexive closure of the vocal cords contributes significantly to airway protection. It is believed to be the only intrinsic laryngeal muscle to have muscle spindles. Although controversial, recent findings suggest that spindles are sparse or absent in the thyroarytenoid, lateral cricoarytenoid, cricothyroid and posterior cricoarytenoid muscles (Brandon et al., 2003; Ludlow, 2005).

#### *Physiology of Vocal Pitch Control*

Pitch is the perceptual correlate of frequency which refers to the sound's physical structure (Patel & Balaban, 2001). The pitch produced by a person's voice is measured as the fundamental frequency (F0). Pitch control is an essential feature of voice production. Titze reflects that "...pitch is one of those dimensions that if correctly adjusted draws little attention to itself, but if incorrect it can reduce the acceptability and intelligibility of the human voice" (p. 214, 1994). For singers, accurate control of pitch and intonation patterns is of paramount importance.

The biomechanical control of singing follows "the principle of trade-off or motor equivalence between the activity of muscles" (Hurme, Laukkanen, & Sonninen, 1999, p. 333). A muscle produces movement by contraction that exerts force on levers such as cartilages and bones, never by extension. Muscle contraction causes either the shortening of a muscle between its origin and insertion points (isotonic contraction), or an increase

in the inner tension of the muscle without affecting the length (isometric contraction) (Hurme, et al., 1999). Pitch production is a combination of biomechanical activity (intrinsic and extrinsic laryngeal muscles) and aerodynamics (Larson, 1998).

Control of vocal pitch is accomplished through a balance of the mass and stiffness of the vocal folds and under the influence of the subglottic air pressure (Hollien & Hicks, 1979; Hurme & Sonninen, 1998; Jafari, Wong, Behbehani, & Kondraske, 1989; Titze, 1994). Vocal fold stiffness is affected by changes in length and tension of the vocal fold. Mass depends on tension and is also influenced by vocal fold length and subglottic pressure (Jafari et al., 1989). Mass is defined as, “the amount of material that is effectively in vibration” (Titze 1994, p. 193).

When the stiffness of the vocal folds is increased, pitch also increases. The longer, thinner, and tenser the vocal folds are, the higher the phonation frequency becomes (Sundberg, 1987). An increase in stiffness and tension of the vocal folds is achieved by contracting the cricothyroid muscle (agonist) while the posterior and lateral cricoarytenoid muscles stabilize the cricoarytenoid joints and adduct the vocal folds. This concerted effort stretches and tenses the thyroarytenoid (antagonist), and thus lengthens the vocal folds. The F<sub>0</sub> is regulated by the differential control of these muscles (Titze, 1994; Webster, 1999; Zemlin, 1999).

In addition to increasing the length of the thyroarytenoid muscles by contracting the cricothyroid, F<sub>0</sub> control is also dependent on the amplitude of vibration of the vocal folds. An increase in muscle tension and subglottic pressure will increase the amplitude of vibration. If the amplitude of vibration is large enough to involve the muscular layer of

the vocal fold, then isometric contraction of the thyroarytenoid occurs increasing the vibrating muscle mass causing an increase in F0 (Hurme et al., 1999; Titze, Lucchi, & Hirano, 1989). However, in general, the effect of an increase in subglottic pressure is not to increase pitch, but rather to increase the intensity (perceived loudness) in phonation (Sundberg, 1987). In order to maintain a constant F0, the activity of the cricothyroid muscle has an inverse relation with subglottic pressure; that is, to maintain a constant F0, the activity of the cricothyroid is reduced as the subglottic pressure is increased. Conversely, if the subglottic pressure is decreased, the activity of the cricothyroid muscle must be increased to prevent the F0 from lowering (Hurme et al., 1999; Sundberg, 1987). If the intrinsic laryngeal muscle contractions remain constant, then subglottic pressure and F0 are naturally balanced.

#### *Vocal Pitch Control – An Integration of Systems*

Physiologically, vocal pitch control requires the integration and coordination of numerous neurological systems including neuromuscular, sensorimotor, auditory, limbic, and executive systems. The ability to produce a precise pitch and rapid pitch changes for singing relies on the rigorous interaction and control of these motor and sensory systems; however, the manner by which these systems are controlled to execute precise pitch production is inadequately understood. In particular, researchers are exploring the interactions between the auditory system and the laryngeal system to achieve instant assessments and adjustments for precise pitch production.

*Phonatory monitoring systems.* Based on an analogy to striated muscles in the extremities, Kirchner and Wyke (1965) proposed that the striated muscles in the larynx have a similar proprioceptive reflex system that signals any deviation from the required condition for accurate pitch production, thereby reducing any performance error to a minimum. Previous electromyographic (EMG) studies documented activity in the cricothyroid and thyroarytenoid muscles *prior* to the production of sound, implicating voluntary *pre-phonatory* tuning (Buchthal, 1959 as reported in Kirchner & Wyke, 1965).

Subsequent research lead to the proposal that singers proceed through a sequence of three precisely controlled neuromuscular events: (1) pre-phonatory tuning, (2) intra-phonatory reflex modulation, and (3) acoustic monitoring (Wyke, 1967, 1974). Pre-phonatory tuning refers to the voluntary posturing of the laryngeal structures for production of an intended pitch (Watts, Murphy, & Barnes-Burroughs, 2003; Wyke, 1967). It is suggested that pre-phonatory tuning of the larynx is the major voluntary contribution to the control of the larynx during singing and speech. The tension pattern of the laryngeal musculature is based on previous experience; that is, neuromuscular memories. Because this event is voluntary, its precision may be enhanced with training.

Once expiratory air is set into motion through the larynx, it is dependent on laryngeal reflex-generating systems to monitor and modify mechanical action for accurate pitch production; that is, intra-phonatory reflex modulation (Wyke, 1974). These mechanoreceptors are located in the intrinsic laryngeal muscles, the subglottic muscles, and in the joints of the laryngeal cartilages (Adzaku & Wyke, 1979; Sundberg, 1987). Stretch receptors in the intrinsic muscles respond to changes in the length of the

thyroarytenoid and cricothyroid muscles and register relative movements of the laryngeal cartilages against each other (Jürgens, 2002). Mucosal mechanoreceptors in the laryngeal mucosa react to direct puffs of air that elicit reflexive laryngeal adduction (Bhabu, Poletto, Mann, Bielałowicz, & Ludlow, 2003). Pressure receptors respond to variations in subglottic air pressure; while joint receptors react to rotations or dislocations of joints that connect the laryngeal cartilages (Baken & Noback, 1971; Keene, 1961 as cited in Titze, 1994; Suzuki & Sasaki, 1977). Since these reflexes are controlling striated muscular activity, vocal training and practice similar to athletic training may increase reflex efficiency (Wyke, 1974). However, as the larynx ages, there is an inevitable reduction in reflex efficiency that is reflected in vocal instability even though the voluntary pre-phonatory tuning and voluntary respiratory muscle control may not be impaired (Wyke, 1974).

Once the vocalization is audible, Wyke (1974) proposed that acoustic monitoring may provide feedback for readjustments of the laryngeal musculature, but the significance of this ability is unclear. He argued that trained singers could sing accurately even when their own voices are masked and that the onset of hearing impairment in trained singers does not lead to immediate deterioration of voice. Although the exact relationship between acoustic monitoring and the laryngeal musculature was unable to be determined, Wyke (1974) concluded, “there is no doubt that acoustic automonitoring ... does permit a musically talented and well-trained singer to impose on the processes of neuro-muscular control of his laryngeal (and respiratory)

muscles a further degree of refinement that cannot be exercised by the untrained subject...” (p. 303).

*Auditory monitoring system.* Evolving from the work of Kirchner and Wyke (1965), researchers argue that the receptor system in the larynx is continuously influenced by the auditory system and that auditory feedback is crucial for controlling vocal F0 (Amir, Amir, & Kishon-Rabin, 2003; Leydon, Bauer, & Larson, 2003; Perry et al., 1999; Titze, 1994). Previous studies in the literature support a closed-loop auditory-governance system; that is, an auditory perceptual monitoring system (Davidson, 1959; Elman, 1981; Lane & Tranel, 1971; Perry et al., 1999). A closed-loop system is sensitive to errors and uses feedback to make adjustments whenever error-performance signals are detected. Closed-loop systems, also known as interactive systems, depend on positive or negative feedback to reach or maintain a targeted goal (Hood, 1998). In contrast, an open-loop system completes a task with no influence by external events (Hood, 1998).

In 1959, Davidson demonstrated that when auditory feedback is artificially delayed, speakers automatically decrease their speaking rate. Lane and Tranel (1971) confirmed that when individuals are subjected to background noise, vocal intensity immediately increases. This occurrence is known as the Lombard effect. Investigations on the effects of frequency-shifted auditory feedback on the production of vocal pitch have found that the fundamental frequency changes when the auditory feedback frequency is altered (Elman, 1981; Larson, 1998). Thus, a concurrence of evidence exists to support a closed-loop system, in which auditory monitoring provides moment-to-moment feedback for the regulation and control of vocal production.

Hearing-impaired individuals have a disruption of the auditory feedback loop and consequently, many have difficulty monitoring their vocal production. Inappropriate vocal register, intermittent and unpredictable pitch breaks, and pitch monotony have been reported (Martony, 1968). Jones and Munhall (2000) report that deterioration of suprasegmental features commonly occurs soon after the onset of hearing loss; however, accuracy of vowel and consonant production is maintained much longer. This implies that control of suprasegmental features of voice; that is, intensity, pitch, intonation patterns, stress, and rate of speech, may be more sensitive to auditory feedback than control of phoneme production. Jones and Munhall (2000) observed that the relationship between auditory perception and vocal production is non-linear.

Auditory monitoring may be artificially restored with a cochlear implant. The cochlear implant is a neuroprosthetic device that converts sound energy to electrical energy which then stimulates the auditory nerve with electrical impulses (Campisi et al., 2005). It is used to provide auditory sensation to individuals with severe to profound deafness. The device does not restore normal hearing; however, it provides auditory feedback cues in timing, intensity, and frequency (Campisi et al., 2005). There are numerous reports in the literature on vocal changes after cochlear implantation; however, many lack standard methodology and statistical data. Participant selection includes both pre-lingually and post-lingually deaf individuals and spans a wide age range. Moreover, these individuals have large inter-individual differences in fundamental frequency pre- and post-cochlear implantation (Langereis, Bosman, van Olphen, & Smoorenburg, 1998). Consequently, results are inconsistent and conflicting (Campisi et al., 2005; Higgins,

McCleary, Carney, & Schulte, 2003; Higgins, McCleary, Ide-Helvie, & Carney, 2005; Perrin, Berger-Vachon, Topouzkhonian, Truy, & Morgon, 1999; Schenk, Baumgartner, & Hamzavi, 2003; Seifert et al., 2002). In general, the results (a) support a non-linear relationship between auditory perception and vocal production (Campisi et al., 2005; Higgins, McCleary, Ide-Helvie, & Carney, 2005; Schenk, Baumgartner, & Hamzavi, 2003), and (b) indicate that development of acoustic speech parameters is better when auditory monitoring is artificially restored in pre-lingually deaf children before the age of 4 (Higgins et al., 2003; Seifert et al., 2002).

Leydon, Bauer, and Larson (2003) and others investigated the degree to which singers rely on auditory input to regulate characteristics of vibrato (Dejonckere, 1995; Jones & Munhall, 2000). Vocal vibrato is characterized by small periodic fluctuations in fundamental frequency and intensity in the singing voice. These pulses typically occur at a rate of 4–7 Hz with a fundamental frequency fluctuation of  $\pm 1$  semitone (Shipp & Izdebski, 1982). A semitone is “the smallest musical interval, but relatively a gross pitch difference” (Bentley, 1966, p. 36). The semitone corresponds to a frequency difference of approximately 6% in Western music. In other cultures, such as Arabic, Indian, and Chinese, the tuning interval is smaller (Tervaniemi & Brattico, 2004). A performer must be able to distinguish between much smaller pitch differences than a semitone to achieve “unison, good intonation, and artistry” (Bentley, 1966, p. 36). Thus, the semitone is further divided into cents; one semitone equals 100 cents. Vocal vibrato is a desirable characteristic for singers as it lends richness to a tone (Seashore, 1939) and helps to distinguish a singer’s voice from the orchestra (Sundberg, 1987).



Leydon and colleagues (2003) proposed that a closed loop negative feedback reflex within the auditory system contributes to sustaining fundamental frequency and intensity modulations in singers during vocal vibrato. They refer to this component of the auditory system as the pitch-shift reflex (PSR). Like a stretch reflex, the PSR is a bi-directional closed loop negative feedback reflex that is triggered in response to discrepancies between the intended and perceived pitch with a latency of approximately 100 ms. Compensatory reflexive responses lead to oscillations in pitch approximately every 200 ms resulting in  $\sim 5$  Hz modulation of the fundamental frequency; thus, the PSR contributes to the production of vocal vibrato (Leydon et al., 2003). PSRs were experimentally elicited from nonsingers by introducing sinusoidal pitch-modulations in auditory feedback at discrete integer frequencies from 1 to 10 Hz with  $\pm 25$  cents amplitude modulation, resulting in a peak-to-peak pitch modulation of 50 cents (0.5 semitones). Modulated auditory feedback induced pitch fluctuations consistent with vocal vibrato with peak energy gains between 4-7 Hz with an average of 5 Hz in the F0 of all subjects, demonstrating the existence of a pitch-shift reflex within the auditory-vocal system.

*Kinesthetic feedback system.* It is well-known that those who have lost their hearing after speech and language acquisition rely on proprioceptive memory and knowledge of previous experience to compute the motor-sequence for the desired vocal production in the absence of auditory feedback (Amir et al., 2003, Waldstein, 1990). This implies not only an auditory loop for vocal production, but a complex and dynamic internal proprioceptive monitoring system.

For professional vocal musicians, auditory feedback alone cannot explain their ability to accurately control pitch when they cannot hear their own voices, such as in choir singing or with orchestral accompaniment (DiCarlo, 1994; Mürbe, Pabst, Hofman, & Sundberg, 2002). This occurrence provides support for an additional feedback system such as an internal kinesthetic model (DiCarlo, 1994; Jones & Munhall, 2000; Mürbe, Pabst, Hofman, & Sundberg, 2004; Mürbe et al., 2002; Murry, 1990; Ward & Burns, 1978).

For speech production, auditory feedback may be the primary control for variation in pitch that constitutes intonation patterns. For singers, auditory feedback has the same function, but by its very nature, real-time auditory feedback does not provide a reliable means for controlling the precision of vocal characteristics for singing. Pitch extraction is fundamental in the perception of speech intonation, but it is crucial to the processing of music.

Ward and Burns (1978) demonstrated that trained singers rely more on kinesthetic feedback for vocal pitch control, while untrained singers rely more on auditory feedback. Trained and untrained singers sang rising and falling scales with and without a masking noise. There was no significant difference between the singers' and nonsingers' control of pitch as long as the subjects could hear the sound of their own voices. When the auditory feedback was masked, all subjects sang out of tune; however, the nonsingers were significantly less accurate than the trained singers. This implies that vocal training may enhance proprioceptive memory and/or sharpen proprioceptive reflexes of laryngeal joints and muscles for superior pitch control.

Murry (1990) compared laryngeal accuracy of nonsingers and singers and the effect of repeated trials when matching pitch to a pre-set tone. Results revealed the trained singers to be more accurate in both of the pitch matching tasks. The performance of the nonsingers was highly variable and less accurate. Murry concluded that singers are able to adjust the physiological parameters of F0 control (vocal fold mass, stiffness, tension and subglottic pressure) more rapidly and precisely than the nonsingers.

DiCarlo (1994) describes 'internal voice sensitivities' as a proprioceptive feedback system used by professional singers. She writes that internal voice sensitivities rely on proprioceptive feedback resulting from the transmission of laryngeal vibrations to the skeletal framework of the thorax and craniofacial structure by means of the extrinsic laryngeal muscles. This description agrees with Wyke (1974) who proposed that the kinesthetic feedback of the intrinsic laryngeal muscle system may be supplemented by discharges from peripheral mechanoreceptors in the thorax, the abdominal wall, and the vocal tract. DiCarlo describes a 'reflex conditioning technique' which allows students over a learning period between two and six years to develop the kinesthetic proprioceptive memory required for the control of voice. She states, "The teacher must guide the students solely by ear, teaching them to associate an auditory image with an internal sensation" (p. 84). For the professional singer, internal voice sensitivities may be a means of control more reliable than auditory feedback alone.

Similar to DiCarlo's description of internal sensitivities, Jones and Munhall (2000) explored the use of acoustic feedback in calibrating an internal feedback system for the control of speaking pitch. Jones and Munhall state that although internal models

might reduce the need for closed loop control, auditory feedback is necessary for the acquisition and maintenance of internal models. The investigators tested the extent to which an individual's habitual speaking pitch is controlled by an internal F0 target. Subjects produced the vowel /a/ under a control condition (normal F0 feedback) and two experimental feedback conditions: (1) F0 shifted up and (2) F0 shifted down. Results indicated two related effects of altered feedback on F0. During the trials of shifted pitch (either up or down), subjects compensated for the pitch shifts in an apparent attempt to maintain habitual pitch; that is, if the pitch was shifted up, subjects lowered their pitch relative to a control condition and conversely, if the pitch was shifted down, subjects raised their pitch relative to a control condition. The subjects also showed evidence of sensorimotor adaptation; that is, after normal feedback was returned for the last 10 test trials, the mean pitch of subjects for the shift-up condition increased significantly to maintain the test stimuli frequency; conversely, the shift-down condition showed a significant decrease when feedback was returned. The results suggest that F0 may be controlled using auditory feedback and an internal pitch representation.

In similar studies of pitch-shifted auditory feedback, Hain and colleagues (2000) noted two responses of the laryngeal mechanism to altered pitch feedback. The first is an automatic response that corrects for small unplanned changes in pitch. The second reaction is a slower and voluntary response that modifies pitch to meet a target or reference pitch, such as in speaking or singing. The latency of the first response is approximately 100-150 ms, while the second response varies between 250-600 ms (Hain et al., 2000; Larson, 1998). It has been suggested that the initial automatic reaction may

be part of a laryngeal-specific reflex path (Sapir, McClean, & Larson, 1983) or an automatic function of the audio-vocal reflex system (Hain et al., 2000) or part of a dual auditory-mediated feedback system that works in parallel and is controlled by the cerebellum (automatic reaction) and the cortex (voluntary response) (Kawahara & Williams, 1996). The effect of music training on either of these responses is unknown.

Mürbe et al. (2002) conducted a three-year longitudinal study investigating the significance of auditory and kinesthetic feedback for pitch control in vocal students and the effects of training on pitch control. At the beginning of their professional singing education, the students sang an ascending and descending triad pattern with and without masking noise. The effect on pitch control was investigated in four tasks: (1) legato slow, (2) staccato slow, (3) legato fast, and (4) staccato fast. Mürbe et al. (2002) noted a significant difference between unmasked and masked regardless of the technique and tempo. The singers' intonation accuracy was reduced in the absence of auditory feedback and the singers relied on kinesthetic feedback to perform the tasks with masking.

The same students were re-examined three years later (Mürbe et al., 2004). The same measurements, procedures, and equipment were used. The contribution of the auditory feedback to pitch control was not significantly different after education; that is, intonation accuracy did not significantly improve after three years of vocal training. However, a significant improvement of pitch accuracy was found for all of the slow singing conditions. Mürbe and colleagues conclude that although education did not improve auditory feedback skills, kinesthetic feedback improved for the slow singing tasks. They report that this improvement "indicates that the accuracy of the absolute

neuromuscular memory of pitch increased after education” (p. 241). The authors speculate that three years of professional training may not be enough time to improve kinesthetic pitch control in demanding vocal tasks such as fast legato or fast staccato. As DiCarlo (1994) reported, it may take 2 to 6 years for kinesthetic feedback to develop for accurate pitch control.

*Summary.* Control of pitch is a complex biomechanical and aerodynamic system. It appears that researchers agree that the ability to rapidly produce a precise pitch is essential for the professional vocal musician. Evidence indicates that accurate pitch control depends on auditory perceptual monitoring, proprioceptive feedback of the laryngeal system and phonatory reflex systems (Amir et al., 2003; Jones & Munhall, 2000; Kirchner & Wyke, 1965; Mürbe et al., 2004; Murry, 1990; Titze, 1994; Ward & Burns, 1978; Wyke, 1974). Trained singers consistently control fundamental frequency and maintain targeted pitch better than untrained singers. The evidence implies that professional vocal training enhances kinesthetic feedback of the laryngeal system, improves neuromuscular memory for pitch control and increases reflex efficiency. Research suggests that neuroanatomical connections may exist between the auditory and vocal systems to regulate vocal pitch (Hain et al., 2000); however, the exact relationship between the laryngeal and auditory systems is unknown.

### *Development of Pitch Control*

*Sequence of development.* Welch (1994) described the activity of singing as “a complex web of interacting factors embracing perception, cognition, physical

development, maturation, society, culture, history, and intentionality” (p. 3). In the literature of music research, investigators have suggested a sequence for the development of singing accuracy in children (Bentley, 1966; Boardman, 1964; Davidson, McKernon, & Gardner, 1981; Goetze, Cooper, & Brown, 1990).

There is general agreement that infants pass through a ‘babbling song’ phase after playing with groups of musical pitches and phrases in a repetitive fashion (Davidson et al., 1981; Ries, 1987; Welch, 1994). Under the age of 12 months, Ries (1987) found that infants’ singing is characterized by a restricted pitch range focused around a central tone, but with no evidence of rhythm. As children mature from toddlers to preschoolers, a sense of rhythm develops first. Children are observed to move their bodies with the pulse of the music. Rhythmic memory is established first and is more highly developed at all ages of childhood than pitch memory (Bentley, 1966). Following the establishment of rhythm, is the addition of melody which is defined by Bentley as a “succession of pitch sounds within a rhythmic framework” (p. 26, 1966). When children recognize a previously heard tune, melodic memory is established. By age 5, children normally gain mastery of words and rhythm of the song before the pitch components (Welch, 1994). Pitch discrimination for the specific perception of melody, followed by the ability to analyze harmony (chords), are the last skills to develop.

In 1966, Bentley published *Musical Abilities in Children* based on his study of 2000 school children between the ages of 7 and 14 from state primary and secondary schools. His conclusions are still quoted in contemporary literature (Davidson et al., 1981; Goetze et al., 1990; Phillips & Aitchison, 1997; Yarbrough et al., 1991). Bentley

found no significant gender differences in musical ability, nor did he find a strong correlation between intelligence and musical abilities. Auditory pitch discrimination appears to be more accurate on sounds near the middle of the vocal range than on sounds at the extremes of the vocal range. By age 7, most children can accurately discriminate pitch differences of a quarter tone (~ 12 Hz difference). By age 12, most can discriminate between one-eighth tones (~ 6 Hz). Although yearly increases are small, pitch discrimination and singing accuracy improve with chronological age throughout childhood.

*Socio-cultural influence.* Singing is an ancient and complex form of human behavior richly influenced by one's cultural familiarity, aesthetic preferences, and artistic intent. Deutsch (1992) reports that musical perception is linked to the patterning of speech and both are developmental in nature and related to membership in particular socio-cultural groups. Observations of children singing provide evidence of patterning, repetition, and transformation, implying a sense of organization that is reflective of familiarity, and an unconscious knowledge of rules significant to the children's particular school and home environments (Welch, 1994). Thus, singing not only follows a developmental pattern, but is strongly influenced by social norms and culture.

#### *Potential Factors Related to Vocal Pitch Control*

The ability to sing with accurate pitch control is the most basic skill of singing and is considered the feature that distinguishes singers from nonsingers (Murry, 1990; Titze, 1994; Watts, Barnes-Burroughs, Adrianopoulos, & Carr, 2003). Much of the



existing research has focused on children who cannot match pitch (Apfelstadt, 1984; Geringer, 1983; Goetze et al., 1990; Green, 1990; Howle, 1992; Joyner 1969; Moore, 1994; Pedersen & Pedersen, 1970; Porter, 1977; Yarbrough et al., 1991). The ability to vocally match a pitch or sing a melody varies among individuals and the prospect that some children may not learn to sing accurately is a challenge for music educators (Yarbrough et al., 1991).

There are those within our society who have exceptional abilities to sing with breathtaking resonance and vocal precision, while other individuals are unable to discriminate between musical tones or to vocally match a pitch. A complete explanation and clarification of such inter-individual variability is lacking.

*Potential functional variables.* Research on children's vocal pitch matching abilities has focused on training models, characteristics of the singing task, singing with text, singing environment (group versus individual), accompaniment, age, gender, and other contributing factors (Moore, 1994). After reviewing 25 years of research literature on the singing abilities of elementary children, Goetze, Cooper, and Brown (1990) summarized the factors affecting children's success as follows:

1. As children grow older, singing accuracy improves.
2. The relationship between pitch discrimination ability and vocal production accuracy remains unclear.
3. Perhaps due to a child's natural tendency to imitate, the presence and quality of the model pitch can inhibit or improve a child's vocal accuracy and vocal range.

4. Simple melodic material and descending as opposed to ascending intervals appear to be most conducive to vocal accuracy.
5. Evidence was inconclusive to indicate whether children sing more accurately with or without text.
6. Some children may sing more accurately alone than in a chorus. It is speculated that children may not hear themselves in a group; therefore, auditory feedback is not sufficient for accurate singing.
7. Children who receive feedback and reinforcement following their singing performance improve significantly.

In general, positive personal characteristics such as motivation, concentration, and musical interest influence singing abilities. In addition, environmental factors including exposure to music within the home environment, education, and training contribute to singing accuracy (Howle, 1992).

*Potential physical variables.* The physical act of singing requires muscular action and fine sensorimotor control and coordination. For the performer, it is an athletic event; an aerobic exercise focused on the respiratory system and the larynx in particular. As in any athletic event, there are those who are more skilled or talented than others.

Joyner (1969) examined children who were characterized as *monotone* to gain insight into the problem and to provide suggestions for remedial training. A *true monotone* is described by Joyner as one who “consistently fails to reproduce the tonal configuration of a melody in a recognizable manner” (p. 115). Joyner proposed that those characterized as monotones are ‘tone-dumb’ rather than ‘tone-deaf.’ He suggested

that the laryngeal mechanism lacks flexibility in those who are monotone and is physically unable to adjust the length and tension for accurate pitch production. Consequently, kinesthetic feedback is diminished and accurate tonal memories do not develop leading to deficiencies in pitch discrimination. Joyner (1969) concluded that in order to produce accurate pitch, a person must be able to do three things: (a) tell one pitch from another; that is, discriminate pitch, (b) recall successions of pitches organized into melodic patterns; in other words, remember pitch, and (c) have a vocal instrument physically capable of reproducing or matching an immediate pitch.

After an extensive review of music literature, Goetz and colleagues (1990) came to very similar conclusions. They found the following skills necessary for singing talent: (a) the ability to discriminate between pitches, (b) the ability to vocalize over a wide range of pitches, (c) the ability to monitor vocal pitch, and (d) the desire to sing.

In a more recent quest to identify factors associated with natural singing talent, Watts, Barnes-Burroughs, Adrianopoulos, and Carr (2003) conducted a national survey among a homogenous group of professional singing pedagogues. Questions addressed three areas: (a) perception of singing talent, (b) physiological variables that distinguish between individuals with singing talent and those without, and (c) factors affecting untrained or natural singing talent. Pitch intonation or 'singing in tune' was identified as the most relevant factor for the perception of singing talent followed by timbre or 'richness of the tone' and stylistic appropriateness. Moreover, pitch-matching ability and pitch discrimination were ranked as the top two physiological factors having the most

influence on natural talent. Survey data predicted that natural singing talent is a product of genetics and environment rather than practice.

*Summary.* In the development of pitch control, researchers agree that potential factors for singing accuracy are a combination of innate characteristics and a stimulating environment. Vocal pitch control and auditory pitch discrimination are consistently identified as factors for singing accuracy. Although many researchers acknowledge a relationship between these two skills, the strength and nature of this relationship is unclear.

#### *Relationship between Pitch Discrimination and Pitch Control*

The role of auditory governance on vocal production is evident from early infancy. By the end of the first year of life, infants with normal hearing produce complex vocal patterns that match the vocal language patterns in their environment (Boone, 1996). For those children who have a severe hearing impairment, voice onset time and control of fundamental frequency appear to be the most sensitive to the effects of diminished auditory feedback (Higgins et al., 2005).

Intuitively, it seems that vocal production and auditory input are directly related. Vocal pitch production is unequivocally affected by acoustic cues and may be manipulated by alterations in auditory F0 feedback (Campisi et al., 2005; Elman, 1981; Haines et al., 2000; Higgins et al., 2003; Higgins et al., 2005; Jones & Munhall, 2000; Larson, 1998; Leydon, et al., 2003; Schenk, Baumgartner, & Hamzavi, 2003; Seifert et al., 2002; Ward & Burns, 1978). The results of these studies imply that the auditory

system plays a substantial role in vocal production; however, in these investigations, the perceptual dimensions were manipulated. Thus, the implications are not directly applicable to the role of auditory perception in normal vocal pitch production. Specifically, auditory frequency discrimination and vocal pitch production reflect abilities to accurately integrate sensory perception with motor planning and execution. Although a relationship is acknowledged between vocal pitch accuracy and auditory pitch discrimination, research is sparse and the nature of this relationship remains uncertain.

#### *Auditory Discrimination and Vocal Pitch Control in Children*

In the literature of music research, previous research has focused predominantly on children. Several studies have found significant correlations between auditory pitch discrimination and singing accuracy among school-aged children, while others have not.

The earliest investigation of the relationship between auditory abilities and vocal production was conducted by Seashore in 1919 (as cited in Amir et al., 2003). He asked a group of singing teachers to evaluate their students' singing accuracy. This was done subjectively with no reported reliability. Seashore then tested the students' auditory discrimination using a series of tuning forks. He concluded that there is "a slight tendency toward relationship" (1919, p. 58). In an early descriptive study by Gould (1969), elementary school teachers of music were surveyed and asked to list the reasons for inaccurate singing. Inattention to pitch, inability to hear pitch changes, and inability to coordinate the vocal mechanism were among the reasons given.

Porter (1977) investigated the training effects on auditory pitch discrimination and vocal pitch matching in randomized groups of elementary children. He questioned whether inaccurate singing results from “inadequate vocal control...or from an inability to discriminate stimuli accurately” (p. 68). Porter found no evidence demonstrating that inaccurate singing results from inaccurate auditory pitch discrimination.

Geringer (1983) examined the relationship between auditory pitch discrimination and vocal pitch-matching abilities among randomly selected preschoolers and fourth-grade children. The older children performed significantly better than the preschoolers on the vocal pitch matching tasks. No correlation was found between auditory pitch discrimination and vocal pitch matching abilities. Geringer proposed that a degree of auditory pitch discrimination may be a pre-requisite skill to vocal pitch matching. He concluded, “It is possible that pitch discrimination and pitch matching are simply two independent abilities, or that maturation and training are necessary to develop an interrelationship” (p. 98).

More recently, Philips and Aitchison (1997) investigated the relationship of singing accuracy to auditory pitch discrimination and tonal aptitude among third-grade students. Vocal pitch-matching skills were evaluated by the investigators and each child was labeled as ‘accurate’ or ‘inaccurate.’ Auditory pitch discrimination was tested as the ability to judge the difference between higher and lower tones. Tonal aptitude was the ability to judge two musical patterns as ‘same’ or ‘different.’ Responses on the auditory pitch discrimination task did not differ significantly between the accurate and inaccurate singers; however, on the tonal aptitude task, the accurate singers performed significantly

better. Philips and Aitchison suggested that tonal aptitude may be more related to singing accuracy than auditory pitch discrimination and concluded that the relationship between auditory and vocal skills is “uncertain” and “may be the case of a lagging development in both aural and vocal skills” (p. 19).

In contrast to the previous studies, investigations by Pedersen and Pedersen (1970), Zwissler (1972), Goetze et al. (1990), and Yarbrough et al. (1991) have found a positive relationship between vocal pitch-matching abilities and auditory pitch discrimination. As in the studies reviewed above, the subjects were elementary children and the procedures and test measures varied.

Pedersen and Pedersen (1970) studied the relationship between auditory pitch discrimination and vocal pitch production of 6<sup>th</sup> graders using a rating system for pitch accuracy. They agree with Joyner (1969) that those who cannot vocally match pitch are deficient in auditory pitch discrimination. They found “a fairly strong relationship between pitch discrimination and vocal production” (p. 271).

Zwissler (1972, as cited in Phillips & Aitchison, 1997) examined the difference in the auditory pitch discrimination skills of 100 first graders. The children’s vocal pitch accuracy for singing was evaluated and the children were divided into two groups, accurate singers (n = 50) and inaccurate singers (n = 50). A test of auditory pitch discrimination was designed that asked the children to choose if the second tone of a pair was higher or lower than the first. The pitches were presented in the child’s vocal range, one octave higher, and one octave lower. Results indicated that the first graders who were judged to be accurate singers performed significantly better on the auditory pitch

discrimination task than the inaccurate singers. Thus, these data support a positive relationship between auditory pitch discrimination abilities and accurate singing. Zwissler also noted that subjects identified pitch differences more accurately when the stimuli were within their singing range rather than an octave above or below.

Yarbrough et al. (1991) examined the effects of different vocal models on vocal pitch-matching accuracy and the effects of different response modes including hand signals and pitch syllables. Children in grades K-3 and 7-8 were selected on the basis of their failure to accurately match pitch ( $n = 163$ ). They were randomly assigned to one of three different response modes. In general, results demonstrated the following: (1) no significant differences among correct responses due to response mode (e.g. hand signals, solfege syllables [do, re, mi], or la-la-la syllable), (2) a significant difference in response to female versus male vocal model suggesting an effect of timbre, and (3) significantly better vocal pitch-matching accuracy for eighth grade students versus kindergarteners, suggesting a maturational effect.

*Summary.* The relationship between auditory pitch discrimination and vocal pitch control as factors of accurate singing in children remains controversial. Researchers have proposed that vocal pitch control and auditory pitch discrimination may be independent abilities between which a relationship develops with training or developmental maturation of the child (Geringer, 1983; Goetze et al., 1990; Yarbrough et al., 1991). Goetze et al. (1990) concluded "...that (a) children who sing accurately are likely to demonstrate accurate pitch discrimination, and (b) children who demonstrate inaccurate pitch discrimination are likely to sing inaccurately" (p. 30). Goetze and colleagues



express concern over those children who have accurate auditory pitch discrimination skills, but do not control vocal pitch accurately for singing. This inconsistency implies that accurate singing may have a positive relationship with accurate auditory pitch discrimination skills; however, this relationship is not reciprocal. It is possible that children with accurate auditory discrimination but inaccurate vocal skills have undeveloped laryngeal control. In addition, there may be poor kinesthetic feedback from the larynx or delayed internal auditory monitoring.

#### *Auditory Discrimination and Vocal Pitch Control in Adults*

Although auditory pitch discrimination (perception) and vocal pitch control (production) have been identified as related abilities and essential skills for vocal musicians, few studies have investigated and compared these variables in formally trained adult singers. For whatever reasons, research has focused predominantly on children or formally trained instrumental musicians, not vocal musicians. Two earlier studies of professional adult singers were reviewed previously in this chapter (Murry, 1990; Ward & Burns, 1978). Ward and Burns (1978) demonstrated that under masking conditions trained singers rely more on kinesthetic feedback rather than auditory input for vocal pitch control compared to untrained singers, implying that vocal training enhances proprioceptive memory. Murry (1990) suggested that singers adjust the physiological parameters for pitch production faster and more accurately than nonsingers.

A more contemporary study examined the relationship of auditory pitch discrimination and vocal pitch matching abilities in adult professional singers compared

to adult subjects who express natural singing talent. Watts, Murphy, and Barnes-Burroughs (2003) examined the vocal pitch-matching abilities of fifteen female subjects divided equally into three groups: trained singers, untrained subjects with expressed singing talent, and untrained subjects with nontalented singing voices. A talented singing voice is defined as “a special natural ability...where the sounds vary over a wide range of frequencies and are in tune with each other, or where such sounds are melodious” (Watts et al., 2003, p. 185). The placement into a particular group was determined by professional voice teachers.

The purpose of this study was to assess the abilities of these three groups to control fundamental frequency (F0) during a pitch-matching task using targeted pure tones, and to investigate whether these abilities were affected differentially when internal auditory feedback was and was not available. It was also questioned whether trained singers are able to pre-tune (i.e., pre-phonatory set) their vocal mechanism to more accurately match pitch when compared to those without training. As expected, the untrained singers with singing talent and the trained singers demonstrated significantly greater pitch-matching accuracy on all measured conditions compared to the nontalented singers.

Watts and colleagues (2003) conclude that the ability to accurately match and produce vocal pitch is a prerequisite for singing talent and requires accurate perception of pitch and coordination of that perception with motor planning, programming, and execution. Moreover, the ability to accurately position the laryngeal structures for production of an intended frequency may be another variable related to singing talent.

While the separation of untrained talented singers from the control group is unique to address issues of ‘natural talent’, the authors caution that results should not be over-generalized since sample size was small and method of voice training was unknown. In addition, placement into a particular group was based on subjective judgment.

Amir, Amir, and Kishon-Rabin (2003) studied the relationship between auditory perception and vocal production between professional musicians and nonmusicians. The musicians played musical instruments (an average of 13 years) and none of the subjects had previous vocal or singing training. In a previous study (Kishon-Rabin, Amir, Vexler, & Zaltz, 2001), these authors compared the frequency discrimination thresholds, also referred to as the difference limen for frequency (DLF), between the same professional musicians and nonmusicians. Difference limen for frequency (DLF) is the smallest detectable frequency difference. They concluded that the professional musicians had superior auditory skills. Amir et al. (2003) questioned whether individuals with superior auditory abilities would also demonstrate ‘better-than-normal’ performance on vocal production accuracy.

Results indicated that the musician group produced the tones approximately three times more accurately than the nonmusician group. A significant correlation ( $r = 0.67$ ,  $p < 0.001$ ) was found between auditory discrimination and vocal production. The analysis of data suggested that 43% of the variance of the production data can be explained by auditory perception. When the data was converted to semitones, the musicians had average production errors no more than  $\frac{1}{2}$  of a semitone for each frequency. In contrast, the nonmusicians had mean errors of approximately 1.3 semitones. On a musical scale,

inaccuracies greater than one semitone are perceived as a melody change. Thus,  $\pm 0.5$  semitone may be viewed by a musician as crossing a categorical boundary and creating an error of music syntax. The authors concluded that individuals with superior frequency discrimination abilities were able to vocally imitate pure tones with greater accuracy. However, frequency discrimination thresholds could not be predicted from vocal production accuracy. The authors speculate that music training enhances a musician's auditory perception of acoustic parameters in vocal productions that are otherwise ignored by nonmusicians.

### *Summary*

Despite variable strategies and limitations of past research, investigators and educators consistently identify auditory pitch discrimination (perception) and vocal pitch control (production) as related abilities and fundamental skills for vocal musicians. It is essential that singers accurately integrate sensory perception with neuromotor planning to precisely execute vocal production. Intuitively, it seems these two abilities are directly related; however, there is a consensus in the literature suggesting the relationship between auditory perception and vocal production may be indirect and complex. Reliable evidence supports the existence of a kinesthetic feedback loop between the auditory and laryngeal systems for accurate voice production. Longitudinal data indicate that professional vocal training enhances this proprioceptive reflex system and alludes to neuromuscular pitch memory. The specific interactions and relationships among these neurophysiological processes have yet to be defined.

## Chapter Three

### Methods and Procedures

#### *Introduction*

Neuroanatomical differences between musicians and nonmusicians support the premise that intense music training and skill acquisition effect functional and structural change in the auditory system (Gaser & Schlaug, 2003; Pantev, Engelien, Candia, & Elbert, 2001; Pascual- Leone, 2001; Schlaug, 2001; Schön, Magne, & Besson, 2004; Zatorre, 2003). Current research data from electroencephalography (EEG) and magnetoencephalography (MEG) suggest that music training influences pitch processing by refining the auditory neural frequency-processing network (Koelsch, Schröger, & Tervaniemi, 1999; Pantev et al., 2001; Schön et al., 2004; Shahin, Bosnyak, Trainor, & Roberts, 2003; Tervaniemi, 1993; Trainor, Shahin, & Roberts, 2003). Following intense music training, auditory neural responses of instrumental musicians have shorter latencies (faster responses) and larger amplitudes (stronger responses) for pitch changes than nonmusicians (Koelsch, Schmidt, & Kansok, 2002; Shahin et al., 2003).

Psychoacoustic studies of auditory frequency discrimination indicate that formally trained instrumental musicians have superior auditory pitch discrimination skills (Kishon-Rabin, Amir, Vexler, & Zaltz, 2001; Spiegel & Watson, 1984). Auditory pitch discrimination and the ability to sing with accurate pitch control are regarded by music

educators as fundamental abilities for musical talent and essential skills of a successful singer (Bentley, 1966; Geringer, 1983; Murry, 1990; Seashore, 1919; Titze, 1994; Watts, Barnes-Burroughs, Adrianopoulos, & Carr, 2003). Accurate vocal production of targeted pitch is a complex biomechanical system. This skill depends on precise neuromuscular control of the larynx, accurate auditory pitch discrimination, and continuous proprioceptive feedback (Kirchner & Wyke, 1965; Wyke, 1974). Longitudinal research of vocalists in training indicates that accuracy for the absolute neuromuscular memory of pitch increases with music education (Mürbe, Pabst, Hofman, & Sundberg, 2003, 2004).

Auditory pitch discrimination and vocal pitch accuracy are two identified processes that demonstrate the integration of sensory perception with motor planning for the execution of vocal production. An accumulation of evidence acknowledges a relationship between these two skills; however, there is an inadequate understanding of the nature of this relationship particularly in formally trained vocal musicians (Amir, Amir, & Kishon-Rabin, 2003; Geringer, 1983; Goetze, Cooper, & Brown, 1990; Watts, Murphy, & Barnes-Burroughs, 2003; Yarbrough, Green, Benson, & Bowers, 1991). Previous psychoacoustic and neurophysiological research has focused on formally trained instrumental musicians rather than formally trained vocal musicians (Münste et al., 2003; Schlaug, 2001; Zatorre, 2003). Moreover, there is a prevalence of evidence to support training-induced neural changes of the auditory system in instrumentally trained musicians; however, auditory neuroplasticity in formally trained vocal musicians has been studied to a much lesser extent.

### *Purpose of the Study*

This study is a beginning step of inquiry into the effects of long-term professional music training on the auditory neural function of vocal musicians. Reliable evidence suggests that formally trained instrumental musicians experience neural changes in the auditory system following skill acquisition and sensory stimulation. Vocal musicians undergo similar intensive training; however, it is unknown whether this class of musicians also experiences neural changes of the auditory system. Prior EEG data indicates that formally trained instrumental musicians compared to nonmusicians have superior pre-attentive auditory discrimination; however, it is unknown whether this superior ability is also present in vocal musicians.

Relationships among the following variables for perception and production of musical stimuli were tested: vocal pitch matching accuracy, active auditory pitch discrimination, and pre-attentive auditory pitch discrimination. In general, this study sought to determine relationships among these variables between the untrained population and formally trained musicians. Moreover, it was questioned whether differences exist between subclasses of formally trained musicians, such as vocal musicians and instrumental musicians. Specifically, the purpose of this study was to assess, compare and correlate three identified variables of perception and production that contribute to the performance of the singing voice.

## *Research Questions*

### *Hypotheses*

Based on a review of previous investigations and on theories of neural plasticity, it was hypothesized that an association exists between perception and production abilities for musical stimuli and that this association would be stronger for the formally trained musicians and strongest for the formally trained vocal musicians. Moreover, due to the requirements for precise pitch control, such as auditory perceptual monitoring and proprioceptive feedback of the laryngeal system, it was predicted that those with formal vocal training would perform best on the perception and performance tasks chosen for this study. It was also hypothesized that intensive music training affects pre-attentive neurophysiological function. Consequently, the formally trained musicians were predicted to respond to small deviances in pitch with a faster and stronger neurological response than the nonmusicians on a pre-attentive auditory discrimination task measured by electroencephalography (EEG).

### *Questions*

The relationship between perception and production abilities for musical stimuli between formally trained musicians and musically untrained subjects was examined. Specifically, relationships between vocal pitch matching accuracy, active auditory pitch discrimination, and pre-attentive auditory pitch discrimination among formally trained vocal musicians, formally trained instrumental musicians and a matched control group of



musically untrained participants was investigated. This study was designed to answer the following questions:

1. Is there a difference in vocal pitch matching accuracy between musicians and nonmusician control subjects and furthermore, is there a difference between the instrumental and vocal musician groups?
2. Is there a difference in active auditory frequency discrimination ability between musicians and the control subjects? Moreover, is there a difference between the instrumental and vocal musician groups?
3. Is there a difference in pre-attentive auditory neural responses to pitch change (i.e., pre-attentive auditory pitch discrimination for musical stimuli) between musicians and the control subjects and particularly between the instrumental and vocal musician groups?
4. Is there an overall correlation between perception and production variables across the groups?
5. Is there a correlation between perception and production variables within each subject group (i.e., controls, instrumental musicians, and vocal musicians)?

#### *Null Hypotheses*

Based on the above research questions, the following were the null hypotheses:

1. There is no difference of vocal pitch matching accuracy between musicians and control subjects, or between the two sub-classes of musicians (i.e., instrumentalists and vocalists).

2. There is no difference of auditory discrimination ability between musicians and control subjects, or between the two sub-classes of musicians (i.e., instrumentalists and vocalists).
3. There is no difference of the pre-attentive auditory neural response (i.e., pre-attentive auditory pitch discrimination) for musical stimuli between musicians and control subjects or between the instrumental and vocal musician groups.
4. There is no correlation of perception and production abilities among the groups.
5. There is no correlation of perception and production abilities within each subject group (i.e., controls, instrumental musicians, and vocal musicians).

### *Research Design*

A quantitative research design following a causal-comparative (ex post facto) format was proposed. Three performance measures were analyzed: two psychoacoustic and one neurophysiological. The two psychoacoustic tasks were designed to assess subjects' vocal pitch matching accuracy and active auditory pitch discrimination ability. The neurophysiological task was used to measure subjects' pre-attentive auditory pitch discrimination ability by means of electroencephalography (EEG). The results of these three tasks were assessed and compared within and between formally trained vocal musicians, formally trained instrumental musicians, and a matched control group of musically untrained subjects.

Administration of the neurophysiological task followed the psychoacoustic measures by approximately one month to avoid a short-term memory effect of stimuli on

the participants' responses. Presentation of the two psychoacoustic tasks was counterbalanced to control for a possible priming effect. Within each task, the order of stimulus conditions was randomized to prevent an order effect.

### *Variables*

*Independent variable.* There was one independent variable, *subject group*, which was subdivided into formally trained vocal musicians, formally trained instrumental musicians, and a matched control group of subjects with less than 12 months of formal music training. This variable is considered an attribute or an assigned variable since it was not actively manipulated.

*Dependent variables.* There were three dependent variables measured: vocal pitch matching accuracy, active auditory pitch discrimination, and pre-attentive auditory pitch discrimination. These dependent variables were measured and reported respectively as: (1) *relative* accuracy for vocal pitch production in percentage (*relPPA%*), (2) *relative* difference limen for frequency in percentage (*relDLF%*), and (3) latency and amplitude of the mismatch negativity (MMN) and other auditory evoked potentials (AEPs) associated with auditory discrimination and perception. An operational definition for each dependent variable is described in the section corresponding to the task.

## *Procedures*

### *Participant Selection*

Sixty-one females participated in this study; that is, 19 formally trained vocal musicians, 21 formally trained instrumental musicians, and 21 nonmusicians. Three groups of subjects were selected to participate in this study using a nonrandom purposive sampling. All participant volunteers were asked to initially complete a Participant Screening Questionnaire to determine if the volunteer met the qualifications for this study (Appendix A).

*Exclusion criteria.* To control for extraneous variables that may affect the larynx and therefore influence vocal quality and/or pitch production, exclusionary prerequisites for all participants included: (a) no history of laryngeal pathology or neurological impairments, (b) no history of drug or alcohol abuse, (c) no history of habitual cigarette smoking, (d) no current allergies or respiratory illnesses, and (e) no voice problems at time of testing. To control for factors that may influence auditory pitch perception, exclusionary criteria also included: (f) no hearing impairment, (g) no previous participation in psychoacoustic studies, and (h) no history of absolute pitch ability.

Previous participation in psychoacoustic experiments has been noted as a possible confounding variable (Ari-Evan Roth, Amir, Alaluf, Buchsenspanner, & Kishon-Rabin, 2003; Spiegel & Watson, 1984). Since prior experience with psychoacoustic testing may have a learning effect on responses of frequency discrimination, subjects with this previous experience were excluded.

Absolute pitch (AP), also referred to as perfect pitch, is the ability to identify by musical note name the pitch of any sound without reference to another sound, or by producing a musical tone when given the musical note name (Zatorre, Perry, Beckett, Westbury, & Evans, 1998). Since the exact etiology and neural characteristics for this ability are controversial, this special ability is a possible confounding variable. Thus, unless AP is the topic of the study, it is usually an exclusionary criterion for studies of music perception. Musicians know if they possess this ability and were simply asked during the subject selection process. An explanation of the concept was given to those control subjects who were not familiar with AP. Any who claimed this ability were excluded from this study.

*Inclusion criteria.* To be included in this study, all participants passed an air-conduction hearing screening at 25 dB HL for the frequencies of 250, 500, 1000, 2000, and 4000 Hz bilaterally. Hearing was screened with a GSI 17 (Grason-Stadler, Inc. Model 1717) portable screening audiometer (ANSI, 1996). In addition, all participants successfully imitated a vocal sweep of frequency stimuli to ensure that the experimental stimuli were within their dynamic vocal range. The vocal sweep was cued by a chromatic pitch instrument and modeled one octave from A3 (220 Hz) to A4 (440 Hz) inclusive of the pitch stimuli for this study. The three groups were approximately matched for age and education.

In addition to these criteria, other inclusion criteria for all subjects included: (a) gender, (b) language background, and (c) handedness. To control for gender effects, all subjects were female. Gender effects on brain symmetry have been detected by voxel-

based methods and fMRI (Good et al., 2001; Schlaug, 2001). Gender has also been found to influence the MMN latency. MMN latency was found to be significantly longer for females than males for automatic discrimination of complex stimuli (Aaltonen et al., 1994). Thus, since the effects of gender are uncertain, mixed gender may be considered a confounding variable. Due to implicit learning of culture-specific musical intervals and pitch inflections (e.g., tone languages), subjects were from Western cultures with English as their native language (Hauser & McDermott, 2003; Tillman, Bharucha, & Bigand, 2000; Welch, 1994). Volunteers who were fluent in tone languages (e.g. Vietnamese and Mandarin) were excluded. Research indicates that speakers of these languages have superior pitch skills compared to speakers of nontone languages (Deutsch, Henthorn, Marvin, & Xu, 2004). Since neural processes were being investigated, all subjects were right-handed so that confounding arguments regarding hemispheric dominance for the task were excluded.

Once a volunteer qualified to participate in the study, she was given a Participant Information Questionnaire to complete (Appendix B). Questions pertained to the subject's education and music training. Although not controlled criteria, the age at which music and/or vocal training began and the number of years of training were noted. In addition, the incidence of any immediate family members who had 5 years or more of formal music training was also recorded. Documented informed consent was obtained from all subjects in accordance with the ethical guidelines established by the University of South Florida's Institutional Review Board (Appendix C).

*Formally trained vocal musicians.* For the purpose of this investigation, formal music training referred to the participation in professionally directed and implemented music instruction and technical exercises provided by a professional musician and/or music educator (McNamara, 2005). A formally trained vocalist was defined as one who has had a minimum of five years of formal vocal training and is either a performing artist, full-time music teacher, or full-time conservatory student (Amir et al., 2003; Gaab & Schlaug, 2003; Gaser & Schlaug, 2003; Shahin et al., 2003). Participants were drawn from the student population in the University of South Florida's (USF) School of Music in the College of Visual and Performing Arts.

*Formally trained instrumental musicians.* For the purpose of this investigation, a formally trained instrumental musician was one who had received a minimum of five years of formal music training to play a musical instrument within any of the following instrument categories: brass, wind, or strings. Those volunteers whose formal training focused mainly on percussion instruments were excluded since training for that category of instruments places greater emphasis on rhythm and tempo rather than pitch. Participants were either a performing artist, full-time music teacher, or full-time conservatory student (Amir et al., 2003; Gaab & Schlaug, 2003; Gaser & Schlaug, 2003; Shahin et al., 2003). Participants were drawn from the student population in the University of South Florida's (USF) School of Music in the College of Visual and Performing Arts.

*Control subjects.* A group of female students approximately matched to the other two groups for age and education were recruited from USF. In addition to the

inclusion/exclusion criteria discussed above, the subjects in the control group had less than twelve months of formal musical or vocal training and did not play a musical instrument. Exposure to general music education in school curriculum is common to the general student population and was not considered ‘formal’ training.

### *Stimuli Considerations*

*Harmonic versus pure tone selection.* The large majority of pitch perception experiments in psychoacoustics and neuroscience use sinusoidal tones (pure tones) consisting of only the fundamental frequency (Novitski, Tervaniemi, Huotilainen, & Näätänen, 2004). However, pure tones are artificial and not a part of our natural acoustic environment. All naturally occurring periodic sounds have a sound spectrum consisting of a time-varying pattern of multiple harmonic partials across a wide frequency range (Novitski et al., 2004). Musical sounds, in particular, are temporally, spectrally, and structurally complex. Event related potentials (ERPs) derived from electroencephalography (EEG) have consistently demonstrated greater sensitivity of the auditory processing system for harmonic complexes rather than pure tones (Novitski et al., 2004; Pantev et al., 1998; Shahin et al., 2003). It is believed that the addition of acoustical information facilitates neural encoding (Tervaniemi & Brattico, 2004). Tervaniemi et al. (2000) systematically investigated the facilitating effects of overtones on the accuracy of pitch discrimination. ERP data revealed that the amplitude for the mismatch negativity task (MMN) was enhanced for complex sounds when compared to pure tones, but there were no significant differences between spectrally rich tones having



3 to 5 partials. Thus, stimuli for each task in this study consisted of harmonic tone complexes that approximated the physical characteristics of piano tones. Each stimulus contained a fundamental frequency (F0) and the first three harmonics. The amplitude of each harmonic was divided by its harmonic number to create a natural amplitude contour in the frequency spectrum.

*Frequency selection.* Since the assumption underlying this investigation was that pitch production accuracy is related to auditory frequency perception, the frequency stimuli for all three tasks were chosen from the mid-frequency range of the untrained female vocal register and extended from music tones C4 to G4 (F0 = 261.63 Hz to F0 = 392 Hz) (Hirano, 1981). In order to better compare and correlate vocal pitch production accuracy to the two auditory discrimination tasks, the following harmonic complexes were digitally generated using Tucker-Davis Technologies (TDT) hardware at a sampling rate of 50,000 Hz: C4 (F0 = 261.63 Hz), 3% increase from C4 (F0 = 269.48 Hz), 6% increase from C4 (F0 = 277.32 Hz or C4#), E4 (F0 = 329.63 Hz), 3% decrease from E4 (F0 = 320.03 Hz), 6% decrease from E4 (F0 = 310.97 Hz or D4#), G4 (F0 = 392 Hz), 3% decrease from G4 (F0 = 380.58 Hz), and 6% decrease from G4 (F0 = 369.81 Hz or F4#). Thus, the stimuli included three whole tones (C4, E4, and G4), three semitones (C4#, D4#, and F4#), and three additional synthesized quarter tones. The frequency difference between two adjacent whole tones is approximately 12%. For example, a 12% frequency increase added to C4 (F0 = 261.63 Hz) creates D4 (F0 = 293.03 Hz). The difference in frequency of the adjacent semitone (e.g., C4#) is half; that is, 6%. Thus, the frequency

difference between two contiguous quarter tones equals 3%; the frequency difference between eighth tones is 1.5% and so on.

#### *Equipment Common to All Tasks*

For all tasks, stimuli were digitally generated, controlled, and presented using a Tucker-Davis Technologies (TDT) RP2 Real-Time Processor with model HB 7 headphone buffer. Stimuli were generated at a sampling rate of 50,000 Hz. Locally written software using Microsoft Visual Basic 6.0 was developed to present the stimuli, record subject responses to the stimuli, and to calculate difference limens of frequency for each condition. Harmonic complexes were calibrated to 75 dB SPL using a Brüel and Kjaer Type I Precision Sound Level Meter (Type 2235) and a Brüel and Kjaer ½ inch condenser microphone (Type 4134) with a 2cc coupler (model DB 0138). The harmonic complexes were presented via Etymotic Research (ER2) insert earphones at 75 dB SPL.

#### *Vocal Pitch Matching*

Pitch is the perceptual correlate of frequency. A vocal pitch is measured as the fundamental frequency (F0) (Patel & Balaban, 2001). For vocal musicians, the ability to rapidly change and produce an accurate pitch is essential.

*Procedure for vocal pitch matching.* In addition to insert earphones, subjects wore a head-set microphone (Parrott Translator VXI) positioned at a constant microphone-to-mouth distance of one inch and placed off-center at the right corner of the

mouth. Each participant was instructed to listen to each stimulus until it ended and then to reproduce it on the vowel /a/ at the same pitch as accurately as possible for 3 seconds. Each stimulus tone was one second in duration and was randomly presented three times, totaling 27 stimuli. Inter-stimulus interval (ISI) was manually controlled by the examiner allowing time for the subject to respond prior to the next presentation. To verify comprehension of the task, each subject had two practice opportunities using a synthesized piano tone other than the test stimuli (e.g., B3, F0 = 246.94 Hz). The productions were directly recorded into a Dell Inspiron (model 2650) laptop computer using a sampling rate of 22,050 Hz and 16 bits per sample.

*Data analysis.* An autocorrelation analysis of fundamental frequency for each production was performed using Praat software (Version 4.4). The middle 50% of each production was selected as a representative portion to measure the fundamental frequency. For each subject, the mean fundamental for each target harmonic complex was calculated from this portion of each of the three productions. A group average and standard deviation for each target stimulus production were calculated from the individual mean fundamentals.

*Relative pitch production accuracy in percent (relPPA%)* was calculated as the absolute difference between the produced F0 and the targeted frequency relative to the targeted frequency in percent ( $relPPA\% = \Delta f/f \times 100$ ) and a mean *relPPA%* and standard deviation were determined for each group and each harmonic complex. The *relPPA%* value decreases as the difference between the produced F0 and the targeted F0 decreases. *RelPPA%* is assumed to reflect the accuracy of pitch production and can be compared

and correlated with measurements of *reIDLF%*. Group data for vocal pitch production was also converted to semitones to compare to the Western musical scale.

### *Active Auditory Frequency Discrimination*

The basic auditory skill of frequency discrimination refers to the ability to detect the smallest change in the frequency of two successive tones (Turner & Nelson, 1982). Not all changes in frequency are perceived. In order for sounds to be detected as differing in pitch, the frequency difference must be at least equal to the subject's frequency discrimination threshold; that is, the difference limen for frequency (DLF) (Gelfand, 1998). Frequency discrimination is one of the least investigated psychoacoustic abilities in musicians, especially vocal musicians (Kishon-Rabin et al., 2001).

*Procedure for frequency difference limen (DLF).* DLF is one of the most common and efficient methods for measuring auditory discrimination for frequencies below 2k Hz (Sek & Moore, 1995). An adaptive three-interval, three-alternative forced-choice (3I/3AFC) paradigm was used in conjunction with a three-down, one-up stepping rule to estimate the frequency discrimination threshold yielding a 79.4% performance level for each subject and condition (Levitt, 1971; Moore & Peters, 1992). The 79% 3I/3AFC paradigm has been shown to be more efficient with less threshold bias than the 2I/2AFC method (Leek, 2001). The auditory discrimination threshold may be underestimated using a 2I/2AFC procedure due to chance performance and the effects of guessing (e.g., 50% for 2I/2AFC, 33.3% for 3I/3AFC). Difference limens were

determined for three conditions, that is, three harmonic complexes:  $F_0 = 261.63$  Hz (C4),  $F_0 = 329.63$  Hz (E4) and  $F_0 = 392$  Hz (G4). Each harmonic complex was 200 ms in duration including a 10 ms rise and fall time with an interstimulus interval (ISI) of 300 ms (Moore & Peters, 1992). Interstimulus interval refers to the time from the end of the previous stimulus to the beginning of the next stimulus.

For this experiment, subjects were seated in front of a computer monitor in a sound treated booth. There were three observation intervals for each trial. These intervals were represented by three boxes that appeared on the monitor screen. Subjects were instructed to select the box representing the sound that was different from the other two stimuli. The choice was made using a mouse click. Visual feedback was provided by a light under the correct selection box.

The frequency difference between the harmonic complexes began with a 6% frequency difference (i.e., one semitone) between a target harmonic stimulus (i.e., C4, E4, or G4) and a comparison stimulus. Pilot data indicated that 6% (a semitone difference) was easily detected by most subjects with no prior music training. For the first three reversals, the frequency difference changed by 3% or one quarter tone. Thereafter, the step-size was 0.375%. The direction of frequency difference was above C4 and below E4 and G4 in order to correspond with piano keys and to remain within the mid-frequency range for the female voice. Following 10 reversals of response, the frequency difference of the final six reversals was averaged and reported as the frequency difference limen (DL) for that run of that condition. A minimum of three runs of each condition was completed. When necessary, additional runs were completed until three

consistent threshold estimates were obtained. Runs were considered consistent when DLs were within a factor of two. The final frequency discrimination threshold for each condition was determined by averaging the three most consistent runs.

*Data analysis.* Average difference limen for frequencies (DLFs) for harmonic complexes C4 (F0 = 261.53 Hz), E4 (F0 = 329.63 Hz), and G4 (F0 = 392 Hz) were determined for each subject. A group average and standard deviation for each harmonic complex was calculated from the individual averages. In an effort to effectively organize, describe and compare data, *relative* values for frequency discrimination of synthesized piano stimuli (i.e., harmonic tone complexes) were determined relative to each targeted frequency (Amir et al., 2003; Kishon-Rabin et al., 2001). The minimal detectable changes in frequency ( $\Delta f$ ) were transformed to *relative* DLF thresholds in percent ( $reIDLf\% = \Delta f/f \times 100$ ) and a mean *reIDLf%* and standard deviation were determined for each group and each condition. *ReIDLf%* is assumed to reflect the accuracy of pitch discrimination and can be compared and correlated with measurements of *rePPA%*. The minimal detectable change in frequency was also converted to semitones.

#### *Pre-Attentive Auditory Pitch Discrimination*

Neural imaging technology provides noninvasive methods to examine the structure and function of the brain and has become a mainstay of neuroscience. In contrast to the high spatial resolution and accuracy of functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), the strength of

electroencephalography (EEG) and its magnetic counterpart, magnetoencephalography (MEG), is in the time domain. EEG and MEG have excellent temporal resolution and allow for the study of processes in the brain within a millisecond of precision (Mody, 2004). EEG and MEG are non-invasive methods to record derived potentials that reflect the activity of a group of neurons in the human cortex (Pantev, Engelien, Candia, & Elbert, 2001). These procedures delineate the time course of neural activity associated with a stimulus and may localize the source of the electromagnetic signal (George, Vikingstad, & Cao, 1998; Mody, 2004). EEG and MEG are particularly well suited for studying the neural representation of sound and speech at the acoustic level (Friesen & Tremblay, 2003).

Electroencephalography is the recording of spontaneous bio-electric activity generated by the central nervous system. EEG is often used in medical facilities to identify sleep and seizure disorders; however, electrophysiologic activity can also be measured in response to various sensory stimuli, including auditory, visual, and somatosensory stimuli (Friesen & Tremblay, 2003). EEG is a noninvasive method of recording continuous electrical activity and changes in real-time cognitive processing in the brain from electrodes placed on the scalp (Mody, 2004; Pantev et al., 2001). This electrical activity is tracked by eliciting event-related potentials (ERPs). An ERP reflects this electrical brain activity in waveforms consisting of positive and negative deflections or peaks (Sams, Paavilainen, Alho, & Näätänen, 1985). The ERPs are time-locked to stimulus events and provide information about electrical activity of cortical neurons as a

response to experimental stimuli (Koelsch & Friederici, 2003; Mody, 2004). ERPs in response to auditory stimuli are referred to as auditory evoked potentials (AEPs).

Typically, AEP waveforms are described in terms of latency (time of occurrence after stimulus onset), polarity (positive or negative waveform), amplitude (height) and amplitude distribution across electrode recording sites (Friesen & Tremblay, 2003; Mody, 2004). Latency is measured in milliseconds and refers to the time at which an evoked response wave component occurs after the presentation of a stimulus. The latencies and amplitudes of particular peaks have been associated with specific cognitive operations (Mody, 2004). For the perception of auditory stimuli, early latency responses occur from 1-10 ms and measure the integrity of the cochlea and eighth cranial nerve. Middle latency responses occur from 10-50 ms; the origin of these potentials is unclear. The late latency responses occur between 50 and 700 ms after the stimulus onset and reflect neural processing in the cortex (Friesen & Tremblay, 2003; Goldstein & Aldrich, 1999). Common AEP components for the study of the auditory cortex include the P1-N1-P2 complex, mismatch negativity (MMN), early right anterior negativity (ERAN) and the P300.

*Mismatch negativity (MMN).* The AEP component of prime interest for this study was mismatch negativity (MMN) which is typically maximal in adults at fronto-central electrode sites and reflects a pre-attentive acoustic discrimination process based on neural representations of acoustic repetitions or regularities (Mody, 2004; Morr, Shafer, Kreuzer, & Kurtzberg, 2002; Näätänen, Gaillard, & Mäntysalo, 1978; Opitz, Mecklinger, Friederici, & von Cramon, 1999; Schröger & Winkler, 1995; Tervaniemi, 2001;



Tervaniemi, Medvedev, Alho, et al., 2000). It is a negative wave that occurs approximately 100-250 ms post-stimulus (Pettigrew et al., 2004). The timing and location of the neural activity underlying the MMN suggest that this neurophysiological response reflects access to an acoustic memory early in central auditory information processing (Nousak, Deacon, Ritter, & Vaughan, 1996).

MMN provides an objective index of individual discrimination ability for different acoustic features (Näätänen, 1995; Näätänen, Pakarinen, Rinne, & Takegata, 2004). It is elicited by infrequent deviations in simple acoustic parameters including frequency, duration, intensity, or relations between sounds such as intervals or melody contour (Nager, Teder-Sälejärvi, Kunze, & Münte, 2003; Pettigrew et al., 2004; Schröger & Winkler, 1995; Trainor, McDonald, & Alain, 2002). A sequence of standard auditory input establishes a memory trace; thus, a deviation from this memory trace generates a mismatch response reflecting the automatic detection of change in a stream of auditory information (Koelsch & Friederici, 2003; Menning et al., 2000). The MMN can be elicited by very small changes in stimuli that approximate the difference limen (i.e., perceptual discrimination threshold) (Sams et al., 1985).

An MMN response is termed 'pre-attentive' as it represents aspects of acoustic information that are encoded without the conscious attention of the subject (Tervaniemi, 2001). The MMN is a highly automatic, passively elicited (not requiring subject participation) neurophysiological response to an acoustically different (deviant) stimulus when presented in a series of homogeneous (standard) stimuli (Näätänen et al., 1978). Since the MMN response can be elicited independent of attention, it is free from

attentional activities that may contaminate behavioral and attention-dependent physiological measures (Näätänen, 1995).

Because of its excellent temporal resolution, the MMN provides a tool for determining the speed of sound-change discrimination. This automatic neural response to stimulus change has been found to co-vary reliably with perceptual and higher cognitive functions and is believed to reflect the neurophysiological processes that underlie auditory discrimination (Sams et al., 1985; Tervaniemi et al., 2005). For example, Lang and colleagues verified a strong relationship between the MMN amplitude recorded in non-attended conditions and behavioral measures of pitch discrimination ability (Lang et al., 1995).

Studies on automatic neural encoding of music prior to conscious attention have employed the mismatch negativity (MMN) paradigm (Tervaniemi, 2001). The value of the change-detection paradigm in the neuroscience of music is its suitability for the study of neural memory function among musicians and nonmusicians without being contaminated by attention, motivation, or demands of the task (Novitski, Tervaniemi, Huotilainen, & Näätänen, 2004; Tervaniemi & Huotilainen, 2003). The MMN provides an objective feature- and stimulus-specific measure of auditory discrimination ability as well as an objective index of training-induced functional neural plasticity (Näätänen, 1995). It provides a method to study the individual components of musical talent (e.g., pitch, interval, duration, rhythm perception) and the effects of music training on these components (Näätänen, 1995). The correlation between MMN parameters and behavioral measures, such as reaction time and hit rate, imply that pre-attentive neural functions

shape the accuracy of subsequent attentive processes (Tervaniemi, 2001), thus rendering the MMN an optimal tool for studying the neural bases of human auditory perception (Menning, Roberts, & Pantev, 2000; Novitski et al., 2004; Pantev et al., 2003).

*P100-N100-P200.* Other AEP components to be measured in this study included the P100-N100-P200 (P1-N1-P2) complex. The P1-N1-P2 complex is the earliest pattern of negative and positive waveforms to occur in the Late Latency Response (LLR) group. These components primarily represent sensory-perceptual stages of processing and may be elicited without the subject's attention to the stimuli (Bertoli et al., 2004). The P1 component, referred to as the P100, is the first positive wave peak and is recorded approximately 30-80 ms after the onset of an auditory stimulus (Bertoli et al., 2004). The P1 is thought to be a neurophysiological index of preferential attention and is often associated with auditory inhibition and suppression of unattended information (Key, Dove, & Maguire, 2005). P1 is associated with sensory gating and thus may reflect the ability of the brain to modulate its sensitivity to incoming stimuli (Braff & Geyer, 1990). Sources of the auditory P1 have been localized in the superior temporal gyrus.

The N1 component, also referred to as N100, is a negative wave peak recorded approximately 80-100 ms after stimulus onset (Mody, 2004; Wood & Wolpaw, 1982). It reflects activation of the large neuronal population in regions of the auditory cortex on the superior surface of the temporal lobe and can be reliably measured in individual subjects (Menning, Roberts, & Pantev, 2000; Mody, 2004). Sources for the N1 response include the primary auditory cortex, the supratemporal plane anterior to the primary auditory cortex and the temporal cortex (Scherg, Vajsar, & Picton, 1989). The recorded

N1 varies as a function of stimulus intensity, presentation rate, and attention (Näätänen & Picton, 1987). The N1 may be augmented by plasticity that takes place either cortically or at subcortical sites that project to the auditory cortex (Menning et al., 2000; Trainor, Shahin, & Roberts, 2003). The robustness of the N1 response holds enormous potential for studying the physiology of the auditory cortex (Mody, 2004).

The P2, known as P200, is the second positive peak and is recorded at approximately 180-250 ms after stimulus onset (Wood & Wolpaw, 1982). The generators of P2 appear to lie within the auditory cortex. It appears to be sensitive to the physical parameters of the stimulus, such as pitch and intensity (Novak, Ritter, & Vaughan, 1992). The P2 has been found to differ between musicians and nonmusicians for musical stimuli and has been enhanced in nonmusician adults by auditory training (Bosnyak, Eaton, & Roberts, 2002 as cited in Trainor et al., 2003).

Thus, the P1-N1-P2 components are sensitive to physical changes in auditory stimuli and reflect a pre-attentive neural response to auditory stimuli. These components were compared among the subject groups prior to measurement of the MMN to establish that encoding of auditory stimuli at the level of the auditory cortex was similar for all groups. A correlation between individual pitch discrimination performance and the amplitude or latency of the P1-N1-P2 components has not been found (Sams et al., 1985).

*Electroencephalographic recording.* The MMN and P1-N1-P2 responses were recorded and analyzed using a Compumedics Neuroscan EEG system with a SynAmps 2 amplifier and Neuroscan Scan 4.3 acquisition software. As described earlier, Tucker-Davis Technologies (TDT) hardware and locally written software were used to generate,

control, and present harmonic tone complexes. TDT hardware and locally written software were used to send triggers to the Neuroscan system to mark the time of the stimulus presentation. A cap of 32 sintered electrodes was placed on the subject's head according to the International 10/20 recording system (Jasper, 1958) using a conductive water-soluble paste applied between electrodes and the subject's scalp. Additional electrodes were placed above and below the left eye and at the outer canthus of each eye to monitor eyeblink activity. An electrode on the nose served as reference and an electrode on the forehead served as ground. After the electrodes were applied, the subject was seated in a reclining chair in a sound treated booth. Etymotic research (ER2) insert earphones were placed in the subject's ear canals for binaural presentation of the stimuli at 75 dB SPL. Electrode impedance was kept below 20k $\Omega$  and was monitored periodically through-out the data acquisition and the continuous EEG data were stored on the computer for off-line averaging. The acquisition of EEG data was by continuous sampling and was recorded at an AD (analog to digital) sampling rate of 1000 Hz. The raw signal was amplified within a frequency band of 0.05–100 Hz.

*Procedure.* To minimize any attentive auditory behavior, the subject was instructed to rest comfortably and watch a closed captioned video of her choice as harmonic complexes were presented. The use of a primary task, such as reading a book or watching a closed captioned video is reported to significantly reduce movement artifact while having no attenuating/enhancing effect on the MMN or the P1-N1-P2 response (Pettigrew et al., 2004; Sinkkonen & Tervaniemi, 2000). Moreover, the MMN

to frequency change seems to be unaffected and strongly independent of attention (Näätänen, 1995; Näätänen, Paavilainen, Tiitinen, Jiang, & Alho, 1993).

The listening task was structured as a multiple deviant oddball paradigm in which the subject was presented with a standard stimulus (70%) and three deviant stimuli (10% each). Multiple deviances may be embedded into the same sequence without significantly affecting the size of the response (Näätänen et al., 2004; Nousak et al., 1996). Not only is the multiple deviant method more time efficient (Näätänen et al., 2004; Nousak et al., 1996; Pettigrew et al., 2004), it is also a more ecologically valid paradigm. That is to say, our natural environment is comprised of a wide variety of sound sources that the auditory system pre-attentively monitors simultaneously (Nager et al., 2003). This is particularly true for musicians performing in an orchestra or vocalists performing in a choir and/or with musical accompaniment.

Previous research suggests that the amplitude of the mismatch response is directly proportional to the logarithm of the stimulus probability (Sinkkonen et al., 1996). Rarely occurring deviant stimuli produce large MMN responses; however, too few deviant stimuli result in a poor signal-to-noise ratio (Sinkkonen & Tervaniemi, 2000). A deviant-stimulus probability between 0.05 and 0.2 has been demonstrated to yield reliable results (Sinkkonen & Tervaniemi, 2000). Thus, deviant-stimulus probability for this study was established at 0.1 for each deviant target.

An MMN response border is sometimes overlapped by N1 activity. This is often seen when there are large frequency differences between the standard stimulus and the deviants; however, deviances up to 10% are considered to produce relatively pure MMN

responses (Sinkkonen & Tervaniemi, 2000). Frequency deviances for this study were 6% or smaller. The standard tone was a harmonic tone complex that approximated the physical characteristics of the piano tone G4 ( $F_0 = 392$  Hz). Based on the best and poorest DLFs obtained from the psychoacoustic task, the following three deviant tones were selected for the electrophysiological testing: 386.21 Hz (Deviant #1), 1.5% difference between the target (an eighth tone); 380.58 Hz (Deviant #2), 3% difference between the target (a quarter tone); and 369.81 Hz (Deviant #3), 6% difference between the target (a semitone). Deviant #1 (1.5% difference) was slightly above the mean frequency discrimination threshold obtained for the musicians in the psychoacoustic task (i.e., 1.35%) and Deviant #2 (3% difference) was slightly below the average DLF for the nonmusicians (3.19%). Thus, the three selected deviant harmonic complexes were musically meaningful and represented a continuum of behavioral performance.

The stimuli were presented in a pseudorandom sequence with at least three standard stimuli separating presentations of deviant stimuli; thus, two deviant stimuli did not occur in succession. Stimulus duration was 200 ms (including a 10 ms rise and fall time) with an interstimulus interval (ISI) of 500 ms presented at 75 dB SPL (Bertoli, Smurzynski, & Probst, 2005). The standard tone occurred on 70% (minimum of 2000) of the trials and each deviant occurred on 10% (minimum of 200) of the trials for a minimum of 2600 stimuli. With the exception of only two participants, the averaged responses to each deviant condition in the multi-paradigm contained a minimum of 185 accepted trials. Due to subtraction of considerable movement artifact, the two exceptions had a minimum of 120 accepted trials for each deviant condition.

Each of the three deviant stimuli was presented alone in a single block of 300 stimuli with the same presentation time and ISI to establish a baseline response to each deviant stimulus when presented as a standard. ERP responses to the deviant alone conditions were used to calculate difference waveforms and to ascertain common waveform conditions (e.g., P1-N1-P2) for the subject groups (Lang et al., 1995). Presentation order of the deviant stimuli was randomized. Total time including electrode setup for the neurophysiological task was approximately 65 minutes.

*Data analysis.* All electrophysiological measurements were made with the use of Compumedics Neuroscan SynAmps 2 amplifier and Scan v. 4.3 acquisition and edit software. Following data collection, continuous EEG waveforms were examined and areas of large muscular artifact were rejected by hand. As a precaution for data analysis, the first 10 ERP responses of each stimulus block were omitted from the averaging process to exclude the variation of the N1 amplitude (i.e., the refractoriness) associated with the start of the stimulation sequence (Pekkonen, Rinne, & Näätänen, 1995; Pettigrew et al., 2002; Sinkkonen & Tervaniemi, 2000). EEG epochs of 350 ms, starting 50 ms prior to stimulus onset, were obtained, baseline corrected (-50-0 ms), and averaged separately for the standard (deviant alone) and deviant/target stimuli. To eliminate ocular movement contamination, epochs containing artifacts exceeding  $\pm 80 \mu\text{V}$  in the HEOG and VEOG channels were rejected from averaging. ERP waves were digitally band-pass filtered at 1-30 Hz. Arithmetic re-referencing of the contributing ERP waveforms to the average of the mastoids has been shown to maximize the MMN amplitudes at the frontal and central electrodes (Fpz, F4, Fz, F3, C4, Cz or C3) (Näätänen, 1995; Pettigrew et al.,



2002; Sinkkonen & Tervaniemi, 2000). In order to maximize signal-to-noise ratio, all of the processed average files were individually re-referenced to the mastoids.

The mismatch negativity response (MMN) is traditionally measured as a difference waveform obtained by subtracting the grand average ERP response to the standard stimulus from the grand average ERP response to a deviant stimulus (Morr et al., 2002; Novitski et al., 2004; Schröger & Winkler, 1995). The difference waveform is considered to reflect the differential neuronal processing of a deviant stimulus compared to the standard stimulus (Tervaniemi, 2001). A number of studies have demonstrated that the first standard following a deviant in an odd-ball paradigm may be perceived as a new standard and thus, the MMN response in the difference waveform is attenuated (Nousak et al., 1996; Sams, Alho, & Näätänen, 1983). To account for possible contamination and/or attenuation of the MMN response, an acceptable alternative method was chosen to calculate the difference waveforms. Using this method, the averaged response to a deviant when it is presented and recorded alone is subtracted from the averaged response to the deviant when it is presented in an oddball paradigm (Pettigrew et al., 2004; Picton, 1995). In addition to determining the MMN difference waveforms, the averaged group ERP waveforms for each deviant alone condition were used to examine the P1-N1-P2 complex.

## Chapter Four

### Results

#### *Participant Demographics*

Participants were 61 female students from the University of South Florida including 21 nonmusician controls, 21 instrumental musicians, and 19 vocal musicians. Ages of those in the control group ranged from 20 to 34 with a mean of 23.4. The musicians were closely matched with a mean age of 21.8 and a range of 18 to 33. None of the women in the control group had more than 12 months of formal music training. By comparison, the musicians began music training between the ages of 3 and 15 with a beginning mean age of 8.5 years. More than half of the musicians (21 of 40) began music training at age 9 or younger. On average, the instrumental musicians had 9.8 years of music training; 11 of the instrumentalists played a string instrument, while 10 played a wind instrument. The vocal musicians had an average of 11.3 years of music training. In addition to formal vocal training, almost half of the singers also received training on a musical instrument (9 of 19). Only one participant in the control group reported having a parent who had received 5 or more years of music training; while one-third of the musicians (13 of 40) had at least one musically trained parent.

Self-reported Scholastic Assessment Test (SAT) scores indicated there was no difference between nonmusicians and musicians for either math or verbal abilities.

Subtest medians for both subject groups were in the 500-599 range. Participant profile data may be found in Appendix D.

All 61 participants completed the two psychoacoustic tasks; however, one control subject and one instrumentalist did not complete the electrophysiological task. Consequently, data for the electrophysiological task is based on 20 controls, 20 instrumental musicians, and 19 vocal musicians.

### *Psychoacoustic Measures*

#### *Vocal Pitch Matching*

Every participant attempted to vocally match the pitch of three presentations of nine harmonic complexes presented in random order for a total of 27 responses. The harmonic complexes represent the Western musical scale from C4 to G4 (F0 = 261.63 Hz, F0 = 269.48 Hz, F0 = 277.32 Hz, F0 = 329.63 Hz, F0 = 320.03 Hz, F0 = 310.97 Hz, F0 = 392 Hz, F0 = 380.58 Hz, and F0 = 369.81 Hz). Individual subject data for the averaged productions of the targeted harmonic complexes are shown in Appendix E. The descriptive group data for pitch production accuracy (PPA) is displayed in Table 1.

Table 1. Pitch Production Accuracy – Group Data

<b>Group</b>	<b>N</b>	<b>Hz</b>	<b>SD</b>	<b>rel%</b>	<b>Semitone</b>
<b>Control</b>	21	25.5	31.3	7.83%	1.30
<b>Musician</b>	40	4.1	5.4	1.28%	0.21
<b>Instrumental</b>	21	4.9	7.0	1.50%	0.25
<b>Vocal</b>	19	3.4	2.6	1.05%	0.17

On average, pitch production accuracy (*relPPA%*) for those without music training deviated from the reference pitch by 7.83% or 25.5 Hz. In other words, the average pitch difference between the target and the production for the nonmusicians was greater than one semitone (6% frequency difference). By comparison, the musicians' mean pitch production accuracy was within 1.28% (4.1 Hz) of the target or within one-eighth of the reference tone. Interestingly, both subgroups of musicians vocally matched pitch with comparable accuracy. Mean *relPPA%* for the vocal musicians was 1.05% (SD = 2.6 Hz), while the instrumental musicians with no vocal training matched the reference pitch with an average *relPPA%* of 1.50% (SD = 7.0 Hz).

*Statistical analysis.* Measurements of psychoacoustic variables are reported in terms of *relative* accuracy in percent (*relPPA%* and *relDLF%*) and thus represent a rank ordering of observations rather than precise measurements. Consequently, non-parametric statistics were deemed more appropriate for analysis of the psychoacoustic variables. Analysis was completed using SPSS software (version 11.0). An alpha level of .05 was used for all statistical tests.

Agreement between the harmonic tone complex stimuli for the pitch production (PPA) task was measured using Kendall's *W coefficient of concordance*. The *W* ranges from 0 to 1 with 1 indicating complete agreement and 0 indicating complete disagreement (Barry, n.d.). PPA performance did not differ across the harmonic complexes for nonmusicians ( $W = 0.08, p = .10$ ) and instrumentalists ( $W = 0.04, p = .57$ ); however, a difference existed among the stimuli for performance by the vocalists ( $W = 0.13, p = .02$ ).

Because there was not complete concordance among the stimuli, the Mann-Whitney U test was used to compare differences between the musicians and nonmusicians and each harmonic complex for an effect of harmonic tone on pitch production accuracy (PPA). The Mann-Whitney U Test is a non-parametric procedure used to evaluate the differences between two independent samples. It is not dependent on the assumption of normal distribution and is appropriate for sample sizes having less than 100 observations. Measures are placed into a composite distribution then ranked from the highest to the lowest scores to determine if the ranks tend to be higher for one group (Glass & Hopkins, 1996).

Overall, the musicians were more accurate than the nonmusicians for all 9 stimulus tones, implying that the musicians' *rel*PPA% was significantly smaller. However, when the Bonferroni correction was applied to compensate for Type I errors ( $p = .006$ ), one of the nine harmonic complexes was not significantly different between the musicians and controls (369.81/F4#,  $U = 274$ ,  $p = .02$ ). Considering the total pitch production data between the musicians and the controls, the effect of this one harmonic complex on pitch production accuracy was felt to be inconsequential to the overall results.

Within the musician group, pitch production accuracy was not significantly different for any of the nine harmonic complexes confirming no significant difference between the vocal musicians and the instrumental musicians for vocal pitch matching accuracy.

Although the *relPPA%* means of the two musician groups were not significantly different (PPA,  $U = 199$ ,  $p = .99$ ), the vocalists appeared to have minimal variability in production compared to the instrumental musicians ( $SD = 2.6$  Hz for vocalists and  $SD = 7$  Hz for instrumentalists). The shapes of variance distribution between the instrumentalists and vocalists were compared with the Wald-Wolfowitz Runs test (Barry, n.d.). Distribution of variance was significantly smaller for the vocalists (PPA,  $Z = 2.39$ ,  $p < .001$ ) compared to the instrumentalists, representing a less variable, more consistent and uniform pattern of response for the vocal musicians.

*Active Auditory Frequency Discrimination*

A difference limen for frequency (DLF) was determined for each individual for three harmonic complexes C4 ( $F_0 = 261.53$  Hz), E4 ( $F_0 = 329.63$  Hz), and G4 ( $F_0 = 392$  Hz) using an adaptive 79% 3I/3AFC paradigm. Individual data are shown in Appendix F. The descriptive group data for DLF is displayed in Table 2.

Table 2. Difference Limen for Frequency – Group Data

<b>Group</b>	<b>N</b>	<b>Hz</b>	<b>SD</b>	<b><i>rel%</i></b>	<b>Semitone</b>
<b>Control</b>	21	10.3	11.7	3.19%	0.53
<b>Musician</b>	40	4.4	1.4	1.35%	0.23
<b>Instrumental</b>	21	4.5	1.6	1.40%	0.23
<b>Vocal</b>	19	4.2	1.1	1.30%	0.22

The just noticeable difference between two harmonic complexes for the nonmusicians was greater than one quarter of a musical tone (*relDLF%* = 3.19%). By

contrast, trained musicians discriminated between two pitches with only one-eighth of a difference in tone frequency ( $relDLF\% = 1.35\%$ ). As a group, the musicians' average  $relDLF\%$  was at least 50% smaller compared to the control group. The instrumentalists and the vocalists had comparable difference limens for frequency ( $relDLF\% = 1.4\%$  and  $1.3\%$ , respectively).

*Statistical analysis.* Comparison of group performance using the Mann-Whitney U test indicated that measures of difference limen for frequency (DLF) were significantly smaller for the musicians compared to the controls (DLF,  $U = 146$ ,  $p < .001$ ). Auditory pitch discrimination for harmonic complexes did not differ between the instrumentalists and the vocalists (DLF,  $U = 170$ ,  $p = .42$ ).

The vocalists and the instrumentalists perceived all harmonic complexes equally well (Kendall's  $W = 0.003$ ,  $p = .95$ ;  $W = 0.05$ ,  $p = .37$ , respectively); however, the nonmusicians did not demonstrate perceptual agreement among the three tones ( $W = 0.25$ ,  $p = .005$ ). Consequently, comparisons between subject group and each harmonic complex were completed using the Mann-Whitney U to evaluate for an effect of harmonic tone on the DLF. Musicians and nonmusicians differed significantly for each tone and for the tones overall indicating no effect of stimulus on pitch discrimination and confirming a smaller DLF for the musicians than for the nonmusicians for each harmonic complex (261.63/C4,  $U = 93.5$ ,  $p = .001$ ; 329.63/E4,  $U = 97$ ,  $p = .002$ ; 392.00/G4,  $U = 118$ ,  $p = .01$ ). Between the two subclasses of musicians (vocalists and instrumentalists), difference limens for frequency (DLF) were equivalent for all of the harmonic complexes.

### *Comparison of DLF and PPA*

The means of the DLF and PPA tasks were compared with dependent t-tests to assess whether these abilities were equivalent within each group. The nonmusicians' auditory skills were significantly more accurate than their vocal pitch matching ability,  $t(20) = 2.46$ ,  $p = .02$ . Although the nonmusicians' just noticeable difference (jnd) between harmonic complexes averaged 3.19%, their *re/PPA* deviated 7.83% from the reference tone. By contrast, as a group, the musicians' auditory discrimination and pitch production skills were comparable,  $t(39) = 0.22$ ,  $p = .83$ . Interestingly, separate analysis of the two musician genres revealed distinct differences. DLF and PPA abilities did not significantly differ for the instrumental musicians,  $t(20) = 0.69$ ,  $p = .50$ . However, for the vocalists, pitch production skills were more accurate than auditory discrimination,  $t(19) = 3.17$ ,  $p = .005$ . The vocal musicians produced a musical tone within 1.05% of a given reference, while their jnd averaged 1.30%. This difference reflects an influence of vocal training on laryngeal reflexes and suggests that long-term practice develops neuromuscular memory for accurate pitch production. Within all groups, auditory pitch discrimination tended to be less variable than pitch production accuracy.

### *Correlation Analysis of DLF and PPA*

Group data was combined to examine the overall relationship between auditory pitch discrimination (*re/DFL%*) and pitch production accuracy (*re/PPA%*). Individual pitch production averages as a function of individual DLF averages are displayed in a scatter plot in Figure 1. Spearman's rho correlation was used to examine the overall



relationship between auditory pitch discrimination and pitch production accuracy for all groups combined. This nonparametric measure assumes that the individual observations can be ranked into two ordered series (Crichton, 1999). The rho coefficient values are between -1 and +1 with a positive correlation indicating that the ranks of both variables increase together. A negative correlation indicates that as the rank of one variable increases, the other decreases.

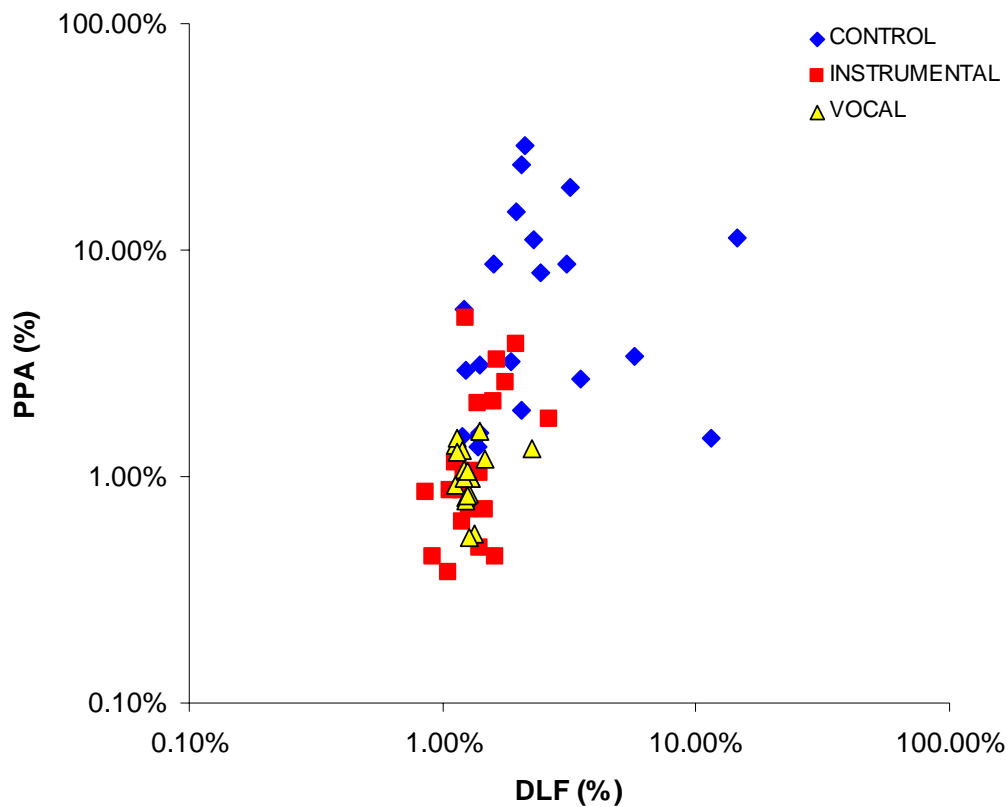


Figure 1. Scatter plot of DLF and PPA. Individual pitch production data (*rel*PPA%) as a function of individual discrimination data (*rel*DLF%) plotted on a logarithmic scale.

A large positive correlation based on rank order of all individuals was found between the two measures ( $r_s = 0.61$ ,  $p < .001$ ). Visual inspection of the scatter plot reveals that the vocalists are tightly clustered between 1% and 2% for PPA and DLF. This illustrates the vocalists' very small distribution of variance. Because there was minimal difference in the DLF and PPA data between subjects, sufficient evidence for a relationship was not found for the vocalists ( $r_s = -0.13$ ,  $p = .60$ ). Analysis also revealed no correlation between DLF and PPA data for the nonmusicians ( $r_s = 0.38$ ,  $p = .09$ ). The scatter plot shows greater performance variability for this group, but no clear relational pattern. Thus, while there is a positive relationship between DLF and PPA overall, the only group to actually have a significant positive correlation between these two variables was the instrumental musicians ( $r_s = 0.49$ ,  $p = .03$ ).

#### *Correlations of DLF and PPA with Questionnaire Variables*

Individual measures of DLF and PPA of all participants were correlated with the following Information Questionnaire variables: age of training onset (before age 9 and after age 9), years of music training (instrumental and vocal), number of immediate family members with music training (including mother, father, and siblings), and Scholastic Assessment Test (SAT) scores (math and verbal). There were no significant correlations within groups between any of the demographic variables and psychoacoustic task performance.

## *Electrophysiological Measures*

### *Pre-Attentive Auditory Pitch Discrimination*

*Sensory perception P1-N1-P2 complex.* For electrophysiological testing, the methods for determining the mismatch negativity (MMN) were based on the assumption that participants would demonstrate equivalent sensory perception of auditory stimuli. As described in Chapters 2 and 3, the P1-N1-P2 components are sensitive to physical changes in auditory stimuli and reflect a pre-attentive neural response to auditory stimuli. Thus, the ERP group grand average waveforms for the deviant-alone conditions (standard stimuli) were visually inspected for similarity of the P1-N1-P2 complex. Inspection of the waveforms revealed that mean latencies of the P1-N1-P2 complex for all conditions fell within the range of 50-200 ms after stimulus onset and there were no remarkable differences in average latency of ERP responses between the groups. However, P1 amplitude was consistently greater for the control group (C-Dev) compared to the musicians (M-Dev) for all deviant-alone waveforms. Figures 2-A, 2-B, and 2-C illustrate these similarities and differences for each condition. The P1 amplitude is visualized as the first positive peak (up) occurring approximately 50 ms after the onset of the auditory stimulus. The N1 component is the first downward dip following the P1. The P2 component is the second positive peak.

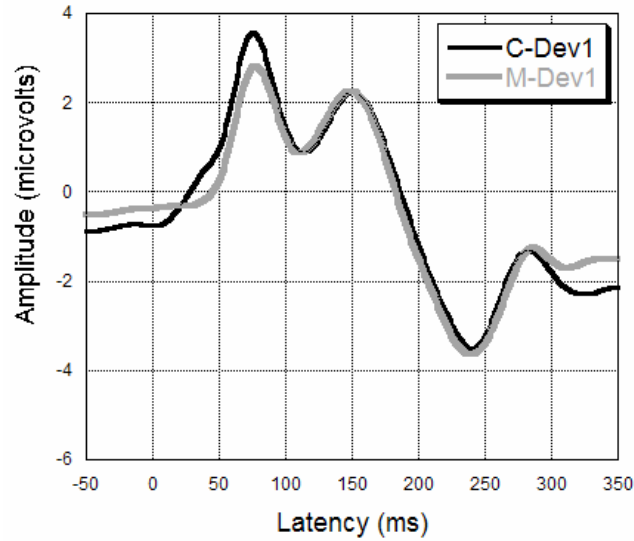


Figure 2-A. Comparison of Group Average Waveforms of P1-N1-P2 Complex for Deviant 1 Alone Condition (386.21 Hz, 1.5% deviance) at Fz between Controls (C-Dev1) and Musicians (M-Dev1)

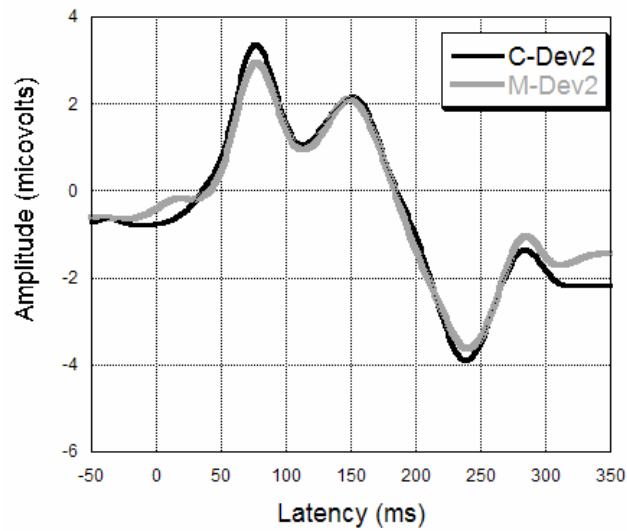


Figure 2-B. Comparison of Group Average Waveforms of P1-N1-P2 Complex for Deviant 2 Alone Condition (380.58 Hz, 3% deviance) at Fz between Controls (C-Dev2) and Musicians (M-Dev2)

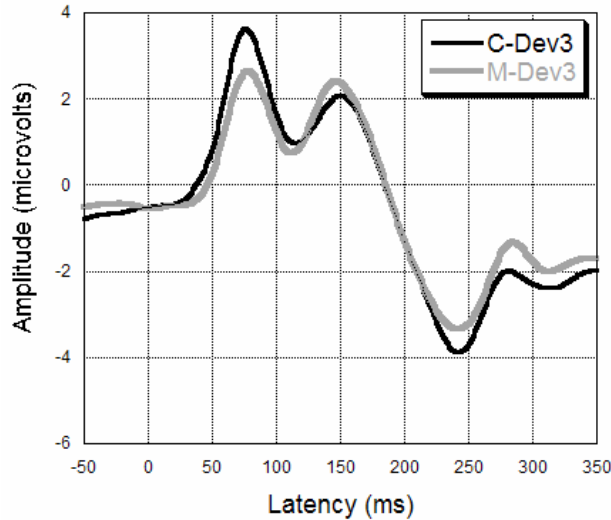


Figure 2-C. Comparison of Group Average Waveforms of P1-N1-P2 Complex for Deviant 3 Alone Condition (369.81Hz, 6% deviance) at Fz between Controls (C-Dev3) and Musicians (M-Dev3)

Individual peak amplitudes and latencies for P1 were determined for each deviant alone condition and group averages were calculated for analysis (Appendices G and H). Analysis of variance (ANOVA) on P1 amplitude revealed a main effect of subject group,  $F(2,168) = 6.68, p = .002$ . Post-hoc group-wise comparison (Tukey HSD) confirmed larger P1 amplitude for the control group (nonmusicians) compared to the instrumentalists ( $p = .001$ ) and vocal musicians ( $p = .04$ ). As discussed in Chapters 2 and 3, the P1 component is considered a neurophysiological indicator of preferential attention to sensory stimuli and reflects differences in regulating excitatory and inhibitory processes. Thus, larger P1 amplitude suggests reduced sensory gating of stimuli (Key, Dove, & Maguire, 2005). There was no significant P1 amplitude difference between the instrumentalists and the vocalists ( $p = .53$ ) indicating that encoding of the stimuli at the level of the auditory cortex was similar for both groups of musicians. There was no

significant effect of stimuli,  $F(2,168) = 0.039$ ,  $p = .96$ , nor was there an interaction between groups and stimuli for P1 amplitude,  $F(4,168) = 0.357$ ,  $p = .84$ . Thus, participants demonstrated equivalent sensory perception of auditory stimuli as indicated by P1-N1-P2 latency and N1 and P2 amplitude. Group differences in P1 amplitude suggests that sensory gating may differ between musicians and nonmusicians.

*Mismatch negativity-MMN.* Visual inspection of the grand average difference waveforms for all electrode sites was used to determine the electrode for subsequent analyses. The MMN response was strongest at electrodes Fz and Cz with the largest amplitudes measured at the fronto-central Fz electrode in the 10-20 system (Figure 3). Thus, reported measures and statistical analysis are based on ERP responses measured from Fz. MMN has been shown to invert in polarity at electrodes below the level of the Sylvian fissure (Näätänen, 1995). Polarity inversion at the mastoids is an accepted method to verify the MMN response to tonal changes as illustrated in Figure 3 (Morr et al., 2002; Sinkkonen & Tervaniemi, 2000).

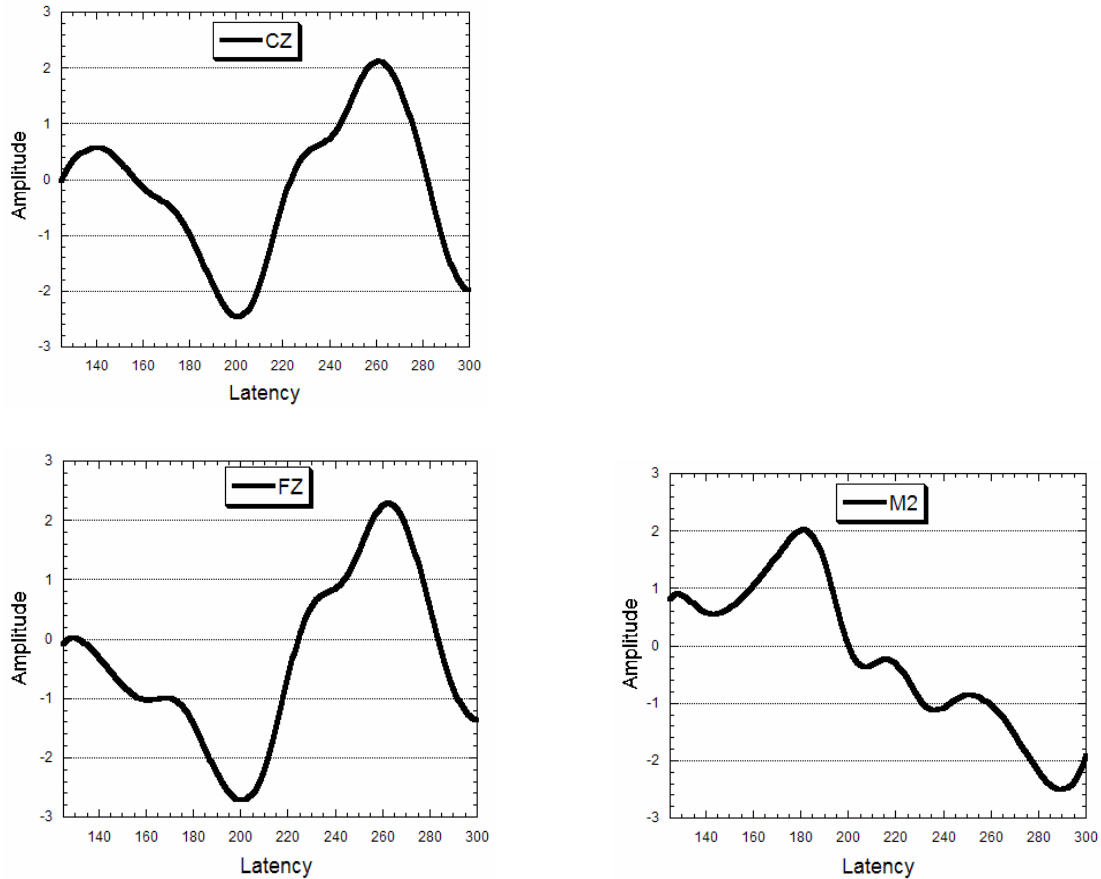


Figure 3. Grand Average Waveform Examples of Fz, Cz, and M2. Grand average waveforms show greater MMN amplitude for the Fz electrode and an inversion of polarity at the right mastoid site (M2). Musician example of response to Dev 3.

Individual and group grand averages were determined for each deviant contrast as an oddball and each deviant-alone condition (standard). For each group, the average ERP response wave of the deviant alone condition (standard) was subtracted from the ERP response of the deviant as the odd-ball stimulus at Fz (Figures 4-A, 4-B, & 4-C). There were three deviant contrasts: 386.21 Hz (1.5%, Deviant #1), 380.58 Hz (3%, Deviant #2), and 369.81 Hz (6%, Deviant #3). Grand average group difference waveforms for each deviant were derived for the controls and the musicians as well as the musicians divided into their respective genre, instrumental and vocal (Figures 5-A, 5-B, and 5-C).

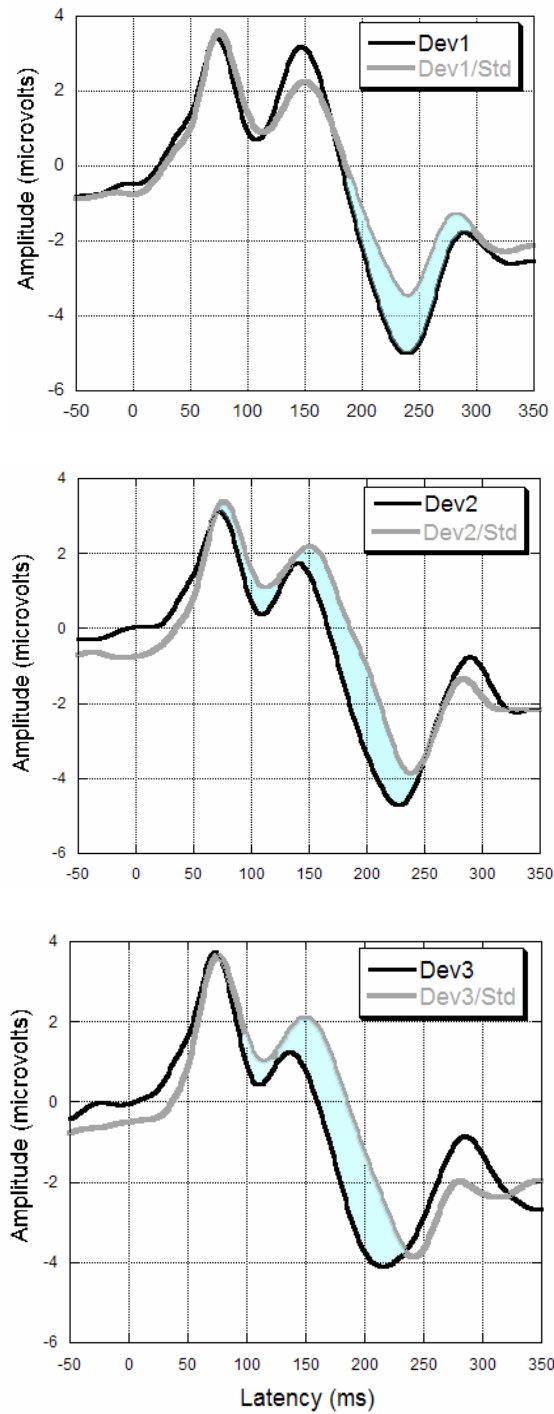


Figure 4-A. Control Group's Mismatch Response (MMN). Shaded area represents the average mismatch response of control group to 1.5% change (Dev 1, 386.21 Hz) from the standard tone (392 Hz), 3% (Dev 2, 380.58 Hz), and 6% (Dev 3, 369.81 Hz) change.



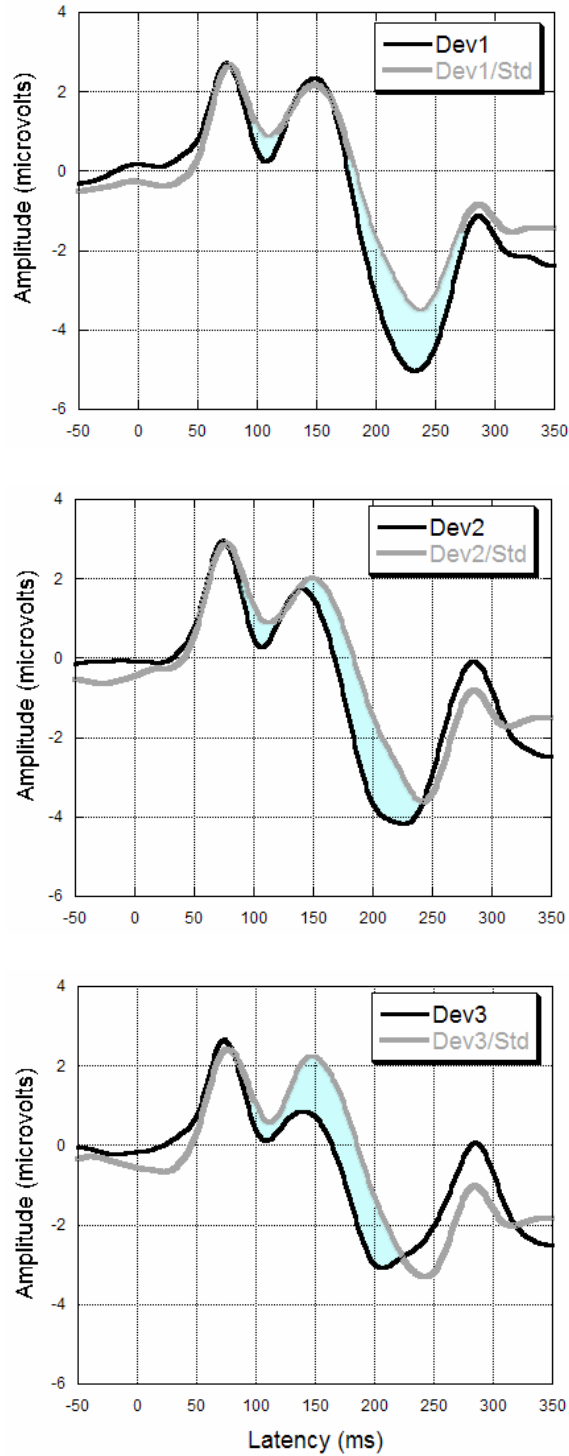


Figure 4-B. Instrumentalists' Mismatch Response (MMN). Shaded area represents average mismatch response of instrumental musicians to 1.5% change (Dev 1, 386.21 Hz) from standard tone (392 Hz), 3% (Dev 2, 380.58 Hz), and 6% (Dev 3, 369.81 Hz).

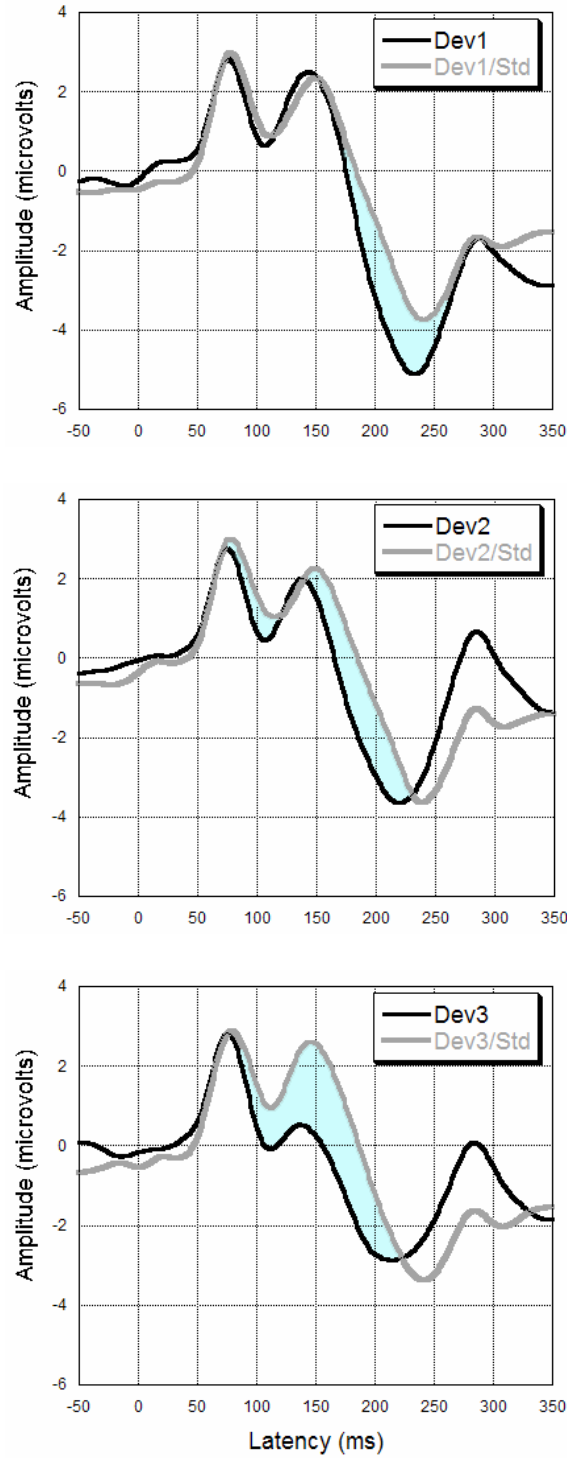


Figure 4-C. Vocal Musicians' Mismatch Response (MMN). Shaded area represents the average mismatch response of vocal musicians to 1.5% change (Dev 1, 386.21 Hz) from the standard tone (392 Hz), 3% (Dev 2, 380.58 Hz), and 6% (Dev 3, 369.81 Hz) change.

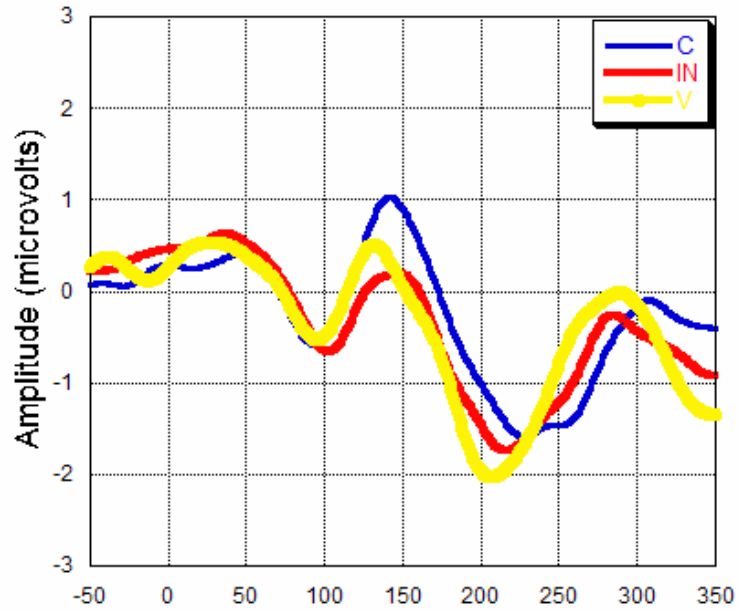


Figure 5-A. Grand Average Difference Waveforms for Deviant 1 (386.21 Hz, 1.5%) comparing control group (C), instrumentalists (IN) and vocalists (V).

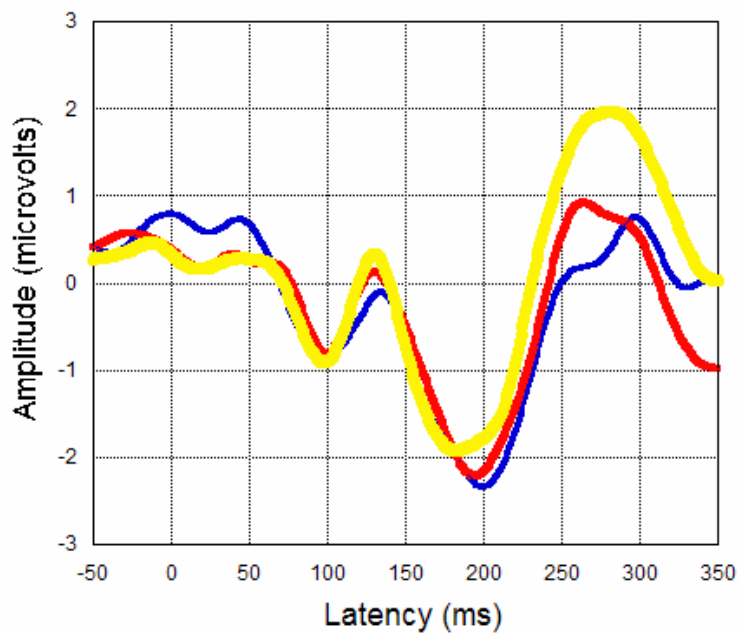


Figure 5-B. Grand Average Difference Waveforms for Deviant 2 (380.58 Hz, 3%) comparing control group (C), instrumentalists (IN) and vocalists (V).

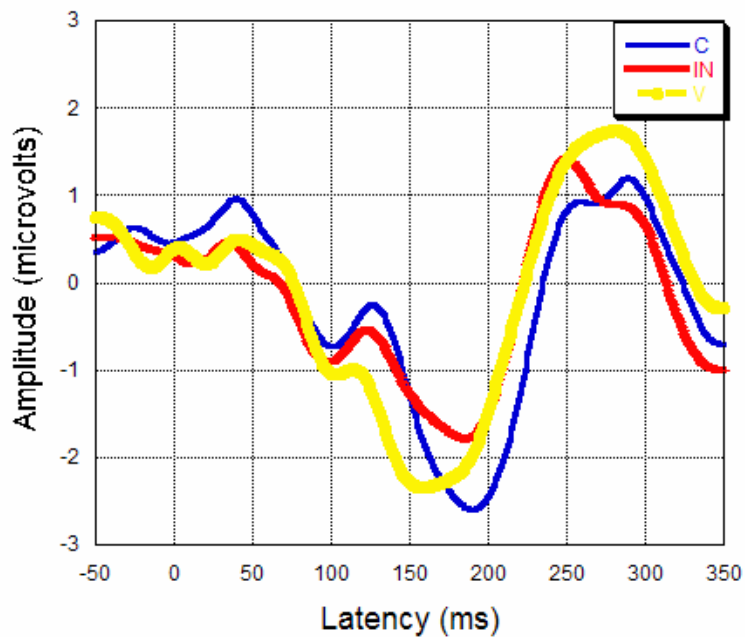


Figure 5-C. Grand Average Difference Waveforms for Deviant 3 (369.81Hz, 6%) comparing control group (C), instrumentalists (IN) and vocalists (V).

MMN responses may be quantified by the latency and amplitude of a negative ‘peak’ in the difference waveform. A ‘strong’ MMN response refers to large amplitude and short latency. Thus, a latency (in milliseconds) and amplitude (in microvolts) were measured for each subject, group, and stimulus condition. Because the MMN amplitude and latency reflect two independent factors influencing the MMN, it is recommended that they be measured and analyzed separately (Lang et al., 1995; Näätänen, 1992).

The grand average difference waveforms for each group and deviant stimulus were used to visually determine the latency region of the MMN peak amplitude. MMN peak latency is typically measured as the largest negative peak occurring between 150 to

300 ms post-stimulus period for each group and frequency condition. In the present study, the MMN latency peaked between 177 and 227 ms depending on the magnitude of the deviance and the subject group (Table 3). Overall average peak latency was 201 ms. Latency windows of 40 ms around the peak for a given group and condition were determined. The average amplitude at Fz within these latency windows was calculated for each individual subject and condition (Appendix I). Within the pre-determined latency windows, MMN peak latency was determined for each subject and condition (Appendix J).

Table 3. Average Peak Latencies Derived from Grand Average Waveforms

<b>Deviant Magnitude</b>	<b>Control</b>	<b>Musicians</b>	<b>Instrumental</b>	<b>Vocal</b>
1.5% (Deviant #1) 386.21 Hz	227 ms	212 ms	216 ms	207 ms
3% (Deviant #2) 380.58 Hz	199 ms	190 ms	195 ms	182 ms
6% (Deviant #3) 369.81 Hz	190 ms	185 ms	185 ms	177 ms

*Statistical Analysis of the Mismatch Negativity*

*MMN Amplitude*

For the control group, MMN amplitude increased as the magnitude of the frequency deviance became larger. Specifically, as the frequency deviance increased from 1.5% to 3% to 6%, the average amplitude of MMN response for the nonmusicians

increased from  $-1.5 \mu\text{V}$  to  $-2.0$  to  $-2.5 \mu\text{V}$ . This neural response pattern was not consistent for the musicians (Figure 6-A).

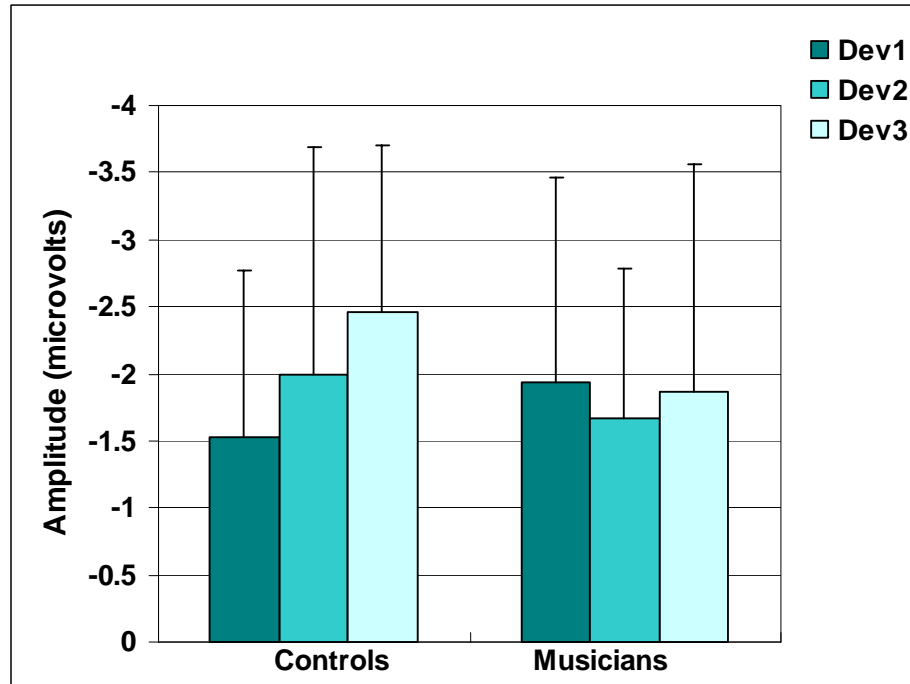


Figure 6-A. MMN Response Amplitudes by Group and Deviant Condition. Deviant magnitudes: Deviant 1 = 1.5%, Deviant 2 = 3%, Deviant 3 = 6%.

As seen in Figure 6-B, the instrumentalists responded with minimal variability between the three deviant stimuli (i.e.,  $0.3 \mu\text{V}$ ); while the vocalists had the largest response amplitude for the smallest deviance magnitude ( $-2.4 \mu\text{V} / 1.5\%$ ).

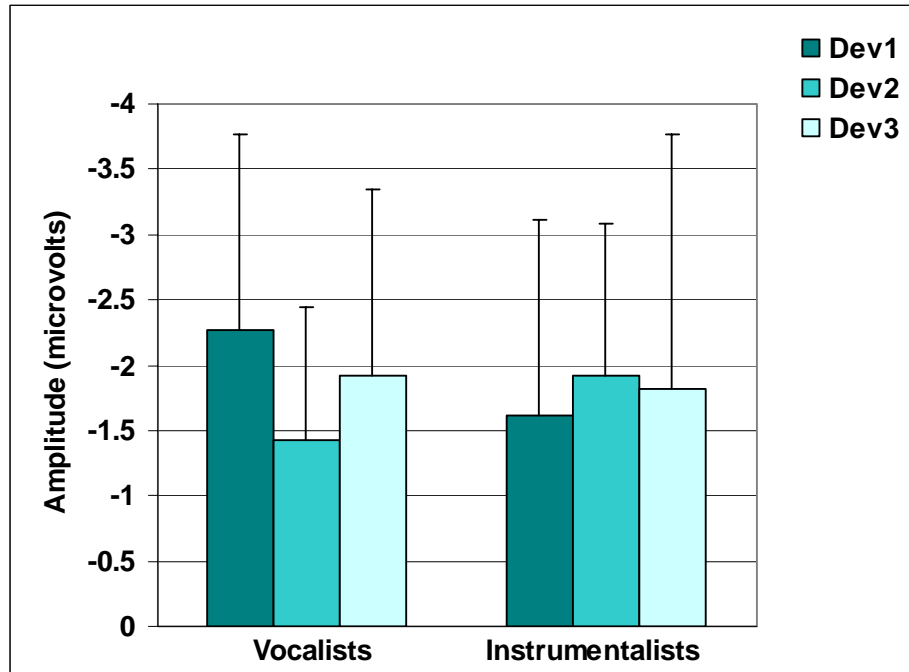


Figure 6-B. MMN Response Amplitude by Musician Genre and Deviant Condition. Deviant magnitudes: Deviant 1 = 1.5%, Deviant 2 = 3%, Deviant 3 = 6%.

To evaluate for the effect of group and deviant stimulus condition on the MMN amplitude, a two-way factorial analysis of variance (ANOVA) was conducted on the individual mean amplitudes. There was no main effect of group,  $F(2, 168) = 0.35$ ,  $p = .70$  or deviant condition,  $F(2, 168) = .71$ ,  $p = .49$  on the MMN amplitudes, nor was there an interaction between the magnitude of the deviance and subject group,  $F(4, 168) = 1.89$ ,  $p = .12$ .

#### *MMN Latency*

For both musicians and nonmusicians, as the magnitude of the frequency deviance increased, the response latency became shorter as shown in Figure 7.

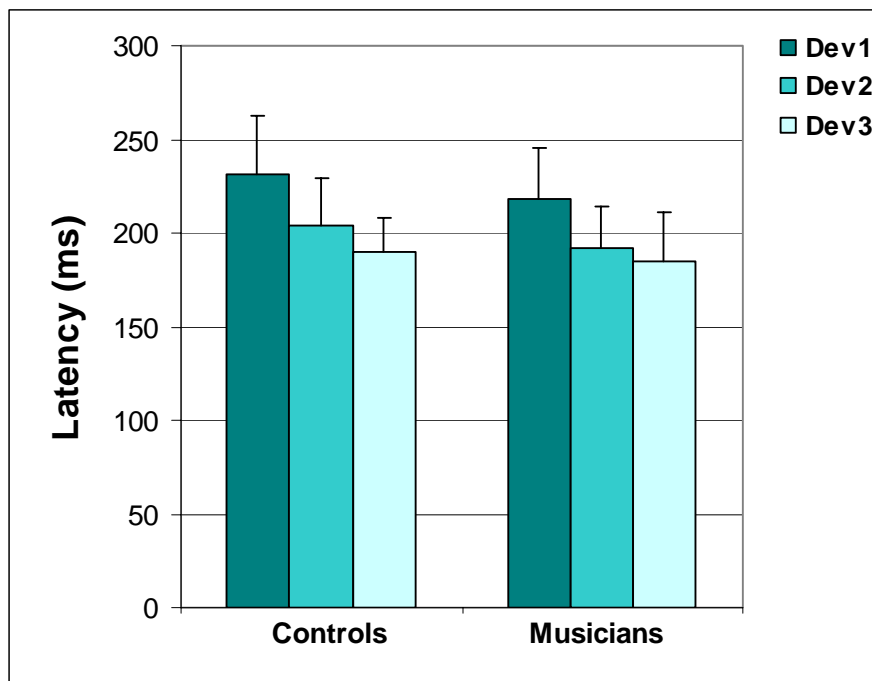


Figure 7. MMN Response Latency by Group and Deviant Condition. Deviant magnitudes: Deviant 1 = 1.5%, Deviant 2 = 3%, Deviant 3 = 6%.

Overall, the neural responses of the musicians occurred earlier than the controls. An ANOVA was conducted on the individual peak latencies to evaluate for an effect of group or deviant stimulus condition on the MMN latency. There was a main effect for group,  $F(2, 168) = 4.93$ ,  $p = .008$ , as well as deviant condition,  $F(2, 168) = 35.38$ ,  $p < .001$ . There was no significant interaction between group membership and deviant magnitude,  $F(4, 168) = 0.24$ ,  $p = .91$ .

Post-hoc analysis for group-wise comparisons (Tukey HSD) confirmed that differences in MMN latency were significant between the vocalists and the controls. The



vocal musicians' auditory neural responses to frequency differences occurred earlier than the nonmusicians for all deviant magnitudes regardless of the size ( $p = .009$ ). However, the differences in response latency between the instrumentalists and the nonmusicians did not quite meet significance ( $p = .06$ ). This implies that the auditory neural responses of the vocal musicians occurred earlier than the instrumental musicians; yet, the MMN latency difference between the two subclasses of musicians did not meet significance ( $p = .73$ ).

Post-hoc testing identified significant differences between all three deviant conditions ( $p < .05$ ) and confirmed that the largest frequency deviance elicited the earliest auditory neural MMN response for musicians and nonmusicians. Conversely, as the magnitude of the frequency difference decreased, latency of response increased; that is, auditory neural response occurred later.

### *Correlation Analysis with Electrophysiological Variables*

#### *Psychoacoustic and Electrophysiological Variables*

Overall correlations between psychoacoustic (i.e., difference limen for frequency and pitch production accuracy) and electrophysiological variables (i.e., MMN amplitude and latency) were not supported by the evidence. In addition, individual DLF measures by subject group for the stimulus condition G4/392 Hz were compared to the corresponding MMN latency and amplitude data for 386.21 Hz (Deviant #1), 380.58 Hz (Deviant #2), and 369.81 Hz (Deviant #3). No significant correlations were found among the variables for any of the subject groups. Individual averages of pitch production

accuracy (PPA) were compared to corresponding measures of MMN latency and amplitude for each deviant condition by subject group. Again, sufficient evidence to support significant correlations among the variables for any subject group was not observed.

As a point of interest, it was questioned whether those vocal musicians who had additional instrumental training (9 of 19) would perform differently than those who did not have this additional musical experience. A comparison of means for electrophysiological and psychoacoustic variables using a series of two-tailed t-tests revealed no significant differences between those singers with instrumental training and those without [Dev3latency:  $t(17) = 0.34$ ,  $p = .74$ ; Dev3amplitude:  $t(17) = 0.6$ ,  $p = .56$ ; difference limen frequency:  $t(17) = 1.2$ ,  $p = .25$ ; pitch production accuracy:  $t(17) = 0.93$ ,  $p = .37$ ].

#### *Years of Music Training and Electrophysiological Variables*

On average, the musicians had 10.5 years of music training ranging from 6 to 19 years. The Pearson product moment correlation coefficient was used to determine if there was any relationship between the total number of years of music training received by the musicians and the electrophysiological variables. The total number of years of music training for each individual musician were compared to the corresponding MMN latency and amplitude data for responses to 386.21 Hz (Deviant #1), 380.58 Hz (Deviant #2), and 369.81 Hz (Deviant #3). Evidence was lacking to support significant correlations between response amplitude and years of training. However, for latency of

response, there was a significant negative correlation for Deviant #3, ( $r = -0.34$ ,  $p = .03$ ) and Deviant #1, ( $r = -0.31$ ,  $p = .05$ ), but no correlation for Deviant #2, ( $r = -0.08$ ,  $p = .62$ ). For the smallest and largest deviances in pitch magnitude, as the number of years of music training increased, the response latency decreased. Thus, the number of years of music training may have influenced the timing of the pre-attentive auditory neural response to pitch deviance.

#### *Age Training Initiated and Electrophysiological Variables*

The average age at which musicians in this study began music training was 8.5 years. More than half of the musicians (21 of 40) began music training by age 9 or younger. Using the Pearson product moment correlation coefficient, the age at which training began for each musician was compared to the corresponding MMN latency and amplitude data for responses to 386.21 Hz (Deviant #1), 380.58 Hz (Deviant #2), and 369.81 Hz (Deviant #3). The evidence did not support any significant correlations between the age at which music training began and the electrophysiological variables (MMN amplitude or latency). As a point of interest, the musician group was divided between those who began training at age 9 or earlier, and those who began music training after age 9. No significant differences were found between the musician groups for PPA,  $t(39) = 0.49$ ,  $p = .62$ ; DLF,  $t(39) = 1.13$ ,  $p = .26$ ; or MMN latency,  $t(39) = 0.92$ ,  $p = .36$ .

### *Summary of Findings*

1. The ability to vocally match a single pitch to a reference pitch was more accurate for musicians than nonmusicians; however, for the particular vocal task in this study, mean pitch production accuracy did not differ between vocal musicians and instrumental musicians.
2. Pitch production accuracy across all frequencies was most consistent for the vocalists.
3. Difference limens for frequency were smaller for musicians than nonmusicians; while DLFs for vocalists and instrumentalists were similar.
4. The musicians were superior to the nonmusicians on both psychoacoustic variables; however, (a) the nonmusicians had better auditory pitch discrimination than vocal pitch matching ability, (b) the instrumental musicians demonstrated equal ability of the two skills, and (c) the vocal musicians were more accurate at vocal pitch matching than auditory pitch discrimination.
5. When all individual data were combined, there appeared to be a positive correlation between *re/DLF* and *re/PPA*. Closer inspection of the data indicated a relationship between these variables only for the instrumentalists. There was minimal performance variability among the vocal musicians and only a tendency towards a relationship for the nonmusicians.

6. All participants demonstrated auditory neural sensory perception to harmonic complexes. Neural responses were different for the musicians compared to the nonmusicians as early as 50 ms after presentation of a harmonic stimulus.
7. All groups demonstrated pre-attentive auditory neural responses to three pitch deviances (1.5%, 3%, and 6%). Interestingly, nonmusicians responded pre-attentively to pitch deviances as small as 1.5%; even though on the behavioral auditory pitch discrimination task, their just noticeable difference was two times greater (3.19%).
8. Amplitude differences in event-related potentials (ERPs) did not differentiate the musicians from the nonmusicians. For the musicians, the strength of the auditory neural response did not depend on the magnitude of pitch deviation; that is, there was no predictable response pattern. On the other hand, the control group tended to have stronger responses to larger pitch changes.
9. For all groups, as the magnitude of pitch deviance increased, pre-attentive auditory neural response to the pitch change occurred earlier.
10. Overall, auditory change detection was faster for the musicians than the nonmusicians.
11. The vocal musicians responded faster to the pitch changes than the nonmusicians, while response latency did not significantly differ between the instrumentalists and the nonmusicians. Latency was shorter for the vocalists than the instrumentalists; however, the difference was not significant.

12. No relationships were found between psychoacoustic variables (DLF and PPA) and electrophysiological variables (MMN amplitude and latency) for any of the groups.
13. The number of years of music training appears to influence pre-attentive auditory neural responses. Those musicians who had more years of music training tended to respond faster to pitch deviances. There were no relationships between the number of years of music training and measures of DLF or PPA.
14. No relationships were found between the age that music training began and psychoacoustic or electrophysiological variables.

## Chapter Five

### Discussion

This study was a beginning step of inquiry into the effects of intensive music training on the auditory neural processes of musicians and subsequently, on the relationship between auditory perception and vocal production. Reliable evidence suggests that instrumental musicians experience changes in the auditory system following skill acquisition and sensory stimulation and have superior auditory pitch discrimination and vocal pitch production compared to nonmusicians; yet little is known about neural changes in the auditory system in formally trained vocal musicians. Auditory pitch perception and laryngeal control are considered essential skills for accurate pitch production; however, the relationship between neurophysiological processes and perception-production abilities is unclear. Electrophysiologic and psychoacoustic measures were used to examine relationships between pitch production accuracy, active pitch discrimination, and pre-attentive pitch discrimination between two genres of musicians (vocalists and instrumentalists) and a musically untrained control group.

## *Discussion of Findings in Relationship to the Research Questions*

### *Vocal Pitch Production Accuracy*

The first hypothesis predicted a difference of vocal pitch matching accuracy between musicians and nonmusicians and between the instrumental and vocal musicians. Although the exact relationship between auditory feedback and laryngeal control is yet to be determined, evidence indicates that accurate pitch production is influenced by auditory monitoring and proprioceptive feedback of the laryngeal system (Amir et al., 2003; Campisi et al., 2005; Kirchner & Wyke, 1965; Leydon et al., 2003; Mürbe et al., 2004; Ward & Burns, 1978; Wyke, 1974; Titze, 1994). Amir et al. (2003) reported that instrumental musicians with no previous vocal training, vocally matched pitch approximately three times more accurately than nonmusicians (i.e., *relative accuracy* based on grand means was 2.88% and 8.94%, respectively). Results of this study reinforce the implication that musicians who have superior auditory pitch perception may also have enhanced pitch production abilities. In the present study, the overall target pitch production was six times more accurate for the musicians than the nonmusician controls (i.e., *relPPA* of the grand means was 1.28% and 7.83%, respectively). However, it should be remembered that one-half of the musicians were formally trained singers. When the vocal musician data was removed, the instrumental musicians were still five times more accurate (i.e., mean *relPPA* = 1.5%) than the nonmusicians. In both studies, musically untrained participants had mean pitch production errors greater than one semitone.



It is suggested that music training nurtures a musician's sensitivity to acoustic parameters (e.g., pitch, rhythm, loudness). During music instruction, whether for an instrument or voice, the accuracy between a reference pitch and the actual produced pitch is developed and proprioceptive memory for pitch is enhanced by continued training and practice (Mürbe et al., 2004). These experiences build and strengthen a sensory perception-motor production relationship that may explain why instrumental musicians not only have exceptional auditory perception skills, but also greater pitch production accuracy than nonmusicians.

It was also questioned whether a difference of vocal pitch production accuracy (PPA) existed between instrumental and vocal musicians. Research suggests that professional vocal training sharpens proprioceptive reflexes of laryngeal joints, refines neuromuscular control of laryngeal and respiratory muscles (Ward & Burns, 1978; Wyke, 1974), and improves neuromuscular memory for pitch control and accuracy (DiCarlo, 1994; Mürbe et al., 2004, 2002). For these reasons, it was anticipated that the formally trained singers would match vocal pitch to a reference pitch more accurately than the instrumental musicians. Surprisingly, this hypothesis was not supported by the data; that is, average *relPPA%* did not significantly differ between the two groups of musicians (i.e., 1.5% for the instrumentalists and 1.05% for the vocalists). Based on the grand means, both groups produced pitch within 1/8 of the reference pitch. Although average *relPPA%* was comparable, the distribution of the musicians' responses differed significantly. It is relevant to note that within the vocal musician group there was very minimal inter-subject variability. Nearly every vocalist produced each pitch within 0% to

3% of the reference; while responses of the instrumental musicians varied between 0% and 18% of the reference. The precision and consistency of performance demonstrated by the trained singers is believed to be a reflection of their vocal training. A plausible explanation for the lack of distinction between the vocalists and the instrumentalists is the simplicity of the vocal task. The single pitch imitation task was designed to determine whether a difference existed between musicians and nonmusicians even for a very basic pitch imitation task. The harmonic tone complexes were purposefully chosen to be within the mid-female vocal range. Imitation was performed for a single tone stimulus at a pace determined by the participant. While even this task appeared to be challenging for some of the nonmusicians, it was simplistic for the musicians, especially for the vocalists. It is likely that a more challenging pitch production task (e.g., sequence of tones, variable pitch range, or faster stimulus presentation) would delineate differences between the two musician groups. The pronounced uniformity of the vocalists' responses implies that intense vocal training has a positive affect on laryngeal control such that pitch production is not only precise, but consistent.

#### *Active Auditory Pitch Discrimination*

The second hypothesis proposed that musicians and nonmusicians would differ in terms of active auditory frequency discrimination ability (DLF). Furthermore, it was questioned whether a difference in this ability exists between instrumental and vocal musicians. Consensus among published research has suggested that formally trained musicians have smaller frequency discrimination thresholds (DLFs) than nonmusicians

(Kishon-Rabin et al., 2001; Spiegel & Watson, 1984). Whether pitch discrimination differs between different genres of musicians is uncertain.

Auditory pitch discrimination of harmonic complexes (musical tones) was more precise for the musicians than the nonmusicians. On average, the musicians' just noticeable difference of pitch change was less than one-half that of the control group (i.e., 1.35% compared to 3.19%). These results are compatible with the approximate 2:1 ratio between nonmusicians and musicians found by Kishon-Rabin et al. (2001) and Spiegel and Watson (1984). It is reasonable to surmise that intense practice and musical instruction hones a musician's categorical perception of pitch. As discussed in Chapter 2, the Western musical scale is based on intervals of tones and semitones. A change in one semitone is perceived by musicians as an alteration in the musical melody. For the musicians in this study, whose jnd averaged 1.35%, a pitch change of plus or minus one-quarter of a semitone (i.e.,  $\pm 1.5\%$ ) crosses a musical boundary and signals a significant change similar to crossing a critical bandwidth in the cochlea. As a group, the formally trained musicians clearly demonstrated superior pitch discrimination and on average detected pitch changes within one-eighth of a difference in tone frequencies.

The *rel*DLF values for musicians reported by Spiegel and Watson (1984) and Kishon-Rabin et al. (2001) were much smaller than those in this study (e.g., approximately 0.01 for instrumental musicians in both studies). This difference may be explained by choices of stimuli and paradigm procedure. Although Spiegel and Watson (1984) used both pure tones and complex (square wave) sounds, component frequencies were above 440 Hz and presented in a 71% 2I/2AFC design; while Kishon-Rabin et al.,

(2001) used a 71% 3I/3AFC paradigm and stimuli consisted of pure tones at 250 Hz, 1k Hz and 2k Hz. In the present study, stimuli were harmonic tone complexes with fundamental frequencies within the mid-female vocal range between 261.63 and 392 Hz. DLF was established by a 79% 3I/3AFC paradigm. Each of the selected conditions (harmonic complexes, low fundamental frequencies, and the 79% three-alternative forced-choice design) has been shown to elicit larger DLFs in the normal population compared to pure tone stimuli at frequencies between 500 and 2k Hz and a 2I/2AFC paradigm (Leek, 2001; Moore, 1989; Moore & Peters, 1992). Consequently, a combination of all three of these conditions is expected to elicit higher DLFs than the previous studies. Interestingly, Kishon-Rabin and colleagues reported that for all subjects the largest *rel*DLF% occurred for 250 Hz. Examination of their data reveals that if the DLFs of the 3 runs for the 250 Hz condition are averaged together, the *rel*DLF% for the musicians and nonmusicians are remarkably similar to those in the present study. Namely, the average *rel*DLF% would be 1.42% for the musicians and 2.86% for the nonmusicians, compared to 1.35% and 3.19%, respectively in the present study.

It has been suggested that auditory skills may differ between musicians of distinct musical genres (Kishon-Rabin et al., 2001; Spiegel & Watson, 1984; Tervaniemi, Castaneda, Knoll, & Uther, 2006). Spiegel and Watson (1984) reported that musicians who tuned their own instrument (e.g., brass, string, wind instruments) had smaller discrimination thresholds, half the size of those who did not tune their own instrument (e.g., piano). These findings were not replicated by Kishon-Rabin et al. (2001); however, their data indicated that musicians of classical training had significantly smaller threshold

estimates than those with a contemporary background. Most recently, Tervaniemi et al., (2006) provided evidence that musicians selectively encode acoustic parameters most relevant to their musical genre.

Since precise pitch discrimination is crucial for a singer's performance and because a singer's *instrument* is endogenous to the body (i.e., the larynx), it was speculated that the just noticeable difference (jnd) may be even smaller for vocal musicians than for instrumentalists. This hypothesis was not supported by the data; difference limens for frequency were almost identical (i.e., 1.3% for the singers and 1.4% for the instrumentalists). While the evidence did not support a difference between these two musical genres on this particular psychoacoustic task, it is the first study to show that formally trained vocal musicians, like instrumental musicians, have superior pitch discrimination abilities.

The musicians' superior and comparable auditory discrimination skills for harmonic tone complexes may be due to the instruction received by student musicians enrolled in the School of Music at the University of South Florida. Musicians receive similar instruction in aural theory including lessons in musical syntax, sight-reading, and pitch perception. Moreover, it is well documented that auditory pitch perception "is a fundamental capacity in musical talent..."(Seashore, 1919, p. 42 as cited in Pedersen & Pedersen) and a vital skill for *all* musicians. Whether this exceptional pitch perception is an inherent advantage, a skill developed from years of intense training or a combination of these two factors, is yet unknown.

Present findings indicate that formally trained musicians, even those whose have never participated in vocal training, have superior auditory perception ability *and* enhanced pitch production accuracy (Table 4). This finding suggests that instrumental music training influences the integration of the body’s motor and sensory systems. This dual effect provides further evidence to support the interaction between the auditory and laryngeal systems. If music training facilitates sensory perception and motor production, then perhaps similar training techniques may be incorporated into treatment strategies for populations facing sensory perception and motor production challenges, including those with dyslexia or hearing impairment and/or persons who are neurologically impaired.

Table 4. *Rel*DLF% and *Rel*PPA% – Group Comparison

<b>Group</b>		<b>N</b>	<b><i>rel</i>%</b>	<b>Semitone</b>
<b>Control</b>				
	DLF	21	3.19%	0.53
	PPA	21	7.83%	1.30
<b>Musician</b>				
	DLF	40	1.35%	0.23
	PPA	40	1.28%	0.21
<b>Instrumental</b>				
	DLF	21	1.40%	0.23
	PPA	21	1.50%	0.25
<b>Vocal</b>				
	DLF	19	1.30%	0.22
	PPA	19	1.05%	0.17

### *Electrophysiological Measures of Pre-Attentive Auditory Pitch Discrimination*

This study proposed an electrophysiological investigation to examine pre-attentive sensory processing of auditory pitch stimuli by formally trained musicians. It was anticipated that small changes in pitch would be detected prior to the participants' attention to the auditory stimuli and that these pre-attentive auditory neural responses would be faster and stronger for musicians than nonmusicians. Moreover, it was hypothesized that auditory neural responses may differ between instrumental and vocal musicians. Measures of latency and amplitude to deviances in harmonic tone complexes were examined for the following ERP components: P1-N1-P2 complex and mismatch negativity (MMN).

*Sensory perception P1-N1-P2 complex.* As described in Chapters 2 and 4, the P1-N1-P2 components are sensitive to physical changes in auditory stimuli. The complex occurs approximately 50 – 200 ms after the onset of an auditory stimulus and is interpreted as an indicator of preferential attention (Key et al., 2005). For the purposes of this study, P1-N1-P2 was examined to establish that all participants had comparable basic pre-attentive sensory perception, similar to verifying hearing acuity prior to behavioral testing. No significant differences at this level of auditory processing were expected. The P1-N1-P2 response latencies and amplitudes for harmonic tone complexes did not appear to differ between the two subclasses of musicians, nor did the P1-N1-P2 latencies or the N1-P2 amplitudes appear to differ between the musicians and nonmusicians. Surprisingly, the nonmusicians had larger P1 amplitudes for each harmonic complex.

The P1 is associated with sensory gating which has been described as the brain's ability to modulate its sensitivity to incoming irrelevant sensory stimuli (Boutros, Torello, Barker, Tueting & Wu, 1995; Braff & Geyer, 1990). The P1 amplitude may be interpreted as a neurophysiological indicator of preferential attention to sensory input (Key et al., 2005). It is considered to reflect differences in regulating excitatory and inhibitory processes; that is, 'gating in' or 'gating out' auditory information. Failure of this process is thought to be a possible underlying contributor to the development of psychotic states, such as schizophrenia (Boutros et al., 1995).

An increase in the P1 amplitude has been shown to reflect pre-attentive recognition of *novel* stimuli in the normal population (Boutros et al., 1995). As a consequence of a musician's training, the central auditory system is familiar with musical tones and thus, probably less sensitive to the presentation of harmonic complexes. Moreover, during the electroencephalographic recording, all participants were instructed to watch a closed captioned video and ignore the presence of sound. By the inherent nature of their training, musicians may be better prepared to ignore or to attend to competing musical stimuli. It is possible that music training influences the brain's sensory gating mechanism. Therefore, it is reasonable to expect that musicians may have smaller P1 amplitudes for familiar musical stimuli than nonmusicians. Findings of this study are the first to suggest that musical expertise influences neural responses as early as 50 ms after the onset of a musically relevant stimulus. The P1-N1-P2 complex has not been specifically examined in adult musicians and warrants further research.



*Mismatch negativity (MMN).* The MMN is a neurophysiological response that reflects access to a neural memory of an acoustic parameter (Nousak, Deacon, Ritter, & Vaughan, 1996) and provides a neurological index of individual discrimination ability (Näätänen, 1995; Näätänen, Pakarinen, Rinne, & Takegata, 2004). It may be described in terms of latency (time of occurrence after stimulus onset) and amplitude (height of epoch representing strength of response). Previous EEG evidence indicates superior pre-attentive auditory processing abilities for musicians and suggests that musical expertise influences pitch processing by refining the neural frequency-processing network (Koelsch et al., 1999; Pantev et al., 2001; Schön et al., 2004; Shahin et al., 2003; Tervaniemi, Just, Koelsch, Widmann, & Schröger, 2005; van Zuijen et al., 2004). Because of the extensive music training and practice received by musicians, the present study predicted that musicians would have larger amplitudes and earlier latencies than nonmusicians for detection of small pitch deviances approaching behavioral DLFs. It was also questioned whether these neurophysiological responses differed between instrumental and vocal musicians.

*MMN amplitude.* Auditory neural responses reflecting sensory memory for pitch were anticipated to be stronger for musicians than nonmusicians. Surprisingly, amplitude values for pre-attentive auditory neural responses to changes in pitch did not significantly differ between controls and musicians. While all groups responded with an amplitude mismatch to the deviant stimuli, the MMN amplitude values did not differentiate the musicians from the nonmusicians nor did they vary between the subclasses of musicians. There was a non-significant trend for the control group to have stronger sensory

responses as the magnitude of deviance increased; that is, as the pitch difference became larger, so did the response amplitude. There was no such pattern or tendency for the musicians.

Musicians have been shown to have larger MMN amplitudes in response to multidimensional deviances, such as harmonically inappropriate chords (Koelsch et al., 2002), pitch change within a familiar scale (Brattico et al., 2001), and note change within a complex melody (Lopez et al., 2003). Koelsch et al. (1999) suggested that the auditory sensory memory traces of musicians contain more acoustic parameter information than the memory traces of musically untrained individuals. This implies that musicians may require less neural effort to extract certain acoustic information. Given this perspective, perhaps the auditory discrimination task in the present study was not complex enough to distinguish the MMN amplitude responses between the musicians and the nonmusicians. This explanation concurs with similar findings reported by Tervaniemi and colleagues (2005) who also questioned whether a similar auditory perceptual task was too easy for musicians.

P1 amplitude findings in the present study provide further evidence for training-induced changes in auditory neural processing. Musicians had smaller P1 amplitudes in response to harmonic complexes compared to nonmusicians implying that the brain's familiarity with musical stimuli moderated the reaction of the sensory gating mechanism. Current evidence reinforces the suggestion that musicians have superior training-enhanced sensory memory representations for acoustic parameters of harmonic stimuli.

Thus, as a consequence of their training, perhaps less neural energy is required for musicians to process simple acoustic parameters of musically relevant stimuli.

*MMN latency.* Electrophysiological evidence indicates that music training modifies neural processing of acoustic input revealing that instrumental musicians have faster neural responses for pitch changes than nonmusicians (Koelsch et al., 2002; Koelsch et al., 1999; Shahin et al., 2003; Tervaniemi et al., 2005). It was anticipated that all subject groups would have a pre-attentive response to changes in pitch deviance approaching behavioral DLFs. It was further hypothesized that musicians would have earlier latencies than nonmusicians and that within the musician group a difference would exist between instrumental and vocal musicians.

Pre-attentive auditory neural responses to changes in pitch frequency were present for all groups and for all three conditions of pitch deviance (1.5%, 3%, and 6%). As the frequency difference between the deviant stimulus and the standard stimulus increased, the auditory neural response to the pitch change occurred faster. For example, the 6% pitch deviance elicited the earliest MMN response for all groups, followed by the 3% change and then the 1.5% pitch change. As predicted, the musicians responded to all pitch changes faster than those without music training and those musicians who had more years of music training tended to respond fastest. These findings provide further evidence that fundamental auditory processing abilities can be facilitated by music training.

Closer inspection of the two musician groups noted that only the vocalists responded earlier to pitch changes than the control group; the instrumentalists did not.

This suggests that latency was shortest for the vocalists; however, this inference was not supported by the analysis. Although MMN latency for detection of pitch deviance occurred earlier for the vocal musicians, the difference did not reach significance. Nevertheless, ERP evidence indicates that formally trained vocal musicians, similar to instrumental musicians, have superior pre-attentive neural frequency processing.

Electrophysiological data from the present study clearly reinforce the philosophy that MMN amplitude and latency reflect two independent factors influencing the mismatch response and should be measured and analyzed separately (Lang et al., 1995; Näätänen, 1992). Moreover, findings support theories that music training and experience facilitate modification of neural processing and enhance sensory memory representations of acoustic parameters.

The exact effect of music training and expertise on the neural frequency-processing network remains unknown. Intense music training has been shown to stimulate microstructural neurological changes (Pantev et al., 2001; Pascual-Leone et al., 1995). Considering the mechanisms by which microstructural plasticity occurs (Calford, 2002), perhaps rigorous musical practice amplifies the communication between neurons by strengthening the synapses and thus increasing the efficiency of neural transmission at a cellular level. This idea is compatible with the proposal that acoustic training enhances the tuning processes of neurons in the auditory cortex (Shahin et al., 2003). Taking this supposition one step further, perhaps modification of the frequency-tuning process affects categorical perception. As described in Chapter 2, pitch differences in music are perceived categorically (Sundberg, 1994). Slight variations in frequency have no effect

on the classification of a pitch or tone; however, at the border of a frequency range, a minor shift radically changes the perception from one category to another. It is speculated that formal music training may sharpen the borders of categorical pitch perception so that slight changes in pitch are detected automatically with greater precision prior to a cognitive decision. This is a plausible explanation for the musicians' earlier reactions to pitch deviances and supports the argument for independent processes underlying amplitude and latency responses.

#### *Relationships between Auditory Perception and Pitch Production Across Groups*

Auditory pitch discrimination (perception) and vocal pitch control (production) have been identified as related abilities and essential skills for musicians. Based on a review of previous investigations and on theories of neural plasticity, it was hypothesized that a positive correlation exists between perception and production abilities for musical stimuli and that this correlation would be stronger for the formally trained musicians and strongest for the formally trained vocal musicians. Specifically, relationships between pitch production accuracy, active auditory pitch discrimination, and pre-attentive auditory neural responses were examined among formally trained musicians and nonmusicians as well as between vocal and instrumental musicians.

*Correlations between DLF and PPA.* A positive relationship between perception and production was expected. At first glance, it appears that this hypothesis is true. A combination of all individual data yielded a significant positive correlation between auditory discrimination and vocal pitch production accuracy ( $r_s = 0.61$ ,  $p < .001$ ). These

results are similar to those of Amir et al. (2003) who reported a positive relationship between vocal production and auditory perception when instrumental musician and nonmusician data was merged ( $r = 0.67$ ). However, in the present study, when the relationship between perception and production is viewed separately for each group, the outcome is not as clear and points to differences between the two musical genres.

Neither the control group nor the vocal musicians demonstrated a significant relationship between perception and production. Perception and production abilities varied greatly within the control group. By severe contrast, the vocalists performed both tasks accurately with minimal response variability reflecting their training and expertise in both areas. Only the instrumental musicians had a positive correlation between auditory discrimination and pitch production accuracy, reinforcing the implication that instrumental music instruction facilitates a sensory perception-motor production relationship.

*Correlations between psychoacoustic and electrophysiological variables.* Others have investigated relationships between neural and behavioral responses to pitch deviances by comparing MMN amplitude and latency to hit rate (HR) and reaction time (RT) for auditory discrimination between two frequencies (Novitski et al., 2004; Lang et al., 1995). There tends to be a positive correlation between HR and MMN amplitude; however, correlations between HR, RT, and MMN latency are inconsistent (Novitski et al., 2004; Lang et al., 1995).

Evidence from the present study indicates that formal music training affects psychoacoustic abilities (DLF and PPA) as well as electrophysiological responses (P1

amplitude, MMN latency); yet, evidence did not support significant relationships between these measures for any subject group. Difference limens for frequency were determined rather than response speed (RT) or accuracy (HR) for pitch discrimination. Since the behavioral variables were not the same as those measured in the prior studies, the discrepancy between correlation outcomes may be due to task measurement differences. Moreover, the variables in this study may not correlate simply because they represent different processes. ERPs reflect automatic neurophysiological memory-based sensory responses to change detection. By contrast, difference limen for frequency and pitch production accuracy are measures of active behavioral choices influenced by attention and short-term memory in addition to subjective motivation and cooperation. Thus, the electrophysiologic variables may represent only a subset of the processes underlying behavioral discrimination and production of frequency.

*Summary of relationships among groups.* Musicians had faster neural responses to pitch deviances and demonstrated superior active (attentive) auditory discrimination and vocal pitch production compared to nonmusicians. A significant correlation between perception and production abilities was apparent for only the instrumental musicians. Sufficient evidence to support relationships between the electrophysiological and psychoacoustic variables was not observed.

#### *Relationships between Auditory Perception and Pitch Production Within Groups*

The final hypothesis questioned relationships between perception and production variables within each group. It was anticipated that within a subject group a pattern of

abilities may exist between pitch production accuracy, auditory pitch discrimination and pre-attentive pitch discrimination.

*Comparison of DLF and PPA.* For those without music training, auditory discrimination was almost 3 times more accurate than pitch production. Whereas the just noticeable difference (jnd) between harmonic complexes was within  $\frac{1}{2}$  of a semitone, vocal pitch production deviated almost  $1\frac{1}{2}$  semitones from the target pitch. Studies of singing development in children attribute this deviance of pitch production from discrimination to inadequate laryngeal muscle control, poor kinesthetic feedback from the larynx and/or delayed internal auditory monitoring (Goetze et al., 1990). By comparison, the instrumental musicians discriminated and vocally produced harmonic complexes equally well reinforcing the supposition that instrumental music training facilitates the integration of the body's motor and sensory systems.

In contrast to the other two groups, vocal musicians were more accurate for pitch control than for pitch perception. Although their jnd was approximately one-quarter of a semitone, their PPA was within one-sixth of a semitone. This implies that the vocalists internally discriminated between a target and a produced pitch with greater precision than they distinguished between two externally presented harmonic tones. The present findings support previous research (DiCarlo, 1994; Kirchner & Wyke, 1965; Mürbe et al., 2002) and concur that formally trained vocal musicians develop explicit sensory memory representations and enhanced laryngeal proprioceptive reflexes secondary to training-induced neural changes. Perhaps the link between auditory perception and pitch production is not exclusively between active pitch discrimination and laryngeal control.



Rather, training also enhances a relationship between auditory sensory memories and laryngeal reflexes.

Consensus among published research suggests that a degree of auditory pitch discrimination may serve as a pre-requisite to vocal pitch matching ability and that these two skills may be two independent abilities between which a relationship strengthens with training and development (Geringer, 1983; Goetze et al., 1990; Yarbrough et al., 1991). Present findings show that the relationship between PPA and DLF can occur on a continuum and agree that this relationship is influenced by music training. Specifically, PPA was poorer than DLF for those with no music training; PPA was equal to DLF for those who received only instrumental training; and PPA was better than DLF for vocalists who were specifically trained for pitch production accuracy.

*Comparison of pre-attentive and active pitch discrimination.* It was not the purpose of this investigation to establish pre-attentive difference limens for frequency (i.e., the just noticeable difference between two frequencies). Previous MMN data has shown that musicians respond to pitch deviances as small as 0.8% (Tervaniemi et al., 2005). The harmonic complexes chosen for this electrophysiologic task were based on the best and poorest DLFs obtained from the psychoacoustic task. The smallest pitch deviation (1.5%) from the standard tone (392 Hz) was slightly above the mean frequency discrimination threshold obtained for the musicians (1.35%). As expected, the musicians responded pre-attentively to the smallest pitch deviance.

Surprisingly, the control group also responded pre-attentively to the 1.5% pitch deviance even though attentively, just noticeable difference for pitch deviance was two

times greater ( $relDLF\% = 3.19\%$ ). This discovery has several implications. While the influence of genetic factors can not be dismissed, it may be argued that superior auditory discrimination is not an inherent ability, but one that may be shaped by specific training. Electrophysiological evidence suggests that music training enhances the neural encoding of memory representations and facilitates retrieval of these sensory memory traces. This implies that nonmusicians, who have not experienced this explicit training, may have less efficient access to neural memories for making attentive behavioral decisions.

Furthermore, this discovery reinforces speculation that automatic memory traces underlie subsequent attentive processes (Sams et al., 1985; Tervaniemi, 2001; Tervaniemi et al., 2005) and lends further support to theories of training-induced cortical plasticity.

*Summary of within group relationships.* It appears that those with no music training have better pre-attentive neural pitch discrimination than active (attentive) discrimination and more accurate auditory pitch discrimination than vocal pitch production. The vocal musicians had superior pitch production skill compared to auditory pitch discrimination, while the instrumental musicians demonstrated equivalent abilities for all three tasks. Formal music training appears to facilitate underlying auditory neural processes that in turn influence attentive auditory discrimination and laryngeal control.

### *Limitations of the Study*

The research design and methods of the present study were successful in addressing the research questions. However, while every effort was made to control for validity and reliability, the following limitations are considered:

1. The sample population of musicians volunteered from the University of South Florida's School of Music and was not randomly selected. Subjects had a mean age of 22 and an average of 10.5 years of music training. Care should be given when generalizing results to all musicians. The type of music instruction and the extent of training, practice, and performance vary greatly among musicians and any one of these factors may influence task performance.
2. There are no formally established procedures or standards of protocol for eliciting and/or analyzing auditory evoked potentials (AEPs) of mismatch negativity (MMN) of the human brain. Methods for procedures and analysis were based on extensive review of current published literature and personal consultation with leading experts in the field. Caution should be exercised when comparing results between studies since protocols may vary.
3. While the pitch perception and production tasks designed for this study were appropriate for nonmusicians, they may have been too simplistic to delineate significant differences between the vocal and instrumental musicians. Thus, performance measures may not be the best representation of the musicians' pitch perception or production abilities.

4. While present findings indicate that musicians have superior pitch perception and production skills secondary to training-induced neural changes in auditory processes, it is not possible to rule out an influence of genetic coding and innate abilities. The musicians in this study reported a much higher incidence of musicians in the immediate family (13 of 40) than the nonmusicians (1 of 21).

#### *Directions for Future Research*

Previous neurophysiological research has identified anatomical and physiological differences between musicians and nonmusicians. Electrophysiological evidence, including the present study, strengthens the premise that auditory neural changes occur following skill acquisition and sensory stimulation. This study was the first to explore and compare the effects of long-term music training on variables of pitch perception and production between vocal and instrumental musicians. Further research is warranted to differentiate the effects of training on neural processes between these two groups. Findings suggest that more complex perception and production tasks may tease out distinctive abilities.

The mismatch negativity (MMN) brain response provides an objective noninvasive index of auditory discrimination and an excellent means to study training effects on auditory neural plasticity. Because of their rigorous training, musicians are an exceptional population in which to examine the influence of expertise on acoustic parameters of perception such as frequency, duration, intensity, timbre, and rhythm. Moreover, there are many diverse genres of musicians with which to compare the

influence of training and practice on the brain. A longitudinal study or comparative analysis of young and old musicians may also provide distinctive information on the effects of aging on their superior perception and production skills, not to mention differentiating age of onset of music training versus number of years of training which necessarily covary in a population of uniform age. Native singers of tone languages (e.g. Vietnamese and Mandarin) offer a unique population in whom to study pitch production and auditory neural responses to pitch perception. Their language specific pitch perception and production skills may provide additional insight into the debate over inherent abilities and genetic coding versus effects of training.

Findings from the present study suggest that music training facilitates pitch perception and production regardless of musical genre. Moreover, published research concurs that musicians have superior pitch detection skills not only for music stimuli, but also for language suggesting that music training enhances pitch processing for both music and language (Schön, Magne, & Besson, 2004). Previous electrophysiologic (Friederici, Pfeifer, & Hahne, 1993) and neural imaging (Koelsch et al., 2000) studies report considerable overlap of neural structures and similar neural systems responsible for the integration of pitch processing of both music and language. The therapeutic effects of music training on pitch perception and production for clinical populations who present with impairments of pitch perception and production, such as those with cochlear implants, dyslexia, and/or Parkinson's disease, warrants further research.

Another area of electrophysiologic research that merits further investigation is cerebral lateralization of activity. Is there hemispheric dominance for the processing of

certain acoustic parameters and does this hemispheric activity differ by population, task or training?

Much remains to be discovered about the diverse effects of long-term training on electrophysiological responses. The present study identified an incidental effect of music training on the P1 AEP component. The P1 amplitude, an index of the brain's ability to modulate sensitivity to sensory input, differed between musicians and nonmusicians and warrants additional study. Visual inspection of ERP data also noted that the P3a response differed between the subject groups. The P3a component is thought to reflect a passive attention switch to stimuli and often follows an MMN response. cursory examination of this component suggested a possible training effect and merits additional investigation.

### *Conclusions*

Electrophysiologic and psychoacoustic measures were used to examine pre-attentive and active pitch discrimination as well as pitch production accuracy between nonmusicians, formally trained instrumental musicians, and formally trained vocal musicians. This study was a beginning step of inquiry to compare the effects of long-term music training on the auditory neural function of nonmusicians compared to musicians from two discrete musical genres. The overall objective was to take an initial step to contribute to the body of basic research regarding the perception and production abilities of formally trained vocal musicians.

All musicians, regardless of specialty, demonstrated superior auditory pitch perception (DLF) and vocal pitch production accuracy (PPA) compared to nonmusicians.

Vocal musicians and instrumental musicians performed equally well on the psychoacoustic tasks. Furthermore, pitch production accuracy across all frequencies was most consistent for the vocalists. Evidence supports the implication that music training facilitates both auditory perception and vocal production regardless of music specialty.

Findings suggest that auditory pitch discrimination may serve as a pre-requisite to pitch production accuracy. Namely, the data reflect that the relationship between PPA and DLF occurs on a continuum. Pitch production accuracy was poorer than auditory pitch discrimination for those with no previous music training. PPA was equal to DLF for those who had only instrumental music training; while pitch production accuracy was superior to auditory pitch discrimination for vocal musicians, reflecting their specialty training. The two psychoacoustic variables were significantly correlated only for the instrumentalists. Vocalists demonstrated minimal inter-subject variability so that a correlation was not detected.

Electrophysiological evidence from the present study indicates that vocal musicians, like instrumental musicians, experience neural changes in the auditory system following skill acquisition and sensory training and demonstrate superior pre-attentive auditory discrimination. This study is the first to report an influence of musical expertise on auditory neural responses as early as 50 ms (P1) after onset of musical stimuli.

MMN responses indicate that vocal musicians, as well as instrumental musician, have superior sensory memory representations for acoustic parameters of harmonic stimuli and imply that auditory neural changes are facilitated by long-term music training. Overall, auditory neural detection of pitch deviance was faster for musicians than nonmusicians.

In other words, the musicians recognized a change in the acoustic parameter of the musical stimuli sooner than the nonmusicians. Based on P1 and MMN amplitude data, it is suggested that perhaps musicians require less neural energy to extract simple acoustic parameters of musically relevant stimuli.

Interestingly, nonmusicians responded pre-attentively to pitch deviances that were  $\frac{1}{2}$  their attentive DLF. This discovery supports the theory that automatic memory traces may underlie subsequent attentive processes and are enhanced and facilitated by music training. The present findings reinforce the hypothesis that plasticity in the neuroanatomical system is reflected in neurological change in the auditory system as a result of long-term music training.

The exact relationship among physiological variables, perceptual abilities, and pitch production remains elusive; however, auditory pitch perception and vocal pitch production appear to be independent abilities between which a relationship develops with training. Perhaps the elusive link is *not* to be found between attentive cortical processes. Rather, a complex connection, as yet to be discovered, may lie within the neural substrates of auditory sensory memories and laryngeal reflexes.



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## Appendices

Appendix A: Participant Screening Questionnaire

**PARTICIPANT SCREENING QUESTIONNAIRE**

Subject Code: \_\_\_\_\_

Birth Date: \_\_\_\_\_

INSTRUCTIONS: Please read each question and answer accordingly. Either circle YES or NO or complete a short response. If you have any questions, please feel free to ask the investigator.

GENERAL INFORMATION

- |   |     |    |
|---|-----|----|
| 1. Are you female?  | YES | NO |
| 2. Are you between the ages of 18 and 35?   | YES | NO |
| 3. Are you a native speaker of English (learned English as a child)?  | YES | NO |
| 4. Are you a fluent speaker of a tonal language (e.g., Vietnamese)?   | YES | NO |
| 5. Are you naturally right-handed?  | YES | NO |
| 6. Have you participated in other experiments where you listened to musical sounds and determined if they were the same or different? | YES | NO |
| 7. Do you have absolute pitch ability (AP), also known as perfect pitch?  | YES | NO |

MEDICAL

- |  |     |    |
|--|-----|----|
| 8. Do you have any history of vocal cord disease or phonosurgery, such as nodules, polyps, cyst?         | YES | NO |
| 9. Do you have any history of neurological illness or disease?   | YES | NO |
| 10. Do you now or have you ever had a habit of cigarette smoking?  | YES | NO |
| 11. Do you now or have you ever abused alcohol or drug use?  | YES | NO |
| 12. Are you currently having allergy symptoms or respiratory problems that affect your voice or hearing? | YES | NO |
| 13. Do you have any known hearing impairment?  | YES | NO |

SCREENINGS

- |                      |        |   |     |     |      |      |         |
|----------------------|--------|---|-----|-----|------|------|---------|
| 1. Hearing Screening | @ 25dB | R | 250 | 500 | 1000 | 2000 | 4000 Hz |
|                      |        | L | 250 | 500 | 1000 | 2000 | 4000 Hz |

PASS or FAIL

- |                |                                 |              |
|----------------|---------------------------------|--------------|
| 2. Vocal Sweep | A <sub>3</sub> → A <sub>4</sub> | PASS or FAIL |
|----------------|---------------------------------|--------------|

**ACCEPT**

**DO NOT ACCEPT**

Appendix B: Participant Information Questionnaire

**PARTICIPANT INFORMATION QUESTIONNAIRE**

Subject Code: \_\_\_\_\_ Birth Date: \_\_\_\_\_

INSTRUCTIONS: Please read each question and answer accordingly. Either circle YES or NO or complete a short response. If you have any questions, please feel free to ask the investigator.

EDUCATION

1. Have you had less than 12 months of musical instruction, such as band, piano, guitar, or voice lessons? YES NO

2. Have you had 5 years or more of singing (voice) lessons/instruction? YES NO

If YES, please answer questions a. through h. then go to question # 4. If NO, go to question # 3.

a. At what age did you begin your music training? \_\_\_\_\_

b. At what age did you begin your vocal training? \_\_\_\_\_

c. How many total years of music training have you had? \_\_\_\_\_

d. How many total years of just vocal training have you had? \_\_\_\_\_

e. Is your vocal training in classical voice? YES NO

f. Is your vocal training in choral voice? YES NO

g. Combination? If yes, please describe. \_\_\_\_\_

h. Other? Please describe. \_\_\_\_\_

3. Have you had 5 years or more of instrumental musical lessons? YES NO

If yes, what is your primary instrument? \_\_\_\_\_

At what age did you begin your music training? \_\_\_\_\_

How many total years of music training have you had? \_\_\_\_\_

4. Has any immediate family member also had 5 years or more of voice or instrumental lessons? If yes, explain YES NO

\_\_\_\_\_

5. What was your best math score on your SAT exam? Please circle the range.

Less than 400      400 →499      500 →599      600 →699      700→800

6. What was your best verbal score on your SAT exam? Please circle the range.

Less than 400      400→499      500→599      600→699      700→800

## Appendix C: Informed Consent Form

Space below reserved for IRB Stamp – Please leave blank

### **Informed Consent**

Social and Behavioral Sciences  
University of South Florida

### **Information for People Who Take Part in Research Studies**

---

The following information is being presented to help you decide whether or not you want to take part in a minimal risk research study. Please read this carefully. If you do not understand anything, ask the person in charge of the study.

**Title of Study:** Auditory Neural Plasticity in Trained Vocal Musicians

**Principal Investigator:** Deborah Adams Nikjeh

**Study Location(s):** University of South Florida; Dept. of Communication Sciences & Disorders, PCD 3008 and PCD 3006

You are being asked to participate because this study will compare pitch perception and production among trained female vocal musicians and musically untrained females.

#### **General Information about the Research Study**

The purpose of this research study is to assess, compare and correlate three identified physiological variables that contribute to the performance of the singing voice. Those three variables are: (1) auditory pitch discrimination, (2) vocal pitch matching accuracy, and (3) pre-attentive auditory pitch discrimination.

#### **Plan of Study**

If you agree to participate, you will first be asked to provide some basic information about your music training, education and language background, and general health. If you meet the criteria for this study, you will then have your vocal pitch range and your hearing screened. If you pass these two screenings, you are ready to begin the study. There are three tasks in this study. First, you will be seated in front of a computer monitor in a sound treated booth. You will hear two sounds through earphones. Then, two boxes will appear on the computer screen, labeled “same” and “different.” You decide if the two sounds are same or different and mouse click on the proper box. For the next task, you will also wear earphones with a microphone in the sound treated booth. You will hear a piano tone for 2 seconds. You then sing the same tone (pitch) aloud on the sound “ah” for 3 seconds into the microphone and your voice is recorded. For the third task, you may rest comfortably in a reclining chair in a sound treated booth and watch a closed captioned movie of your choice without the sound. Instead, you will be wearing earphones and very soft and fast sounds will be played through the earphones. A cap with small electrodes will be placed on your head to record your brain’s responses to the sounds. A tiny amount of cream is applied between each electrode and your scalp. There is no pain whatsoever. You can relax and watch the movie while your brain waves are recorded.

The total time for participation is typically 2 to 3 hours and will be broken down into 2 visits, approximately 60 to 90 minutes each.

## Appendix C: (Continued)

### **Payment for Participation**

You will be entitled to one of the following: (1) Extra credit in a pre-determined course in Communication Sciences and Disorders, (2) Extra credit in a pre-determined course in the School of Music or (3) \$10 per hour for your participation. If you withdraw from the study before completion, payment or extra credit will be pro-rated based on actual time volunteered to the closest hour.

### **Benefits of Being a Part of this Research Study**

You will not benefit directly from this study. However, your participation will help to increase our understanding of the function and adaptability of the human brain.

### **Risks of Being a Part of this Research Study**

There are no known risks from participation in this study.

### **Confidentiality of Your Records**

Your privacy and research records will be kept confidential to the extent of the law. Authorized research personnel, employees of the Department of Health and Human Services, and the USF Institutional Review Board may inspect the records from this research project.

The results of this study may be published. However, the data obtained from you will be combined with data from others in the publication. The published results will not include your name or any other information that would personally identify you in any way. The computer files with your data will be identified by an arbitrary code that will not be connected to your name. The consent forms and questionnaires will be kept separately in a locked file cabinet.

### **Volunteering to Be Part of this Research Study**

Your decision to participate in this research study is completely voluntary. You are free to participate in this research study or to withdraw at any time. There will be no penalty or negative consequences if you stop taking part in the study.

### **Questions and Contacts**

- If you have any questions about this research study, contact Dee Adams Nikjeh at [Nikjeh@mail.usf.edu](mailto:Nikjeh@mail.usf.edu) or Dr. Stefan A. Frisch at (813) 974-6563 or [Frisch@cas.usf.edu](mailto:Frisch@cas.usf.edu)
- If you have questions about your rights as a person who is taking part in a research study, you may contact the Division of Research Compliance of the University of South Florida at (813) 974-5638.

### **Consent to Take Part in This Research Study**

By signing this form I agree that:

- I have fully read or have had read and explained to me this informed consent form describing this research project.
- I have had the opportunity to question one of the persons in charge of this research and have received satisfactory answers.
- I understand that I am being asked to participate in research. I understand the risks and benefits, and I freely give my consent to participate in the research project outlined in this form, under the conditions indicated in it.

Appendix C: (Continued)

- I have been given a signed copy of this informed consent form, which is mine to keep.

\_\_\_\_\_  
Signature of Participant

\_\_\_\_\_  
Printed Name of Participant

\_\_\_\_\_  
Date

**Investigator Statement**

I have carefully explained to the subject the nature of the above research study. I hereby certify that to the best of my knowledge the subject signing this consent form understands the nature, demands, risks, and benefits involved in participating in this study.

\_\_\_\_\_  
Signature of Investigator  
Or authorized research  
investigator designated by  
the Principal Investigator

\_\_\_\_\_  
Printed Name of Investigator

\_\_\_\_\_  
Date

Appendix D: Participant Profile Data

<b>GROUP</b>	<b>SUBJECTS</b>	<b>AGE MOS</b>	<b>AGE TRNG INITIATED</b>	<b>TTL YRS TRNG</b>	<b>YRS and INSTRUM</b>	<b>AGE VCL TRNG INIT</b>	<b>YEARS VOCAL</b>	<b>MOTHER</b>	<b>FATHER</b>	<b>SIBLING</b>	<b>SAT- MATH</b>	<b>SAT- VERBAL</b>
CONTROL	C01	245									4	4
CONTROL	C02	266										
CONTROL	C03	399									4	6
CONTROL	C04	250										
CONTROL	C05	406									5	5
CONTROL	C06	242									5	4
CONTROL	C07	249									5	5
CONTROL	C08	241										
CONTROL	C09	256									5	5
CONTROL	C10	239									5	5
CONTROL	C11	403									6	7
CONTROL	C12	361								X	5	5
CONTROL	C13	253									5	7
CONTROL	C14	247									4	4
CONTROL	C15	252									6	4
CONTROL	C16	256									6	5
CONTROL	C17	265									5	6
CONTROL	C18	254									5	4
CONTROL	C19	292									5	6
CONTROL	C20	262									5	5
CONTROL	C21	251							X		5	5



Appendix D: (Continued)

GROUP	SUBJECTS	AGE MOS	AGE TRNG INITIATED	TTL YRS TRNG	YRS and INSTRUM	AGE VCL TRNG INIT	YEARS VOCAL	MOTHER	FATHER	SIBLING	SAT- MATH	SAT- VERBAL
INSTRUMENTAL	IN01	260	11	10	10 wind		0				7	6
INSTRUMENTAL	IN02	237	10	8	8 wind		0			X	5	7
INSTRUMENTAL	IN03	254	3	15	15 string		0				5	5
INSTRUMENTAL	IN04	223	7	8	8 string		0				6	5
INSTRUMENTAL	IN05	265	6	15	15 wind		0	X			6	6
INSTRUMENTAL	IN06	226	11	8	8 string		0				4	6
INSTRUMENTAL	IN07	267	11	11	11 wind		0				4	5
INSTRUMENTAL	IN08	244	10	9	9 wind		0			X	4	5
INSTRUMENTAL	IN09	265	7	8	8 string		0				7	5
INSTRUMENTAL	IN10	262	5	13	13 string		0	X			5	5
INSTRUMENTAL	IN11	259	4	8	8 string		0				6	5
INSTRUMENTAL	IN12	252	15	7	7 wind		0				4	4
INSTRUMENTAL	IN13	228	11	7	7 wind		0				5	5
INSTRUMENTAL	IN14	257	11	9	9 string		0				5	5
INSTRUMENTAL	IN15	356	11	7	7 wind		0	X	X	X	6	6
INSTRUMENTAL	IN16	303	10	15	15 string		0	X	X	X	5	6
INSTRUMENTAL	IN17	335	11	9	9 wind		0			X	7	5
INSTRUMENTAL	IN18	234	11	10	10 string		0			X	5	6
INSTRUMENTAL	IN19	220	4	8	8 string		0			X	6	6
INSTRUMENTAL	IN20	286	5	13	13 string		0				5	5
INSTRUMENTAL	IN21	233	10	8	8 wind		0				6	4

Appendix D: (Continued)

GROUP	SUBJECTS	AGE MOS	AGE TRNG INITIATED	TTL YRS TRNG	YEARS INSTRUM	AGE VCL TRNG INIT	YEARS VOCAL	MOTHER	FATHER	SIBLING	SAT-MATH	SAT-VERBAL
VOCAL	V01	224	5	13	0	5	13				4	5
VOCAL	V02	293	11	13	9	17	7		X	X	3	3
VOCAL	V03	281	6	17	9	9	9	X			5	5
VOCAL	V04	227	5	13	9	13	5	X			5	5
VOCAL	V05	234	8	6	0	8	6				5	4
VOCAL	V06	221	11	8	0	11	8			X	6	5
VOCAL	V07	263	8	14	0	8	14			X	6	5
VOCAL	V08	232	11	9	5	11	9		X		5	6
VOCAL	V09	270	8	11	6	8	6		X		6	6
VOCAL	V10	229	9	10	0	9	10	X		X	6	5
VOCAL	V11	225	7	11	4	12	6	X			5	6
VOCAL	V12	235	9	10	0	9	7				5	5
VOCAL	V13	270	6	8	5	8	8			X	6	5
VOCAL	V14	248	12	8	6	16	5				6	5
VOCAL	V15	258	11	10	0	14	7				5	5
VOCAL	V16	276	12	11	0	12	11	X	X	X	4	5
VOCAL	V17	335	8	19	13	8	19	X	X		5	7
VOCAL	V18	257	8	13	0	12	9				6	4
VOCAL	V19	396	5	13	0	5	13					
VOCAL	V20	265	10	8	0	10	8				5	5

Appendix D: (Continued)

**SUMMARY OF SUBJECT DATA**

<b>GROUP</b>		<b>AGE- YEARS</b>	<b>AGE TRAINING INITIATED</b>	<b>TOTAL YEARS TRAINING</b>	<b>YEARS INSTRUM</b>	<b>AGE VOCAL TRNG INIT</b>	<b>YEARS VOCAL</b>	<b>MOTHER</b>	<b>FATHER</b>	<b>SIBLING</b>	<b>SAT- MATH</b>	<b>SAT- VERBAL</b>
<b>CONTROL</b>	Mean	23.4	N/A	N/A	N/A	N/A	N/A	1.0	0.0	1.0	5.0	5.1
	Max	33.8	N/A	N/A	N/A	N/A	N/A				6.0	7.0
	Min	19.9	N/A	N/A	N/A	N/A	N/A				4.0	4.0
<b>INSTRUMENTAL</b>	Mean	21.7	8.8	9.8	9.8	N/A	0.0	4.0	2.0	7.0	5.4	5.3
	Max	29.7	15.0	15.0	15.0	N/A	0.0				7.0	7.0
	Min	18.3	3.0	7.0	7.0	N/A	0.0				4.0	4.0
<b>VOCAL</b>	Mean	21.8	8.5	11.3	3.3	10.3	9.0	6.0	5.0	6.0	5.2	5.1
	Max	33.0	12.0	19.0	13.0	17.0	19.0				6.0	7.0
	Min	18.4	5.0	6.0	0.0	5.0	5.0				3.0	3.0

## Appendix E: Individual Data for Pitch Production Accuracy

Subj	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff%	Stimulus	Prod Hz	Diff Hz	Diff%
C01	261.63/C4	309.54	47.91	18.3%	269.48/C4+qtr	291.59	22.11	8.2%	277.32/C4#	265.97	11.35	4.1%
C02	261.63/C4	272.88	11.25	4.3%	269.48/C4+qtr	321.95	52.47	19.5%	277.32/C4#	266.45	10.87	3.9%
C03	261.63/C4	234.94	26.69	10.2%	269.48/C4+qtr	238.26	31.22	11.6%	277.32/C4#	266.65	10.67	3.8%
C04	261.63/C4	194.68	66.95	25.6%	269.48/C4+qtr	205.27	64.21	23.8%	277.32/C4#	206.12	71.2	25.7%
C05	261.63/C4	255.91	5.72	2.2%	269.48/C4+qtr	259.71	9.77	3.6%	277.32/C4#	266.53	10.79	3.9%
C06	261.63/C4	261.33	0.3	0.1%	269.48/C4+qtr	259.52	9.96	3.7%	277.32/C4#	275.28	2.04	0.7%
C07	261.63/C4	252.14	9.49	3.6%	269.48/C4+qtr	268.38	1.1	0.4%	277.32/C4#	277.9	0.58	0.2%
C08	261.63/C4	263.23	1.6	0.6%	269.48/C4+qtr	273.82	4.34	1.6%	277.32/C4#	280.12	2.8	1.0%
C09	261.63/C4	227.02	34.61	13.2%	269.48/C4+qtr	224.91	44.57	16.5%	277.32/C4#	231.27	46.05	16.6%
C10	261.63/C4	236.53	25.1	9.6%	269.48/C4+qtr	249.35	20.13	7.5%	277.32/C4#	273.65	3.67	1.3%
C11	261.63/C4	254.81	6.82	2.6%	269.48/C4+qtr	255.3	14.18	5.3%	277.32/C4#	276.1	1.22	0.4%
C12	261.63/C4	252.28	9.35	3.6%	269.48/C4+qtr	264.81	4.67	1.7%	277.32/C4#	274.4	2.92	1.1%
C13	261.63/C4	245.17	16.46	6.3%	269.48/C4+qtr	245.3	24.18	9.0%	277.32/C4#	253.74	23.58	8.5%
C14	261.63/C4	265.06	3.43	1.3%	269.48/C4+qtr	270.23	0.75	0.3%	277.32/C4#	276.1	1.22	0.4%
C15	261.63/C4	207.57	54.06	20.7%	269.48/C4+qtr	237.9	31.58	11.7%	277.32/C4#	219.87	57.45	20.7%
C16	261.63/C4	202.68	58.95	22.5%	269.48/C4+qtr	187.17	82.31	30.5%	277.32/C4#	213.18	64.14	23.1%
C17	261.63/C4	265.2	3.57	1.4%	269.48/C4+qtr	272.79	3.31	1.2%	277.32/C4#	282.12	4.8	1.7%
C18	261.63/C4	254.33	7.3	2.8%	269.48/C4+qtr	257.74	11.74	4.4%	277.32/C4#	272.92	4.4	1.6%
C19	261.63/C4	259.98	1.65	0.6%	269.48/C4+qtr	270.41	0.93	0.3%	277.32/C4#	283.3	5.98	2.2%
C20	261.63/C4	253.18	8.45	3.2%	269.48/C4+qtr	252.92	16.56	6.1%	277.32/C4#	270.39	6.93	2.5%
C21	261.63/C4	258.14	3.49	1.3%	269.48/C4+qtr	269.85	0.37	0.1%	277.32/C4#	277.59	0.27	0.1%

Appendix E: (Continued)

Subj	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff%	Stimulus	Prod Hz	Diff Hz	Diff%
C01	329.63/E4	341.34	11.71	3.6%	320.03/E4-qtr	355.6	35.57	11.1%	310.97/D4#	351	40.03	12.9%
C02	329.63/E4	378.49	48.86	14.8%	320.03/E4-qtr	342.21	22.18	6.9%	310.97/D4#	345.37	34.4	11.1%
C03	329.63/E4	305.6	24.03	7.3%	320.03/E4-qtr	304.26	15.77	4.9%	310.97/D4#	276.7	34.27	11.0%
C04	329.63/E4	242.28	87.35	26.5%	320.03/E4-qtr	221.11	98.92	30.9%	310.97/D4#	233.98	76.99	24.8%
C05	329.63/E4	338.53	8.9	2.7%	320.03/E4-qtr	315.01	5.02	1.6%	310.97/D4#	276.4	34.57	11.1%
C06	329.63/E4	322.78	6.85	2.1%	320.03/E4-qtr	314.24	5.79	1.8%	310.97/D4#	308.32	2.65	0.9%
C07	329.63/E4	327.36	2.27	0.7%	320.03/E4-qtr	304.26	15.77	4.9%	310.97/D4#	291.47	19.5	6.3%
C08	329.63/E4	323.63	6	1.8%	320.03/E4-qtr	315.55	4.48	1.4%	310.97/D4#	307.88	3.09	1.0%
C09	329.63/E4	238.75	90.88	27.6%	320.03/E4-qtr	236.84	83.19	26.0%	310.97/D4#	277.03	33.94	10.9%
C10	329.63/E4	326.47	3.16	1.0%	320.03/E4-qtr	325.68	5.65	1.8%	310.97/D4#	301.15	9.82	3.2%
C11	329.63/E4	326.82	2.81	0.9%	320.03/E4-qtr	317.46	2.57	0.8%	310.97/D4#	310.67	0.3	0.1%
C12	329.63/E4	314.07	15.56	4.7%	320.03/E4-qtr	325.78	5.75	1.8%	310.97/D4#	301.6	9.37	3.0%
C13	329.63/E4	318.82	10.81	3.3%	320.03/E4-qtr	286.78	33.25	10.4%	310.97/D4#	255.22	55.75	17.9%
C14	329.63/E4	323.77	5.86	1.8%	320.03/E4-qtr	319.77	0.26	0.1%	310.97/D4#	309.61	1.36	0.4%
C15	329.63/E4	238.63	91	27.6%	320.03/E4-qtr	249.17	70.86	22.1%	310.97/D4#	283.81	27.16	8.7%
C16	329.63/E4	307.95	21.68	6.6%	320.03/E4-qtr	227.31	92.72	29.0%	310.97/D4#	219.93	91.04	29.3%
C17	329.63/E4	331.67	2.04	0.6%	320.03/E4-qtr	301.54	18.49	5.8%	310.97/D4#	311.7	0.73	0.2%
C18	329.63/E4	312.22	17.41	5.3%	320.03/E4-qtr	311.83	8.2	2.6%	310.97/D4#	294.37	16.6	5.3%
C19	329.63/E4	286.15	43.48	13.2%	320.03/E4-qtr	316.82	3.21	1.0%	310.97/D4#	311.61	0.64	0.2%
C20	329.63/E4	300.31	29.32	8.9%	320.03/E4-qtr	272.76	47.27	14.8%	310.97/D4#	264.92	46.05	14.8%
C21	329.63/E4	324.43	5.2	1.6%	320.03/E4-qtr	318.77	1.26	0.4%	310.97/D4#	305.53	5.44	1.7%

Appendix E: (continued)

Subj	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %
C01	392.00/G4	405.44	13.44	3.4%	380.58/G4-qtr	412.64	32.06	8.4%	369.81/F4#	376.96	7.15	1.9%
C02	392.00/G4	428.19	36.19	9.2%	380.58/G4-qtr	405.95	25.37	6.7%	369.81/F4#	373.7	3.89	1.1%
C03	392.00/G4	360.43	31.57	8.1%	380.58/G4-qtr	340.99	39.59	10.4%	369.81/F4#	329.75	40.06	10.8%
C04	392.00/G4	255.13	136.87	34.9%	380.58/G4-qtr	258.88	121.7	32.0%	369.81/F4#	230.85	138.96	37.6%
C05	392.00/G4	382.85	9.15	2.3%	380.58/G4 -qtr	373.66	6.92	1.8%	369.81/F4#	364.87	4.94	1.3%
C06	392.00/G4	387.46	4.54	1.2%	380.58/G4 -qtr	374.8	5.78	1.5%	369.81/F4#	364.88	4.93	1.3%
C07	392.00/G4	390.48	1.52	0.4%	380.58/G4 -qtr	381.36	0.78	0.2%	369.81/F4#	372.81	3	0.8%
C08	392.00/G4	385.08	6.92	1.8%	380.58/G4 -qtr	372.15	8.43	2.2%	369.81/F4#	366.93	2.88	0.8%
C09	392.00/G4	248.34	143.66	36.6%	380.58/G4 -qtr	253.93	126.65	33.3%	369.81/F4#	242.98	126.83	34.3%
C10	392.00/G4	429.68	37.68	9.6%	380.58/G4 -qtr	438.65	58.07	15.3%	369.81/F4#	371.74	1.93	0.5%
C11	392.00/G4	384.12	7.88	2.0%	380.58/G4 -qtr	377.39	3.19	0.8%	369.81/F4#	367.87	1.94	0.5%
C12	392.00/G4	384.6	7.4	1.9%	380.58/G4 -qtr	368.76	11.82	3.1%	369.81/F4#	357.12	12.69	3.4%
C13	392.00/G4	315.56	76.44	19.5%	380.58/G4 -qtr	301.49	79.09	20.8%	369.81/F4#	349.78	20.03	5.4%
C14	392.00/G4	393.23	1.23	0.3%	380.58/G4 -qtr	461.27	80.69	21.2%	369.81/F4#	367.18	2.63	0.7%
C15	392.00/G4	354.39	37.61	9.6%	380.58/G4 -qtr	345.36	35.22	9.3%	369.81/F4#	357.57	12.24	3.3%
C16	392.00/G4	361.83	30.17	7.7%	380.58/G4 -qtr	374.78	5.8	1.5%	369.81/F4#	300.9	68.91	18.6%
C17	392.00/G4	396.31	4.31	1.1%	380.58/G4 -qtr	377.14	3.44	0.9%	369.81/F4#	367.89	1.92	0.5%
C18	392.00/G4	386.88	5.12	1.3%	380.58/G4 -qtr	363.55	17.03	4.5%	369.81/F4#	371.46	1.65	0.4%
C19	392.00/G4	385.16	6.84	1.7%	380.58/G4 -qtr	344.33	36.25	9.5%	369.81/F4#	369.93	0.12	0.0%
C20	392.00/G4	318.55	73.45	18.7%	380.58/G4 -qtr	321.26	59.32	15.6%	369.81/F4#	315.51	54.3	14.7%
C21	392.00/G4	380.15	11.85	3.0%	380.58/G4 -qtr	365.48	15.1	4.0%	369.81/F4#	363.31	6.5	1.8%

Appendix E: (Continued)

Subj	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %
IN01	261.63/C4	253.71	7.92	3.0%	269.48/C4+qtr	267.6	1.88	0.7%	277.32/C4#	278.28	0.96	0.3%
IN02	261.63/C4	250.81	10.82	4.1%	269.48/C4+qtr	257.93	11.55	4.3%	277.32/C4#	275.86	1.46	0.5%
IN03	261.63/C4	258.23	3.4	1.3%	269.48/C4+qtr	268.5	0.98	0.4%	277.32/C4#	273.39	3.93	1.4%
IN04	261.63/C4	259.67	1.96	0.7%	269.48/C4+qtr	269.81	0.33	0.1%	277.32/C4#	276.6	0.72	0.3%
IN05	261.63/C4	262.75	1.12	0.4%	269.48/C4+qtr	274.51	5.03	1.9%	277.32/C4#	282.87	5.55	2.0%
IN06	261.63/C4	260.42	1.21	0.5%	269.48/C4+qtr	269.47	0.01	0.0%	277.32/C4#	275.19	2.13	0.8%
IN07	261.63/C4	239.41	22.22	8.5%	269.48/C4+qtr	270.41	0.93	0.3%	277.32/C4#	278.7	1.38	0.5%
IN08	261.63/C4	260.87	0.76	0.3%	269.48/C4+qtr	273.94	4.46	1.7%	277.32/C4#	277.94	0.62	0.2%
IN09	261.63/C4	263.61	1.98	0.8%	269.48/C4+qtr	263.56	5.92	2.2%	277.32/C4#	274.28	3.04	1.1%
IN10	261.63/C4	260.47	1.16	0.4%	269.48/C4+qtr	267.53	1.95	0.7%	277.32/C4#	277.15	0.17	0.1%
IN11	261.63/C4	254.73	6.9	2.6%	269.48/C4+qtr	248.92	20.56	7.6%	277.32/C4#	250.49	26.83	9.7%
IN12	261.63/C4	268.36	6.73	2.6%	269.48/C4+qtr	271.64	2.16	0.8%	277.32/C4#	281.51	4.19	1.5%
IN13	261.63/C4	260.77	0.86	0.3%	269.48/C4+qtr	270.17	0.69	0.3%	277.32/C4#	276.78	0.54	0.2%
IN14	261.63/C4	266.3	4.67	1.8%	269.48/C4+qtr	271.8	2.32	0.9%	277.32/C4#	281.25	3.93	1.4%
IN15	261.63/C4	259.73	1.9	0.7%	269.48/C4+qtr	268.8	0.68	0.3%	277.32/C4#	275.82	1.5	0.5%
IN16	261.63/C4	263.52	1.89	0.7%	269.48/C4+qtr	272.69	3.21	1.2%	277.32/C4#	276.57	0.75	0.3%
IN17	261.63/C4	259.12	2.51	1.0%	269.48/C4+qtr	266.15	3.33	1.2%	277.32/C4#	276.6	0.72	0.3%
IN18	261.63/C4	263.1	1.47	0.6%	269.48/C4+qtr	270.4	0.92	0.3%	277.32/C4#	279.2	1.88	0.7%
IN19	261.63/C4	261.09	0.54	0.2%	269.48/C4+qtr	268.95	0.53	0.2%	277.32/C4#	279.97	2.65	1.0%
IN20	261.63/C4	254.09	7.54	2.9%	269.48/C4+qtr	271.18	1.7	0.6%	277.32/C4#	268.06	9.26	3.3%
IN21	261.63/C4	255.96	5.67	2.2%	269.48/C4+qtr	273.17	3.69	1.4%	277.32/C4#	273.27	4.05	1.5%

Appendix E: (Continued)

Subj	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %
IN01	329.63/E4	344.4	14.77	4.5%	320.03/E4 -qtr	317.78	2.25	0.7%	310.97/D4#	332.46	21.49	6.9%
IN02	329.63/E4	321.83	7.8	2.4%	320.03/E4 -qtr	305.52	14.51	4.5%	310.97/D4#	309.38	1.59	0.5%
IN03	329.63/E4	324.68	4.95	1.5%	320.03/E4 -qtr	315	5.03	1.6%	310.97/D4#	305.89	5.08	1.6%
IN04	329.63/E4	330.71	1.08	0.3%	320.03/E4 -qtr	322.22	2.19	0.7%	310.97/D4#	308.64	2.33	0.7%
IN05	329.63/E4	330.08	0.45	0.1%	320.03/E4 -qtr	319.24	0.79	0.2%	310.97/D4#	311.69	0.72	0.2%
IN06	329.63/E4	325.38	4.25	1.3%	320.03/E4 -qtr	315.41	4.62	1.4%	310.97/D4#	307.51	3.46	1.1%
IN07	329.63/E4	334.2	4.57	1.4%	320.03/E4 -qtr	314.63	5.4	1.7%	310.97/D4#	304.58	6.39	2.1%
IN08	329.63/E4	329.89	0.26	0.1%	320.03/E4 -qtr	323.95	3.92	1.2%	310.97/D4#	311.72	0.75	0.2%
IN09	329.63/E4	328.42	1.21	0.4%	320.03/E4 -qtr	320.67	0.64	0.2%	310.97/D4#	308.95	2.02	0.6%
IN10	329.63/E4	327.99	1.64	0.5%	320.03/E4 -qtr	318.52	1.51	0.5%	310.97/D4#	312.06	1.09	0.4%
IN11	329.63/E4	269.7	59.93	18.2%	320.03/E4 -qtr	322.09	2.06	0.6%	310.97/D4#	307.15	3.82	1.2%
IN12	329.63/E4	330.96	1.33	0.4%	320.03/E4 -qtr	321.8	1.77	0.6%	310.97/D4#	312.04	1.07	0.3%
IN13	329.63/E4	328.89	0.74	0.2%	320.03/E4 -qtr	319.89	0.14	0.0%	310.97/D4#	312.19	1.22	0.4%
IN14	329.63/E4	330.48	0.85	0.3%	320.03/E4 -qtr	318.34	1.69	0.5%	310.97/D4#	313.3	2.33	0.7%
IN15	329.63/E4	326.84	2.79	0.8%	320.03/E4 -qtr	317.46	2.57	0.8%	310.97/D4#	313.07	2.1	0.7%
IN16	329.63/E4	325.26	4.37	1.3%	320.03/E4 -qtr	317.17	2.86	0.9%	310.97/D4#	307.2	3.77	1.2%
IN17	329.63/E4	329.18	0.45	0.1%	320.03/E4 -qtr	316.85	3.18	1.0%	310.97/D4#	307.9	3.07	1.0%
IN18	329.63/E4	330.67	1.04	0.3%	320.03/E4 -qtr	316.55	3.48	1.1%	310.97/D4#	310.6	0.37	0.1%
IN19	329.63/E4	329.48	0.15	0.0%	320.03/E4 -qtr	321.77	1.74	0.5%	310.97/D4#	307.51	3.46	1.1%
IN20	329.63/E4	292.86	36.77	11.2%	320.03/E4 -qtr	323.53	3.5	1.1%	310.97/D4#	291.85	19.12	6.1%
IN21	329.63/E4	347.67	18.04	5.5%	320.03/E4 -qtr	321.41	1.38	0.4%	310.97/D4#	305.04	5.93	1.9%



Appendix E: (Continued)

Subj	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %
IN01	392.00/G4	391.15	0.85	0.2%	380.58/G4 -qtr	370.48	10.1	2.7%	369.81/F4#	370.62	0.81	0.2%
IN02	392.00/G4	385.95	6.05	1.5%	380.58/G4 -qtr	371.7	8.88	2.3%	369.81/F4#	357.44	12.37	3.3%
IN03	392.00/G4	382.64	9.36	2.4%	380.58/G4 -qtr	372.66	7.92	2.1%	369.81/F4#	355.87	13.94	3.8%
IN04	392.00/G4	391.96	0.04	0.0%	380.58/G4 -qtr	370.65	9.93	2.6%	369.81/F4#	370.36	0.55	0.1%
IN05	392.00/G4	392.06	0.06	0.0%	380.58/G4 -qtr	373.44	7.14	1.9%	369.81/F4#	365.86	3.95	1.1%
IN06	392.00/G4	387.66	4.34	1.1%	380.58/G4 -qtr	369.69	10.89	2.9%	369.81/F4#	368.7	1.11	0.3%
IN07	392.00/G4	364.92	27.08	6.9%	380.58/G4 -qtr	372.23	8.35	2.2%	369.81/F4#	348.76	21.05	5.7%
IN08	392.00/G4	393.64	1.64	0.4%	380.58/G4 -qtr	380.34	0.24	0.1%	369.81/F4#	370.46	0.65	0.2%
IN09	392.00/G4	389.31	2.69	0.7%	380.58/G4 -qtr	369.7	10.88	2.9%	369.81/F4#	372.62	2.81	0.8%
IN10	392.00/G4	391.42	0.58	0.1%	380.58/G4 -qtr	379.09	1.49	0.4%	369.81/F4#	366.54	3.27	0.9%
IN11	392.00/G4	388.41	3.59	0.9%	380.58/G4 -qtr	376.51	4.07	1.1%	369.81/F4#	359.37	10.44	2.8%
IN12	392.00/G4	382.97	9.03	2.3%	380.58/G4 -qtr	382.98	2.4	0.6%	369.81/F4#	374.31	4.5	1.2%
IN13	392.00/G4	390.51	1.49	0.4%	380.58/G4 -qtr	377.88	2.7	0.7%	369.81/F4#	366.68	3.13	0.8%
IN14	392.00/G4	381.55	10.45	2.7%	380.58/G4 -qtr	378.67	1.91	0.5%	369.81/F4#	368.26	1.55	0.4%
IN15	392.00/G4	394.7	2.7	0.7%	380.58/G4 -qtr	374.14	6.44	1.7%	369.81/F4#	370.42	0.61	0.2%
IN16	392.00/G4	390.64	1.36	0.3%	380.58/G4 -qtr	375.84	4.74	1.2%	369.81/F4#	368.2	1.61	0.4%
IN17	392.00/G4	390.18	1.82	0.5%	380.58/G4 -qtr	377.55	3.03	0.8%	369.81/F4#	367.52	2.29	0.6%
IN18	392.00/G4	392.78	0.78	0.2%	380.58/G4 -qtr	382.59	2.01	0.5%	369.81/F4#	370.26	0.45	0.1%
IN19	392.00/G4	387.79	4.21	1.1%	380.58/G4 -qtr	374.25	6.33	1.7%	369.81/F4#	362.5	7.31	2.0%
IN20	392.00/G4	397.65	5.65	1.4%	380.58/G4 -qtr	355.64	24.94	6.6%	369.81/F4#	375.1	5.29	1.4%
IN21	392.00/G4	379.05	12.95	3.3%	380.58/G4 -qtr	375.43	5.15	1.4%	369.81/F4#	375.75	5.94	1.6%

Appendix E: (Continued)

Subj	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %
V01	261.63/C4	263.28	1.65	0.6%	269.48/C4+qtr	264.31	5.17	1.9%	277.32/C4#	274.09	3.23	1.2%
V02	261.63/C4	261.05	0.58	0.2%	269.48/C4+qtr	268.13	1.35	0.5%	277.32/C4#	275.6	1.72	0.6%
V03	261.63/C4	261.08	0.55	0.2%	269.48/C4+qtr	262.96	6.52	2.4%	277.32/C4#	275.52	1.8	0.6%
V04	261.63/C4	257.32	4.31	1.6%	269.48/C4+qtr	263.94	5.54	2.1%	277.32/C4#	272.88	4.44	1.6%
V05	261.63/C4	263.53	1.9	0.7%	269.48/C4+qtr	274.25	4.77	1.8%	277.32/C4#	279.84	2.52	0.9%
V06	261.63/C4	258.89	2.74	1.0%	269.48/C4+qtr	269.47	0.01	0.0%	277.32/C4#	277.31	0.01	0.0%
V07	261.63/C4	259.26	2.37	0.9%	269.48/C4+qtr	268.75	0.73	0.3%	277.32/C4#	274.46	2.86	1.0%
V08	261.63/C4	258.8	2.83	1.1%	269.48/C4+qtr	275.57	6.09	2.3%	277.32/C4#	276.76	0.56	0.2%
V09	261.63/C4	281.97	20.34	7.8%	269.48/C4+qtr	273.35	3.87	1.4%	277.32/C4#	276.14	1.18	0.4%
V10	261.63/C4	258.65	2.98	1.1%	269.48/C4+qtr	265.73	3.75	1.4%	277.32/C4#	275.83	1.49	0.5%
V11	261.63/C4	261.01	0.62	0.2%	269.48/C4+qtr	270.14	0.66	0.2%	277.32/C4#	277.28	0.04	0.0%
V12	261.63/C4	258.1	3.53	1.3%	269.48/C4+qtr	268.03	1.45	0.5%	277.32/C4#	272.95	4.37	1.6%
V13	261.63/C4	257.88	3.75	1.4%	269.48/C4+qtr	272.23	2.75	1.0%	277.32/C4#	276.01	1.31	0.5%
V14	261.63/C4	255.35	6.28	2.4%	269.48/C4+qtr	271.27	1.79	0.7%	277.32/C4#	271.79	5.53	2.0%
V15	261.63/C4	255.92	5.71	2.2%	269.48/C4+qtr	274.18	4.7	1.7%	277.32/C4#	279.43	2.11	0.8%
V16	261.63/C4	260.57	1.06	0.4%	269.48/C4+qtr	268.86	0.62	0.2%	277.32/C4#	275	2.32	0.8%
V17	261.63/C4	263.99	2.36	0.9%	269.48/C4+qtr	267.06	2.42	0.9%	277.32/C4#	278.32	1	0.4%
V18	261.63/C4	259.46	2.17	0.8%	269.48/C4+qtr	266.73	2.75	1.0%	277.32/C4#	273.75	3.57	1.3%
V19	261.63/C4	268.46	6.83	2.6%	269.48/C4+qtr	276.24	6.76	2.5%	277.32/C4#	271.45	5.87	2.1%
V20	261.63/C4	260.64	0.99	0.4%	269.48/C4+qtr	273.34	3.86	1.4%	277.32/C4#	277.34	0.02	0.0%

Appendix E: (Continued)

Subj	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Prod Hz	Diff Hz	Diff %
V01	329.63/E4	327.65	1.98	0.6%	320.03/E4 -qtr	322.21	2.18	0.7%	310.97/D4#	309.39	1.58	0.5%
V02	329.63/E4	327.22	2.41	0.7%	320.03/E4 -qtr	318.11	1.92	0.6%	310.97/D4#	312.1	1.13	0.4%
V03	329.63/E4	330.8	1.17	0.4%	320.03/E4 -qtr	316.52	3.51	1.1%	310.97/D4#	308.83	2.14	0.7%
V04	329.63/E4	326.94	2.69	0.8%	320.03/E4 -qtr	316.59	3.44	1.1%	310.97/D4#	307.47	3.5	1.1%
V05	329.63/E4	328.5	1.13	0.3%	320.03/E4 -qtr	314.64	5.39	1.7%	310.97/D4#	310.38	0.59	0.2%
V06	329.63/E4	332.04	2.41	0.7%	320.03/E4 -qtr	318.06	1.97	0.6%	310.97/D4#	310.96	0.01	0.0%
V07	329.63/E4	324.25	5.38	1.6%	320.03/E4 -qtr	317.42	2.61	0.8%	310.97/D4#	309.03	1.94	0.6%
V08	329.63/E4	333.21	3.58	1.1%	320.03/E4 -qtr	318.19	1.84	0.6%	310.97/D4#	315.01	4.04	1.3%
V09	329.63/E4	333.32	3.69	1.1%	320.03/E4 -qtr	318.5	1.53	0.5%	310.97/D4#	314.68	3.71	1.2%
V10	329.63/E4	325.22	4.41	1.3%	320.03/E4 -qtr	316.47	3.56	1.1%	310.97/D4#	309.54	1.43	0.5%
V11	329.63/E4	329.06	0.57	0.2%	320.03/E4 -qtr	319.44	0.59	0.2%	310.97/D4#	312.43	1.46	0.5%
V12	329.63/E4	323.63	6	1.8%	320.03/E4 -qtr	310.44	9.59	3.0%	310.97/D4#	310.26	0.71	0.2%
V13	329.63/E4	326.75	2.88	0.9%	320.03/E4 -qtr	321.04	1.01	0.3%	310.97/D4#	314.22	3.25	1.0%
V14	329.63/E4	323.87	5.76	1.7%	320.03/E4 -qtr	319.49	0.54	0.2%	310.97/D4#	307.24	3.73	1.2%
V15	329.63/E4	328.87	0.76	0.2%	320.03/E4 -qtr	323.95	3.92	1.2%	310.97/D4#	311.54	0.57	0.2%
V16	329.63/E4	324.87	4.76	1.4%	320.03/E4 -qtr	315.99	4.04	1.3%	310.97/D4#	306.6	4.37	1.4%
V17	329.63/E4	328.87	0.76	0.2%	320.03/E4 -qtr	318.84	1.19	0.4%	310.97/D4#	313.85	2.88	0.9%
V18	329.63/E4	327.6	2.03	0.6%	320.03/E4 -qtr	316.09	3.94	1.2%	310.97/D4#	307.68	3.29	1.1%
V19	329.63/E4	324.95	4.68	1.4%	320.03/E4 -qtr	317.54	2.49	0.8%	310.97/D4#	313.54	2.57	0.8%
V20	329.63/E4	327.63	2	0.6%	320.03/E4 -qtr	316.85	3.18	1.0%	310.97/D4#	309.66	1.31	0.4%

Appendix E: (Continued)

Subj	Stimulus	Prod Hz	Diff Hz	Diff %	Stimulus	Diff			Stimulus	Prod Hz	Diff Hz	Diff %
						Prod Hz	Hz	Diff %				
V01	392.00/G4	388.05	3.95	1.0%	380.58/G4-qtr	374.8	5.78	1.5%	369.81/F4#	368.85	0.96	0.3%
V02	392.00/G4	390.81	1.19	0.3%	380.58/G4-qtr	375.32	5.26	1.4%	369.81/F4#	370.96	1.15	0.3%
V03	392.00/G4	392.65	0.65	0.2%	380.58/G4-qtr	373.59	6.99	1.8%	369.81/F4#	370.32	0.51	0.1%
V04	392.00/G4	388.15	3.85	1.0%	380.58/G4-qtr	371.13	9.45	2.5%	369.81/F4#	367.89	1.92	0.5%
V05	392.00/G4	387.09	4.91	1.3%	380.58/G4-qtr	369.41	11.17	2.9%	369.81/F4#	370.55	0.74	0.2%
V06	392.00/G4	382.77	9.23	2.4%	380.58/G4-qtr	371.44	9.14	2.4%	369.81/F4#	363.75	6.06	1.6%
V07	392.00/G4	392.06	0.06	0.0%	380.58/G4-qtr	375.67	4.91	1.3%	369.81/F4#	367.45	2.36	0.6%
V08	392.00/G4	394.15	2.15	0.5%	380.58/G4-qtr	378.8	1.78	0.5%	369.81/F4#	364.95	4.86	1.3%
V09	392.00/G4	393.57	1.57	0.4%	380.58/G4-qtr	380.62	0.04	0.0%	369.81/F4#	368.44	1.37	0.4%
V10	392.00/G4	390.19	1.81	0.5%	380.58/G4-qtr	371.4	9.18	2.4%	369.81/F4#	362.54	7.27	2.0%
V11	392.00/G4	388.48	3.52	0.9%	380.58/G4-qtr	377.54	3.04	0.8%	369.81/F4#	363.13	6.68	1.8%
V12	392.00/G4	386.63	5.37	1.4%	380.58/G4-qtr	369.74	10.84	2.8%	369.81/F4#	363.96	5.85	1.6%
V13	392.00/G4	389.53	2.47	0.6%	380.58/G4-qtr	373.1	7.48	2.0%	369.81/F4#	365.64	4.17	1.1%
V14	392.00/G4	385.89	6.11	1.6%	380.58/G4-qtr	384.23	3.65	1.0%	369.81/F4#	366.08	3.73	1.0%
V15	392.00/G4	389.49	2.51	0.6%	380.58/G4-qtr	372.33	8.25	2.2%	369.81/F4#	371.52	1.71	0.5%
V16	392.00/G4	387.7	4.3	1.1%	380.58/G4-qtr	373.24	7.34	1.9%	369.81/F4#	366.32	3.49	0.9%
V17	392.00/G4	389.25	2.75	0.7%	380.58/G4-qtr	374.8	5.78	1.5%	369.81/F4#	365.87	3.94	1.1%
V18	392.00/G4	386.41	5.59	1.4%	380.58/G4-qtr	371.61	8.97	2.4%	369.81/F4#	363.22	6.59	1.8%
V19	392.00/G4	390.75	1.25	0.3%	380.58/G4-qtr	383.81	3.23	0.8%	369.81/F4#	368.2	1.61	0.4%
V20	392.00/G4	389.5	2.5	0.6%	380.58/G4-qtr	375.56	5.02	1.3%	369.81/F4#	363.74	6.07	1.6%

Appendix F: Individual Data for Difference Limen for Frequency

GROUP	SUBJ	STIM	DLF Hz	DLF %	STIM	DLF Hz	DLF%	STIM	DLF Hz	DLF%
CONTROL	C01	261.63/C4	10.43	3.99%	329.63/E4	6.65	2.02%	392.00/G4	5.34	1.36%
CONTROL	C02	261.63/C4	4.59	1.75%	329.63/E4	5.25	1.59%	392.00/G4	5.5	1.40%
CONTROL	C03	261.63/C4	7.66	2.93%	329.63/E4	9.54	2.89%	392.00/G4	13.32	3.40%
CONTROL	C04	261.63/C4	5.83	2.23%	329.63/E4	5.51	1.67%	392.00/G4	9.64	2.46%
CONTROL	C05	261.63/C4	11.33	4.33%	329.63/E4	32.96	10.00%	392.00/G4	10.99	2.80%
CONTROL	C06	261.63/C4	31.28	11.96%	329.63/E4	35.56	10.79%	392.00/G4	44.97	11.47%
CONTROL	C07	261.63/C4	4.92	1.88%	329.63/E4	9.01	2.73%	392.00/G4	5.82	1.48%
CONTROL	C08	261.63/C4	3.93	1.50%	329.63/E4	4.42	1.34%	392.00/G4	5.02	1.28%
CONTROL	C09	261.63/C4	7.11	2.72%	329.63/E4	5.24	1.59%	392.00/G4	7.19	1.83%
CONTROL	C10	261.63/C4	2.11	0.81%	329.63/E4	4.62	1.40%	392.00/G4	5.67	1.45%
CONTROL	C11	261.63/C4	3.26	1.25%	329.63/E4	4.01	1.22%	392.00/G4	4.45	1.14%
CONTROL	C12	261.63/C4	8.67	3.31%	329.63/E4	18.76	5.69%	392.00/G4	5.99	1.53%
CONTROL	C13	261.63/C4	35.85	13.70%	329.63/E4	57.35	17.40%	392.00/G4	48.08	12.27%
CONTROL	C14	261.63/C4	3.1	1.18%	329.63/E4	3.74	1.13%	392.00/G4	5.5	1.40%
CONTROL	C15	261.63/C4	6.25	2.39%	329.63/E4	5.24	1.59%	392.00/G4	7.44	1.90%
CONTROL	C16	261.63/C4	17.32	6.62%	329.63/E4	5.17	1.57%	392.00/G4	5.58	1.42%
CONTROL	C17	261.63/C4	3.7	1.41%	329.63/E4	4.63	1.40%	392.00/G4	5.1	1.30%
CONTROL	C18	261.63/C4	3.96	1.51%	329.63/E4	5.56	1.69%	392.00/G4	3.89	0.99%
CONTROL	C19	261.63/C4	5.8	2.22%	329.63/E4	6.78	2.06%	392.00/G4	5.18	1.32%
CONTROL	C20	261.63/C4	8.76	3.35%	329.63/E4	7.13	2.16%	392.00/G4	5.5	1.40%
CONTROL	C21	261.63/C4	4.14	1.58%	329.63/E4	4.7	1.43%	392.00/G4	4.78	1.22%

Appendix F: (Continued)

GROUP	SUBJ	STIM	DLF Hz	DLF %	STIM	DLF Hz	DLF%	STIM	DLF Hz	DLF%
INSTRUM	IN01	261.63/C4	4.47	1.71%	329.63/E4	4.96	1.50%	392.00/G4	6.07	1.55%
INSTRUM	IN02	261.63/C4	3.54	1.35%	329.63/E4	7.79	2.36%	392.00/G4	6.47	1.65%
INSTRUM	IN03	261.63/C4	6.41	2.45%	329.63/E4	13.07	3.97%	392.00/G4	5.83	1.49%
INSTRUM	IN04	261.63/C4	2.38	0.91%	329.63/E4	4.15	1.26%	392.00/G4	5.58	1.42%
INSTRUM	IN05	261.63/C4	2.77	1.06%	329.63/E4	4.42	1.34%	392.00/G4	4.45	1.14%
INSTRUM	IN06	261.63/C4	4.42	1.69%	329.63/E4	4.08	1.24%	392.00/G4	5.1	1.30%
INSTRUM	IN07	261.63/C4	4.58	1.75%	329.63/E4	4.83	1.47%	392.00/G4	6.71	1.71%
INSTRUM	IN08	261.63/C4	3.26	1.25%	329.63/E4	5.51	1.67%	392.00/G4	5.1	1.30%
INSTRUM	IN09	261.63/C4	4.2	1.61%	329.63/E4	3.33	1.01%	392.00/G4	5.5	1.40%
INSTRUM	IN10	261.63/C4	1.89	0.72%	329.63/E4	3.34	1.01%	392.00/G4	3.88	0.99%
INSTRUM	IN11	261.63/C4	3.92	1.50%	329.63/E4	3.68	1.12%	392.00/G4	4.29	1.09%
INSTRUM	IN12	261.63/C4	3.48	1.33%	329.63/E4	3.4	1.03%	392.00/G4	3.89	0.99%
INSTRUM	IN13	261.63/C4	2.71	1.04%	329.63/E4	3.68	1.12%	392.00/G4	3.89	0.99%
INSTRUM	IN14	261.63/C4	3.48	1.33%	329.63/E4	3.75	1.14%	392.00/G4	4.62	1.18%
INSTRUM	IN15	261.63/C4	4.36	1.67%	329.63/E4	4.7	1.43%	392.00/G4	5.18	1.32%
INSTRUM	IN16	261.63/C4	1.95	0.75%	329.63/E4	2.93	0.89%	392.00/G4	3.72	0.95%
INSTRUM	IN17	261.63/C4	3.48	1.33%	329.63/E4	3.95	1.20%	392.00/G4	5.02	1.28%
INSTRUM	IN18	261.63/C4	4.75	1.82%	329.63/E4	4.42	1.34%	392.00/G4	6.71	1.71%
INSTRUM	IN19	261.63/C4	2.33	0.89%	329.63/E4	4.29	1.30%	392.00/G4	3.97	1.01%
INSTRUM	IN20	261.63/C4	6.55	2.50%	329.63/E4	6.85	2.08%	392.00/G4	5.1	1.30%
INSTRUM	IN21	261.63/C4	3.76	1.44%	329.63/E4	5.3	1.61%	392.00/G4	4.29	1.09%

Appendix F: (Continued)

GROUP	SUBJ	STIM	DLF Hz	DLF %	STIM	DLF Hz	DLF%	STIM	DLF Hz	DLF%
VOCAL	V01	261.63/C4	2.82	1.08%	329.63/E4	3.4	1.03%	392.00/G4	4.86	1.24%
VOCAL	V02	261.63/C4	4.36	1.67%	329.63/E4	3.74	1.13%	392.00/G4	4.61	1.18%
VOCAL	V03	261.63/C4	3.87	1.48%	329.63/E4	3.54	1.07%	392.00/G4	4.94	1.26%
VOCAL	V04	261.63/C4	3.31	1.27%	329.63/E4	3.68	1.12%	392.00/G4	3.81	0.97%
VOCAL	V05	261.63/C4	4.53	1.73%	329.63/E4	11.95	3.63%	392.00/G4	11.29	2.88%
VOCAL	V06	261.63/C4	3.47	1.33%	329.63/E4	4.43	1.34%	392.00/G4	4.86	1.24%
VOCAL	V07	261.63/C4	2.66	1.02%	329.63/E4	4.22	1.28%	392.00/G4	5.42	1.38%
VOCAL	V08	261.63/C4	3.32	1.27%	329.63/E4	4.29	1.30%	392.00/G4	5.1	1.30%
VOCAL	V09	261.63/C4	2.38	0.91%	329.63/E4	4.13	1.25%	392.00/G4	4.86	1.24%
VOCAL	V10	261.63/C4	4.64	1.77%	329.63/E4	4.89	1.48%	392.00/G4	4.53	1.16%
VOCAL	V11	261.63/C4	3.42	1.31%	329.63/E4	4.08	1.24%	392.00/G4	4.94	1.26%
VOCAL	V12	261.63/C4	3.98	1.52%	329.63/E4	5.22	1.58%	392.00/G4	4.37	1.11%
VOCAL	V13	261.63/C4	3.04	1.16%	329.63/E4	4.22	1.28%	392.00/G4	4.78	1.22%
VOCAL	V14	261.63/C4	3.32	1.27%	329.63/E4	3.61	1.10%	392.00/G4	4.86	1.24%
VOCAL	V15	261.63/C4	2.71	1.04%	329.63/E4	4.29	1.30%	392.00/G4	5.02	1.28%
VOCAL	V16	261.63/C4	4.14	1.58%	329.63/E4	3.54	1.07%	392.00/G4	4.37	1.11%
VOCAL	V17	261.63/C4	3.15	1.20%	329.63/E4	3.88	1.18%	392.00/G4	5.1	1.30%
VOCAL	V18	261.63/C4	2.66	1.02%	329.63/E4	3.47	1.05%	392.00/G4	5.34	1.36%
VOCAL	V19	261.63/C4	6.92	2.64%	329.63/E4	5.37	1.63%	392.00/G4	9.68	2.47%
VOCAL	V20	261.63/C4	2.77	1.06%	329.63/E4	4.56	1.38%	392.00/G4	5.1	1.30%

## Appendix G: P1 Individual Peak Amplitude at Fz

Group	Dev 1 Amp	Dev 2 Amp	Dev 3 Amp	Group	Dev 1 Amp	Dev 2 Amp	Dev 3 Amp	Group	Dev 1 Amp	Dev 2 Amp	Dev 3 Amp
C01	4.03	6.12	5.16	IN01	3.92	3.09	2.71	V01	5.71	4.33	5.69
C02	3.72	4.36	7.19	IN02	1.89	2.8	2.19	V02	3.83	3.01	2.49
C03	3.74	4.38	2.86	IN03	3.84	3.56	2.27	V03	4.28	3.94	3.62
C04	5.71	5.26	4.93	IN04	2.87	3.56	4.3	V04	4.23	3	4.11
C05	2.52	3.23	2.35	IN05	1.48	3.55	2.5	V05*			
C06	3.64	3.04	3.5	IN06	3.14	2.53	2.21	V06	4.2	4.37	4.51
C07	4.9	4.16	5.46	IN07	1.96	2.22	0.75	V07	1.45	2.2	1.8
C08	6.71	5.52	5.54	IN08	2.28	3.67	2.27	V08	1.86	4.7	0.9
C09	2.62	2.36	1.6	IN09	1.87	2.17	3.12	V09	2.66	4.04	3.14
C10	0.19	1.55	2.28	IN10	5.43	3.5	3.5	V10	3.16	4.02	4.3
C11	2.64	2.52	3.29	IN11	0.43	0.56	0.48	V11	2.11	1.64	1.41
C12	2.56	2.83	2.33	IN12	1.96	2.24	3.2	V12	2.64	2.81	3.24
C13	4.59	3.51	5.2	IN13	4.2	3.67	5.17	V13	4.31	4.99	3.57
C15	2.2	2.61	2.35	IN14	3.64	4.04	2.47	V14	2.31	2.73	3.64
C16	4.79	3.53	5.16	IN16	4.64	5.22	2.87	V15	3.48	1.62	1.65
C17	4.97	4.17	5.41	IN17	2.89	2.24	2.34	V16	2.93	2.25	2.58
C18	5.06	3.67	4.66	IN18	2.41	1.98	2.81	V17	4.18	3.36	3.57
C19	2.95	3.37	3.04	IN19	5.15	5.36	5.04	V18	1.79	2.58	2.72
C20	3.97	2.95	4.09	IN20	1.91	4.03	3.5	V19	4.15	4.11	3.96
C21	4.26	4.42	2.84	IN21	2.72	4.08	3.74	V20	3.41	2.76	3.08

\*V05 did not meet inclusion criteria

### Summary Data

GROUP	Mean Dev1/Amp	Std Error	Mean Dev2/Amp	Std Error	Mean Dev3/Amp	Std Error
Control	3.79	1.46	3.68	1.14	3.96	1.51
Musician	3.08	1.21	3.21	1.01	3.00	1.16
Vocal	3.24	1.12	3.22	1.04	3.13	1.16
Instrumental	2.93	1.30	3.20	1.14	2.87	1.17
Grand Mean	3.32		3.37		3.32	



## Appendix H: P1 Individual Peak Latency at Fz

Group	Dev 1 Amp	Dev 2 Amp	Dev 3 Amp	Group	Dev 1 Amp	Dev 2 Amp	Dev 3 Amp	Group	Dev 1 Amp	Dev 2 Amp	Dev 3 Amp
C01	-1.12	-1.15	-0.91	IN01	-3.83	-4.41	-3.24	V01	-4.64	-2.7	-2.94
C02	-2.37	-1.09	-4.53	IN02	-1.44	-0.14	0.11	V02	-3.78	-2.57	-2.91
C03	-0.99	-0.83	-1.98	IN03	-1.06	-1.16	0.95	V03	-0.79	-0.5	-2.5
C04	-2.43	-2.93	-3.54	IN04	-2.03	-0.92	-1.19	V04	-2.39	-0.56	-4.82
C05	-1.04	-2.6	-3.07	IN05	-2.34	-3.49	-3.58	V05*			
C06	-0.98	-2.8	-2.93	IN06	-2.19	-1.42	-3.47	V06	-0.36	-1.47	-2.76
C07	-3.61	-3.5	-2.18	IN07	0.34	-0.04	-3.17	V07	-1.74	-0.82	-2.17
C08	-1.19	-3.79	-3.36	IN08	0.33	-2.01	-3.27	V08	-2.34	-2.15	-2.3
C09	0.75	1.55	-0.34	IN09	-0.67	-2.59	-2.72	V09	-3.26	-2.34	0.26
C10	-3.25	-0.58	-2.05	IN10	-1	-3.05	-6.25	V10	-2.62	-2.39	-1.65
C11	-1.36	-2.6	-2.55	IN11	0.02	-0.31	-0.1	V11	-3.7	-1.42	-2.75
C12	-0.09	-2.03	-3.13	IN12	-2.42	-2.23	-2.16	V12	-3.08	-2.13	-2.6
C13	-1.46	-4.21	-3.13	IN13	-2.81	-1.96	-0.09	V13	-3.42	0.43	1.38
C15	-1.24	-4.79	-5.1	IN14	-1.85	-2.69	-2.78	V14	-2.05	-2.97	-2.39
C16	-1.34	-2.56	-2.29	IN16	0.55	-1.88	-2.7	V15	0.51	0.05	-1.5
C17	-3.55	-3.51	-2.26	IN17	-0.95	-3.07	0.17	V16	-4.8	-1.99	-3.57
C18	0.64	-1.61	-2.19	IN18	-1.17	-1.78	2.13	V17	-1.61	-1.12	-2.09
C19	-3.4	1.1	-0.68	IN19	-3.25	-1.72	-1.5	V18	-1.88	0.37	0.23
C20	-1.02	0.07	-0.51	IN20	-0.98	-0.84	-2.51	V19	-1.26	-1.6	-1.6
C21	-1.38	-1.97	-2.48	IN21	-5.47	-2.77	-0.99	V20	-2.64	-1.82	-1.06

\*V05 did not meet inclusion criteria

### Summary Data

GROUP	Mean Dev 1/Amp	Std Error	Mean Dev 2/Amp	Std Error	Mean Dev 3/Amp	Std Error
Control	-1.52	1.25	-1.99	1.69	-2.46	1.24
Musician	-1.94	1.53	-1.67	1.11	-1.87	1.69
Vocal	-2.26	1.51	-1.42	1.03	-1.92	1.43
Instrumental	-1.61	1.51	-1.92	1.16	-1.82	1.96
Grand Mean	-1.80		-1.78		-2.07	

## Appendix I: Mismatch Negativity Individual Peak Amplitude at Fz

Group	Dev 1 Lat	Dev 2 Lat	Dev 3 Lat	Group	Dev 1 Lat	Dev 2 Lat	Dev 3 Lat	Group	Dev 1 Lat	Dev 2 Lat	Dev 3 Lat
<b>C01</b>	69	70	88	<b>IN01</b>	67	68	70	<b>V01</b>	76	74	74
<b>C02</b>	80	82	84	<b>IN02</b>	80	92	70	<b>V02</b>	80	103	84
<b>C03</b>	74	76	72	<b>IN03</b>	82	80	90	<b>V03</b>	74	82	84
<b>C04</b>	76	76	74	<b>IN04</b>	76	68	67	<b>V04</b>	82	82	84
<b>C05</b>	76	70	67	<b>IN05</b>	72	70	68	<b>V05*</b>			
<b>C06</b>	78	82	82	<b>IN06</b>	80	82	82	<b>V06</b>	84	86	82
<b>C07</b>	82	96	78	<b>IN07</b>	78	80	78	<b>V07</b>	100	94	98
<b>C08</b>	74	72	72	<b>IN08</b>	68	70	70	<b>V08</b>	100	84	80
<b>C09</b>	72	72	80	<b>IN09</b>	86	88	90	<b>V09</b>	72	70	68
<b>C10</b>	74	84	78	<b>IN10</b>	72	76	72	<b>V10</b>	80	78	80
<b>C11</b>	70	74	63	<b>IN11</b>	80	86	70	<b>V11</b>	82	82	82
<b>C12</b>	82	86	86	<b>IN12</b>	90	84	94	<b>V12</b>	65	70	65
<b>C13</b>	78	80	82	<b>IN13</b>	78	78	84	<b>V13</b>	74	74	74
<b>C15</b>	47	74	72	<b>IN14</b>	72	67	63	<b>V14</b>	72	72	74
<b>C16</b>	88	82	92	<b>IN16</b>	76	76	76	<b>V15</b>	68	68	72
<b>C17</b>	82	92	78	<b>IN17</b>	68	70	70	<b>V16</b>	94	94	90
<b>C18</b>	72	72	72	<b>IN18</b>	82	88	92	<b>V17</b>	80	80	78
<b>C19</b>	70	74	72	<b>IN19</b>	82	80	92	<b>V18</b>	80	80	84
<b>C20</b>	80	84	82	<b>IN20</b>	90	92	86	<b>V19</b>	82	78	82
<b>C21</b>	82	82	76	<b>IN21</b>	84	113	111	<b>V20</b>	76	76	80

\*V05 did not meet inclusion criteria

## Summary Data

GROUP	Mean	Std	Mean	Std	Mean	Std
	Dev 1/Lat	Error	Dev 2/Lat	Error	Dev 3/Lat	Error
<b>Control</b>	75.30	8.35	79.00	7.24	77.50	7.22
<b>Musician</b>	78.73	8.38	80.07	10.11	80.20	10.44
<b>Vocal</b>	79.30	9.84	79.75	9.27	80.65	8.46
<b>Instrumental</b>	78.15	6.82	80.40	11.12	79.75	12.32
<b>Grand Mean</b>	77.58		79.72		79.30	

Appendix J: Mismatch Negativity Individual Peak Latency at Fz

Group	Dev 1 Lat	Dev 2 Lat	Dev 3 Lat	Group	Dev 1 Lat	Dev 2 Lat	Dev 3 Lat	Group	Dev 1 Lat	Dev 2 Lat	Dev 3 Lat
C01	200	182	188	IN01	204	197	189	V01	230	197	175
C02	270	219	179	IN02	261	206	208	V02	189	156	167
C03	276	231	212	IN03	261	197	177	V03	197	216	173
C04	222	206	171	IN04	226	177	164	V04	200	197	189
C05	190	168	185	IN05	220	169	187	V05*			
C06	231	185	198	IN06	233	206	175	V06	245	183	202
C07	236	220	201	IN07	173	185	177	V07	237	228	189
C08	193	199	159	IN08	228	212	202	V08	267	216	179
C09	267	232	203	IN09	214	173	164	V09	235	185	166
C10	218	168	187	IN10	210	162	179	V10	206	208	197
C11	283	206	203	IN11	257	167	179	V11	158	150	146
C12	263	250	187	IN12	255	228	210	V12	195	191	185
C13	219	201	161	IN13	239	177	202	V13	230	235	241
C15	182	197	183	IN14	179	197	152	V14	228	164	142
C16	259	241	222	IN16	187	222	199	V15	195	202	195
C17	237	220	200	IN17	179	206	224	V16	202	160	166
C18	193	177	177	IN18	210	191	152	V17	197	210	152
C19	237	166	156	IN19	224	191	175	V18	212	160	171
C20	208	195	195	IN20	237	166	197	V19	218	166	167
C21	239	226	222	IN21	191	195	167	V20	212	208	218

\*V05 Did not meet inclusion criteria

Summary Data

GROUP	Mean		Mean		Mean	
	Dev 1/Lat	Std Error	Dev 2/Lat	Std Error	Dev 3/Lat	Std Error
Control	231.15	31.09	204.45	25.13	189.45	19.03
Musician	217.87	27.45	192.00	22.57	184.42	26.37
Vocal	216.35	27.55	192.80	26.15	184.90	32.24
Instrumental	219.40	27.98	191.20	18.98	183.95	19.70
Grand Mean	222.30		196.15		186.10	

### About the Author

Dee Adams Nikjeh received a Bachelor's Degree in Speech Pathology and Audiology in 1978 from West Virginia University where she also received her Master of Science Degree in Speech Pathology in 1979. She has more than 25 years of clinical experience focusing in neurogenic communication disorders and has given numerous professional presentations. For the past 11 years, Mrs. Nikjeh has been employed by an otolaryngology practice where she specializes in endoscopic procedures for the evaluation and management of voice and swallowing disorders.

She presently serves on the American Speech Language and Hearing Association's (ASHA) Health Care and Economics Committee and has extensive knowledge of national reimbursement and coding issues as they pertain to speech-language pathologists and audiologists. Mrs. Nikjeh has served on ASHA's Legislative Council, the Executive Board of the Council of State Association Presidents and is a past-president of the Florida Association of Speech Language Pathologists and Audiologists.