THE EFFECT OF AUDITORY DEVICE, ONSET OF HEARING LOSS, AND CHRONOLOGIC AGE ON MUSIC PERCEPTION AND APPRECIATION IN ADULT LISTENERS

by

Stephanie L. Fowler

APPROVED BY SUPERVISORY COMMITTEE:

Andrea Warner-Czyz, Chair

Peter F. Assmann

W. Jay Dowling

Colleen G. Le Prell

Linda M. Thibodeau

To the listeners, who persist in their dedication to lead fulfilling musical lives:

“All music is what awakens from you when you are reminded by the instruments”

-Walt Whitman, *Leaves of Grass* (1855)

THE EFFECT OF AUDITORY DEVICE, ONSET OF HEARING LOSS, AND CHRONOLOGIC AGE ON MUSIC PERCEPTION AND APPRECIATION IN ADULT LISTENERS

by

STEPHANIE L. FOWLER, BA, AuD

DISSERTATION
Presented to the Faculty of
The University of Texas at Dallas
in Partial Fulfillment
of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY IN
COMMUNICATION SCIENCES AND DISORDERS

THE UNIVERSITY OF TEXAS AT DALLAS
May 2021

ACKNOWLEDGMENTS

Pursuing my PhD and completing this research would not have been possible without the individuals who have encouraged, challenged, and supported me in my journey.

First, to the participants with hearing loss, who shared their stories, strategies, and musical performances, I have sincere gratitude for how you let me in to your lives. Your dedication to music and giving back to your peers through research endeavors is imperative to our pursuit to improve these experiences.

Many thanks to all my professional mentors along the way. To Kimberly Engber, my first mentor, who showed me the importance of humanities in science education, who cemented my commitment to lifelong learning, and who taught me that Walt Whitman has a quote for everything. To Carol Cokely, whose mentorship challenged me to become the best clinician-scientist I could be by pursuing my PhD. To my chair Andrea Warner-Czyz, whose dedication to student independence fostered my pursuit of this engaging line of research, and who consistently models the energy and passion needed to ensure research considers the whole person, not just their ears. To my committee members, Peter Assmann, Jay Dowling, Colleen Le Prell, and Linda Thibodeau, whose diverse experiences in psychoacoustics, music, study design, and musical training elevated this project to a truly interdisciplinary endeavor. I have deep appreciation for the time and energy you have invested in me and this project. And to the extensive professional network who has participated in this project’s design and provided commentary on its improvement, your feedback has saved me much time and folly.

To my colleagues, without whose support I could not have persisted in this endeavor. To the Class of 2019, for your deep commitments to audiology and to friendship. To the Class of 2020, for accepting me as one of your peers. And to my lab mates, for paving the way to become well-trained and impactful clinician-scientists.

Finally, to my family, whose values of hard work and compassion permeate my every decision. To Mom and Bob and Dad and Kathie, for your unwavering love and pride in my abilities and accomplishments. To Melanie and August, for allowing me to experience non-academic life vicariously through you. To Tanner, for making me become the best role model I can be. And to my partner Jordan, who supported me while I turned our home into a virtual laboratory, who never indulged my doubts, and who provided daily encouragement by word and example. I strive to be the best version of myself I can because of you all.

April 2021

THE EFFECT OF AUDITORY DEVICE, ONSET OF HEARING LOSS, AND CHRONOLOGIC AGE ON MUSIC PERCEPTION AND APPRECIATION IN ADULT LISTENERS

Stephanie L. Fowler, PhD
The University of Texas at Dallas, 2021

Supervising Professor: Andrea Warner-Czyz

Adults with hearing loss perceive music through a degraded auditory filter initially designed for enhanced speech perception. Although they exhibit difficulty perceiving musical characteristics in research and clinic, adults with hearing loss do not exhibit a consistent decrease in appreciation of musical activities. Poor perception, in general, does not result in lower appreciation of music. Previous studies have assessed the perceptual skills of cochlear implant (CI) listeners, hearing aid (HA) listeners, and typical hearing (TH) adults, as well as the subjective music experiences of these groups. To date, few studies have investigated these groups on both subjective and objective measures together; assessed the distinct music experiences of pre- and postlingual adults; or determined how chronologic age influences music experiences.

This project aims to understand the differences in objective music perception and self-reported music experiences among (a) TH, CI, and HA listeners; (b) pre-lingual (i.e., onset of deafness before age three) and post-lingual (i.e., onset of deafness after age three) CI listeners; and (c) younger compared to older (≥ 60 years) adult CI listeners.

Sixty participants 18 years or older were grouped according to device status, onset of deafness, and age. Participants with a bimodal configuration used only one of their devices during testing. Demographic and audiologic characteristics were obtained from an *ad hoc* survey. The Clinical Assessment of Music Perception (CAMP) assessed behavioral perception of pitch, familiar melody, and instrument identification. In addition, one subtest of the Profile of Musical Skills (PROMS) assessed behavioral perception of unfamiliar melodies. These four subtests comprise the objective evaluation of music perception. The Music-Related Quality of Life (MuRQoL) assessed subjective exposure to musical characteristics and situations and their relative importance. Two domains (Music Abilities and Music Importance) comprise the subjective evaluation of music appreciation.

Participants with TH discriminated pitches, recognized familiar melodies, recognized instruments, and discriminated unfamiliar melodies better than postlingual CI listeners, but not those with HAs. CI listeners stratified by age at diagnosis of hearing loss and chronologic age performed in similar ways on all objective measures, and large variability was present. Overall, all groups with and without hearing loss reported similar levels of music importance. Across all participants grouped together, objective and subjective measures were correlated, such that individuals who scored well on objective measures also tended to self-report higher music abilities, in general. Furthermore, across all participants grouped together, subjective self-report of music skills tended to correlate with objective performance on that specific skill. However, when examined within each group, objective measures largely did not correlate with subjective measures.

Because auditory devices have thus far been optimized for speech, research regarding the musical experiences of those who use them is extremely limited. However, participants in this study report that music remains important in their lives and that hearing loss and auditory devices diminish the perceptual characteristics necessary for access to typical music experiences. There remains a need to develop clinically feasible measures of real-world musical experiences and develop interventions to improve access to music.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Music pervades humans' auditory environments. Among other things, music fills the auditory background of restaurants and shops and can enhance or distract from other activities, such as exercising. In addition, music carries messages far beyond the instantaneous perception of each auditory stimuli. Music can evoke nostalgia with a popular song from one's childhood or bring rage in an otherwise calm person. Due to the variable nature of the messages received while listening to music, this auditory stimuli is difficult to study in the typical hearing (TH) population and even more so when perception of music is distorted by the biological processes of hearing loss and the auditory technology prescribed to treat the patient's communication difficulties.

Hearing loss originates from various etiologies. Approximately 1-3 in 100 babies are born with permanent hearing loss (Mehra et al., 2009). By the time children reach school (i.e., ages 6-19), about 5-10 in 100 children reportedly have developed a hearing loss (Niskar et al., 1998). Often, hearing loss occurs due to a cochlear site of lesion, called a sensorineural hearing loss, or an outer or middle ear site of lesion, called a conductive hearing loss. Individuals may also experience a mixed hearing loss, originating from problems in multiple parts of the ear (i.e., outer, middle, and inner). Finally, and more rarely, individuals may experience a neural or cortical hearing impairment, with typical threshold responses to sound stimuli when tested with standard audiometric tests but other abnormal perceptions of sounds. These numbers and definitions have fluctuated throughout studies and years but consistently suggest that hearing loss is a pervasive chronic condition affecting approximately 48.1 million individuals across the lifespan (Lin et al., 2011).

To treat permanent hearing loss, individuals typically turn to auditory technology such as hearing aids (HAs) or cochlear implants (CIs). Overall estimates suggest that about 28.8 million (or about 8.9% of Americans) could benefit from HAs (National Institute on Deafness and Other Communication Disorders, 2016). Similarly, estimates suggest that CIs, which treat a more severe degree of hearing loss, could benefit the 464,000-738,000 individuals in the United States (approximately .002%-.003% of the population) with moderate or severe to profound hearing loss (Blanchfield et al., 2001). Modern HAs digitally increase the audibility of sounds, convert the sounds back to an acoustic signal, which is then perceived via the natural hearing system. In contrast, CIs are appropriate for adults with moderate or severe to profound hearing losses. CIs digitally process sounds picked up from an external microphone, which are delivered post-processing via an implanted electrode array delivering pulsed electrical signals to the auditory nerve. The electrical signals of the internal electrode array take the place of the neural firings of the natural hair cells within the cochlea. With advancements in the signal processing and delivery of sound, auditory technology has come far since its inception to represent speech to individuals with varying degrees of hearing loss. However, these advancements have yet to consistently restore full music perception skills to all individuals using these devices, despite improved speech perception and speech perception in noise.

The discrepancy between performance on speech reception and music perception tasks with HAs and CIs has yet to be resolved. General research trends show three elements potentially contributing to this discrepancy: (a) music is a more complex acoustic signal than speech; (b) auditory technologies accentuate audibility and accessibility to speech with little emphasis on accurate and efficient processing of the high fidelity acoustic information presented in music; and (c) biological distortions as a result of hearing loss at the level of the cochlea, auditory brainstem, or auditory cortex may contribute to poor representation of music, even after processing done by auditory technologies. A combination of these elements likely best represents difficulties listening to music, but such explanations require diverse background knowledge from the fields of musicology, music performance, acoustics, sound engineering, audiology, and neuroscience. While it is beyond the scope of this study to unravel all interconnections among these fields, perspectives from each will contribute to the justification for this study.

CHAPTER 2

ACOUSTICS OF MUSIC PRODUCTION

With nearly two-thirds of audiologists reporting no training in musical concepts, a foundation of music production is necessary to understand the strengths and difficulties of individuals with hearing loss while they engage with music (Greasley et al., 2019). This section briefly reviews four important music concepts: dynamics, temporal elements, spectral elements, and sound quality.

2.1 Dynamics

In music, dynamics refers to the instantaneous or overall loudness of a piece of music. In communication disorders and sound processing, we would consider this to be intensity, energy, power, or dynamic range of a piece of music. Intensity, typically measured in decibels (dB), varies with increasing or decreasing energy output from the sound source. In music, this energy is produced by the instrument, and the methods for increasing the intensity of a note (i.e., a short duration sound source) vary based on the instrument. Pianists increase the intensity of their playing by manipulating the force of the hammer hitting the strings. Although this seems relatively straightforward, coordinated biomechanical movements of fingers, wrists, elbows, and shoulders contribute to the overall intensity of a note played on a piano (Furuya et al., 2012). For instruments in the string family (i.e., those typically played with bows, such as violins), musicians apply more pressure to the bow while pulling across the strings to increase the intensity of the strings' vibrations. Finally, for instruments played with air (e.g., brass instruments like trumpets and woodwind instruments like clarinets), increased lung pressure will make the instrument louder (Levitin et al., 2002). Within each of these instrument families are ways to vary the intensity of individual notes, and thus express a wide range of intensities for the listener.

Collectively, the changes in intensity over the course of these notes contribute to the overall loudness of a segment of music, or what is commonly called dynamic range. Dynamic range refers to the property of sound stimuli characterizing the range of loudness between the quietest and loudest parts of the stimulus. Many methods exist to calculate this number. While most researchers generally consider music to have a larger dynamic range than speech (Chasin & Russo, 2004; Eargle, 2003), one recent analysis directly compared a large corpus of music of different genres and speakers of different languages, and suggested that music may actually have a smaller dynamic range than speech (Kirchberger & Russo, 2016). While the average dynamic range across different sound stimuli remains to be determined, the capacity for instruments to have a larger dynamic range seems intuitive for any individual who has experienced a piece of music with very quiet and very loud sections.

2.2 Temporal Elements

Broadly, rhythm is described as the "measurement, description and organization of … duration and 'temporality,' at every level and in every manner" (Gasser, 2019, p. 120). Referred to collectively in this paper as temporal elements, these characteristics include the duration of a sound stimulus, the duration of silence, and the rate and pattern at which these two occur. Temporal elements also relate to the strength of the pattern, namely the stress (or lack thereof) attributed to each beat of a song.

Almost imperceptibly, the temporal elements of music have a foundation of slow oscillations corresponding to sound generators for musical instruments (e.g., the vocal tract for singers, or the arm's movement of the bow for stringed instrument players). These sound generators move regularly at a low frequency, creating a measurable pattern of which humans are often unaware, but which stimulate auditory nerve fibers to fire at a complementary rate as measured by electrophysiological tests (e.g., electroencephalograms) as theta waves (4-8 Hz) and delta waves (1-3 Hz) (Ding et al., 2017; Ghitza, 2013). This neural synchrony to temporal elements of external sound stimuli is known as entrainment. Researchers believe entrainment gives humans the unique ability to predict the next beat in a sequence (Gasser, 2019).

Temporal elements can describe musical characteristics that are also very perceptible. Any time someone taps along to the beat of a song, they are tracking a time-based part of the song. Two temporal elements, tempo and rhythm, are important here. When someone taps in a regular, equally-spaced fashion, he is likely following the tempo of the music (colloquially called "keeping the beat"). Tempo can also be illustrated by runners who change the pace of their running when a new song with a different overall speed comes over their earphones (Van Dyck et al., 2015). In contrast, when someone taps along in an unequally-spaced fashion (i.e., to the syllables in the lyrics of the song or the drummer's playing), she is following the rhythm of the song. Different instruments often play contrasting or complementary rhythms within one piece of music, and multiple rhythms exist within the same song. Finally, each rhythm is accompanied by a pattern of stressed and unstressed notes. The stressed notes are used to place emphasis on either the boundaries of the repeating patterns of rhythm or to create an unexpected emphasis on a non-boundary note. Typically, stressed notes sound louder than the unstressed notes around them.

Encompassed above are only some of the temporal elements present in music. Readers are directed to Clarke (1999) for further research on the production of temporal elements of music.

2.3 Spectral Elements

Sound stimuli are created when sound waves travel through the air and reach the auditory system. The rate of these sound waves, and more specifically the rate of the vibrations of the sound generators, are what determine the sound’s fundamental frequency and naturally occurring higher-order harmonics. The human auditory system interprets these different frequencies of vibration as pitch. A slow vibration becomes a low pitch, or bass sound, such as that created by pressing the keys on the leftmost part of the piano, while a fast vibration registers a high pitch, a treble or soprano sound, such as that created by pressing the keys on the rightmost part of the piano.

Establishing a foundational knowledge of the generation of spectral characteristics of sound requires review of the source-filter theory (Fant, 1960), comprised of three primary spectrally-based concepts: (a) fundamental frequency; (b) harmonics; and (c) formants or resonance. Fundamental frequency (f_0) is created at the source of the energy, (e.g., the vibrations of the vocal fold for speech). This is the slowest frequency of vibrations generated for a single speech sound. Additional frequencies at intervals of the f_0 are generated in addition to the fundamental frequency. For example, while making a neutral vowel sound (i.e., /ə/) with 200 vibrations per second of the vocal folds (i.e., 200 Hz), additional sound waves will be generated at 400 Hz, 600 Hz, 800 Hz, and so on. Each of these higher frequencies is called a harmonic, and each harmonic is generated with a lower intensity. Finally, resonances of the vocal articulators, including the space between and movement of the velum, tongue, mouth and lips, generate formants, or a set of “filters” that selectively enhance some of the generated frequencies, whether fundamental or harmonic. Without fundamental frequency, harmonics, and formants, speech can sound unnatural; however, the identification of messages within speech do not degrade with misaligned harmonics (Watson & Schlauch, 2008). With improvements in understanding of these physical properties, generation of more complex speech sound signals has improved the quality and realism of synthesized stimuli.

Musical instruments produce fundamental frequencies, harmonics, and formants as well. For example, a bow drawn across an A string on a violin will cause the string to vibrate at a fundamental frequency of 440 Hz, with naturally occurring harmonics at 880 Hz, 1320 Hz, 1760 Hz, etc. Some of those harmonics will be emphasized as formants, which emerge due to the filtering of the acoustics through the body cavity of the violin. This complicated structure lays the foundation for higher-order concepts of pitch within music.

Full musical compositions rely upon strict rules about intervals, the relationships between pitches; Gasser (2019) describes this as “the distance between one pitch and the next.” Composers consciously choose specific intervals to convey certain messages or evoke certain emotions. For example, composers usually intend to generate unease in the listener by playing two notes with a disharmonious or dissonant relationship, or to generate ease in the listener by playing two notes with a harmonious or consonant relationship. While listeners with TH rate dissonant music as unpleasant, CI listeners report dissonant notes sound pleasant, indicating that they cannot tell whether music is “in tune” or “out of tune” (Caldwell et al., 2016). Because CI listeners cannot detect when two notes are in or out of tune, overall perception of the spectral relationships throughout musical compositions is hindered.

Disruptions in musical intervals can impair music perception. In music, notes played sequentially are related by their respective intervals, and a series of sequential notes generates a melody. This melody, based upon the intervals between the notes, can have various contours, including rising, falling, or a mixture. Repetition, variation, and novelty in melodic phrases continues throughout the composition, as do secondary and sometimes even tertiary harmonic lines, providing complement and contrast to the melody while following the rules of intervals and musical composition.

Musical compositions are dependent upon the arrangement of pitches, whether sequential or simultaneous (i.e., a chord). When pitch perception is impaired, as it is for many individuals with hearing loss, following or understanding the tune of a song can be likewise impaired. Current measures to test music perception in the spectral domain often focus on the relationship between two pitches (i.e., which note is higher?) or following the contour of a melody (i.e., did those notes go up or down in pitch?). As demonstrated, however, the arrangement of musical pitches can be much more complex than this in real-world music listening situations.

2.4 Sound Quality

The final aspect of sound generation during this discussion is timbre, a concept more heavily discussed in music than in speech. Timbre is typically defined as the “sound color” of music, which can be illustrated by imagining the same melody played on two different instruments. In speech, there are a few studied corollaries, primarily differing characteristics of steady-state vowels. Research into these topics often focuses on accuracy of identification and perceptual characteristic ratings of sounds with different acoustics properties and mapping these to acoustic correlates. Methodological approaches to these studies vary – in some studies, participants rate various sound stimuli on a scale from one perceptual dimension to its opposite (e.g., from static to dynamic), and researchers correlate these perceptual dimensions to acoustic cues present in the stimuli. In other studies, participants rate various sound stimuli on their similarity or dissimilarity to one another, and researchers extrapolate the acoustic cues and their relationships to one another using the statistical methods of multidimensional scaling.

In music, results of multidimensional scaling models have resulted in two to five reported timbre dimensions. In a classic study by Grey (1977) using 16 instruments, three dimensions emerged. These were semantically described as (1) spectral energy distribution, or bandwidth of the instrument's stimuli; (2) temporal cues, such as onset and offset characteristics and the overall fluctuation in the spectral energy over time; and (3) low-amplitude, high-frequency energy in the onset of the signal, which may or may not dissipate over the course of the signal. Later studies suggest four or even five dimensions to be best for characterizing timbre (Elliott et al., 2013), though succinct semantic descriptions of the dimensions become less available with increasing number of dimensions. In summary, these studies show that timbre comprises the characteristics of sounds that remain after controlling for overall intensity, fundamental frequencies, and formants. Timbre relies heavily on spectral cues primarily generated by the source's resonant characteristics, which emphasize the intensity of select formants and are a unique signature to different speech sounds (e.g., vowels) and instruments (e.g., strings vs. horns). Additionally, temporal cues are responsible for a large portion of the acoustic characteristics that contribute to timbre, such as the onset and offset characteristics of the instrument. Collectively, these spectrotemporal cues produced by the instruments are used by the listener to make music a richer listening experience.

Detecting differences in timbre is often assessed by instrument identification tasks. This is because different instruments playing the same melodies with the same temporal qualities (i.e., tempo, rhythm) can be distinguished due to their timbre. A trumpet sounds like a trumpet because of a generally increasing pattern of resonances (i.e., gradual increase in intensity of first through sixth harmonic), while a violin sounds like a violin because of its resonance of the first and second harmonics (Gasser, 2019). These spectral cues are complemented by the temporal cues of these two instruments. For example, the sharp sounds of a trumpet are made by placing the tongue against the mouthpiece until ready to make a sound, which increases the air pressure much like the stop consonant /t/. This abrupt onset contrasts the gentle rise time of a bowed instrument, like the violin. Although instrument identification is a common task for timbre perception, timbre is also present in the vocal quality of some singers, such as Tom Waits' "gritty" voice compared to Bob Dylan's "nasal" voice (Gasser, 2019).

Timbre's spectrotemporal basis has been well-established in acoustic and perceptual models but has not been extensively evaluated in populations with hearing loss. Because of known limitations in spectral perception for listeners through auditory technology, it can be surmised that TH listeners would outperform listeners with hearing loss on timbre perception tasks, and thus most current findings with TH individuals are not generalizable. Furthermore, the effects of impaired timbre perception have yet to be fully correlated with subjective evaluation of music. As such, this important musical characteristic deserves further investigation, especially for individuals with hearing loss.

2.5 Summary of Acoustics of Music Production

This summary of common musical concepts lays the groundwork for understanding how music is perceived by healthy auditory systems, as well as where disordered hearing might affect music perception. Loudness (i.e., dynamics), temporal elements (i.e., tempo and rhythm), pitch (i.e., frequency) and melody, and timbre (i.e., instruments) are the foundation of musical compositions, with unique combinations emerging every day from the minds of composers and lyricists.

CHAPTER 3

TECHNOLOGICAL AND BIOLOGICAL PROCESSING OF MUSIC

Human ears are uniquely tuned to receive and process auditory signals. The prior section described each element of the *production* of musical characteristics. However, understanding the *perception* of musical sounds is paramount to understanding how to improve music quality for individuals with hearing loss. First, typical peripheral processing of music will be discussed, including the manipulations of the auditory signal provided by the external ear (i.e., pinna and ear canal), the middle ear system (i.e., tympanic membrane, ossicles, middle ear cavity, and round window), and the inner ear system (i.e., the cochlea, including its fluid and biomechanics). Then, peripheral processing through devices that supplement (i.e., HAs) or replace (i.e. CIs) natural auditory processing will be discussed.

3.1 Typical Peripheral Auditory Processing

The visible portion of the external ear, referred to as the pinna, has unique contributions to the resonances of sounds that are processed by the auditory system. The contours of the pinna and the shape and composition of the ear canal contribute resonance to sounds that originate in the soundfield and impinge upon the external ear. Together, the overall intensity of sounds is increased by about 10-18 dB from 2000 to 5000 Hz (see Fig. 3.1 in Gelfand, 2009). Averaged across all frequencies, the total increase in sound from the structures of the occluded ear canal is about 14.3-15.9 dBA and the overall transfer function of the entire external ear system averages out to 10.1-10.7 dBA (Grinn & Le Prell, 2019). These sounds, which are important for understanding consonants in speech, have likely been advantageous to humans since oral and aural communication exchanges emerged.

Past the external ear lies the tympanic membrane, the middle ear cavity and the ossicles or three bones of the middle ear. Each of these components increase resonance at certain frequencies. The average resonance of the middle ear system is around 1.2-1.7 kHz (Homma et al., 2009). Without the middle ear system, hearing levels would fall to a moderate or moderately-severe range, with maximum conductive hearing losses around 40-60 dB HL across all frequencies (Feldman, 1963; Gelfand, 2009). This benefit provided by the middle ear system, is often overlooked but is imperative to making sure that soft sounds can be processed by the inner ear (Feldman, 1963).

Upon entering the fluid-filled cochlea of the inner ear, the mechanical sound waves from the middle ear are transferred to fluid motions along a long, spiral tract, called the cochlear duct. The cochlear duct houses the Organ of Corti, a collection of minute structures imperative for transforming the fluid waves of sound vibrations into neural activity. In short, the fluid motion agitates the thin tectorial membrane resting upon a collection of small stereocilia attached to inner and outer hair cells. When the tectorial membrane moves, it opens ion chambers into the stereocilia of the hair cells generating biochemical reactions that initiate a neural firing response of the inner hair cells (Gelfand, 2009).

Along the Organ of Corti lie hair cells and neurons that are more sensitive to some frequencies than others. At the entrance of the cochlea, near the stapes of the middle ear system, are regions of the cochlea that are sensitive to high frequencies, while areas at the innermost part of the curve (i.e., the apex) are most sensitive to low frequencies. This sensitive arrangement of the cochlea, termed tonotopicity, allows for efficient conversion of multiple frequencies at a time throughout the auditory system. Tonotopicity helps to explain to important components of how sound waves are converted to neural impulses. First, the different locations along the cochlea that respond best to different sound frequencies is termed “place encoding.” This contrasts with “temporal encoding,” which emerges because of observations that specific auditory nerve fibers respond to sounds at precise points of the external waveform, syncing the firing of the neuron to the stimulating waveform in a process known as phase-locking. Some researchers argue that place encoding is the primary determinant of the brain’s interpretation of pitch, while others argue that temporal encoding is the primary determinant. Other models suggest that both place and rate encoding are important for pitch representation in the human auditory system (Oxenham, 2018).

Sound waves produced by instruments undergo a complex transformation before they arrive as neural impulses at the auditory nerve. For individuals with TH, these processes are usually instantaneous and imperceptible, leading to healthy and typical processing of music. However, a deviation from typical functioning along any part of the healthy auditory system can minutely or broadly affect the representation of music along the auditory nervous system.

3.2 Peripheral Auditory Processing by HAs

For individuals with hearing loss from the mild to severe range, regardless of type of hearing loss (i.e., sensorineural, conductive or mixed), HAs are typically the treatment of choice, as long as the patient is able to achieve sufficient speech recognition with the devices appropriately programmed. HAs intensify the signal at specific frequencies which are otherwise inaudible to the listener. The basic structure of a HA includes three parts: (a) input features, such as microphones that pick up external sound stimuli and an analog-to-digital converter that transforms the external sounds to digital signals; (b) an amplifier that enhances sounds according to particular equations and prescriptive formulas, usually with the goal to improve speech audibility on the basis of the individual's hearing loss; and (c) output features, such as a digital-to-analog converter, a speaker to send the sounds back to the ear, and a coupler that directs the sound back into the ear canal. Depending on the type and severity of hearing loss, different styles of HAs are appropriate. Behind-the-ear HAs have a main component resting behind the pinna and the coupler descending to the entrance of the ear canal, while more discrete HAs range from devices where all components of the HA are resting either right at the entrance to the ear canal or deeply settled within the ear canal. Behind-the-ear HAs are disadvantaged by their inability to capture the effects of the external ear resonances because the placement of their microphones is behind the pinna. However, many modern devices have included these so-called pinna cues within their device processing strategies. Behind the ear devices are often advantageous, however, because many devices worn behind the ear have the speaker in the ear canal (called a receiver-in-the-canal device) and have the option to leave the ear canal at least partially exposed to natural sound stimuli. This is particularly useful when individuals have normal or near-normal hearing in the low frequencies and only require amplification in the mid and high frequencies.

While HAs have greatly improved the ability of individuals with losses across some or all frequencies to better understand speech, these sound manipulations involve an inherent degradation of a high-quality auditory signal. HAs reduce the quality of music by reducing the overall dynamic range of the signal's intensity, compressing the relationships between soft, average, and loud sounds (i.e., wide dynamic range compression, WDRC), and compressing the relationships between low and high frequencies (i.e., non-linear frequency compression, NLFC). Although these manipulations have become commonplace, they were developed with the understanding that speech signals could be well-represented even with these manipulations, though the impact of these technologies on music perception remains unknown.

One of the first manipulations done during HA processing of sound is to limit the input of the dynamic range that the HA will process. This approach, commonly used in sound engineering to develop digital recordings of audio in digital audio formats (i.e., MP3), saves processing power. The rationale behind digital audio processing is to selectively remove information to which the ear will be insensitive (e.g., very low intensity inputs) (Plyler et al., 2019). In dynamic range limiting, the overall intensity taken into the HA is about 95 dB HL, a significant reduction when compared to the typical auditory system's dynamic range of hearing of 120 dB HL. However, for music, many sounds meet or exceed 95 to 120 dB HL in live scenarios (Hockley et al., 2012; Killion, 2009). While this could be potentially damaging for hearing, it is nonetheless the accurate representation of music in live venues. The input signal that comes in at 95 dB HL is at the maximum of the device's capabilities, and thus provides a distortion, known as saturation. Saturation is not of concern in speech, as typical speech information does not exceed 95 dB HL (Hockley et al., 2012). Because this is a common occurrence in music, nearly all HAs introduce distortion with very loud musical inputs due to the input dynamic range compression present in nearly all devices performing analog-to-digital conversions.

The second problem for music perception encountered with HAs is the pervasive use of WDRC. Prior to WDRC, HAs used a linear compression scheme, meaning that an equal amount of increased intensity (i.e., gain) was added regardless of whether the input intensity of the signal was quiet, average, or loud. For example, to account for a flat 30 dB HL hearing loss, 30 dB gain might be added to the quiet (input at 30 dB HL, output at 60 dB HL), average (input at 55 dB HL, output at 85 dB HL), and loud (input at 80 dB HL, output at 110 dB HL) signals (see Figure 3.1). This makes intuitive sense for conductive hearing losses, in which listeners only need to overcome a mechanical obstruction of sound (i.e., fluid in the middle ear system) after which the cochlea has typical functioning. However, linear processing became a problem for the more common sensorineural hearing losses.

For listeners with sensorineural hearing losses, quiet sounds may not be audible while loud sounds may be just as loud as they are to individuals with TH. This phenomenon, known as recruitment, reflects the need for HAs to amplify lower intensity sounds while not overamplifying higher intensity sounds. Therefore, the gain needed to accommodate an individual's inability to hear quiet sounds (i.e., input at 30 dB HL, output at 60 dB HL) would suddenly become too loud, near the threshold of pain, if the same amount of gain was applied to a sound with more intensity (i.e., input at 80 dB HL, output at 110 dB HL). WDRC solves this problem by providing more gain to the quieter sounds and less gain to the more intense sounds (see Figure 3.1), so that the quieter sounds are audible, and the louder sounds are not intolerable (Rosengard et al., 2005). WDRC provides great benefit for speech but does not effectively represent music. Not only does it change the musicians' intended relationships between quiet and loud sections of a musical composition, it may also affect other skills, such as detecting individual instruments within a large arrangement of many instruments (Madsen & Moore, 2014).

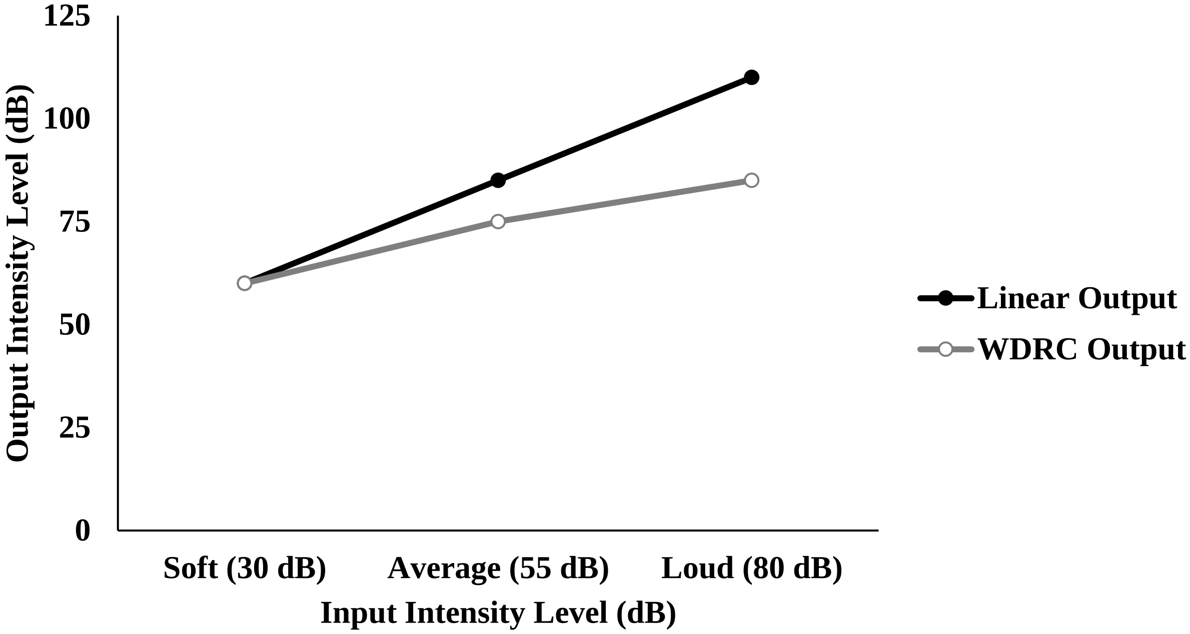


Figure 3.1. Comparison of hypothetical linear gain and wide dynamic range compression (WDRC) in amplifying intensity for hearing aid circuits. Linear output adds an equal amount of gain at each input level, while WDRC adds a variable amount of gain based on input level, in an effort not to exceed patients' loudness tolerance levels at higher intensity input levels.

While WDRC changes the intensity of HA outputs, another type of compression changes the relationships between pitches perceived by the listener. This compression scheme, NLFC, can hinder music perception and appreciation in individuals with hearing loss. The intent of NLFC is to move sounds that are difficult or impossible to amplify into a region of hearing by transposing them to a lower frequency that is audible and aidable. This is most often considered helpful for individuals with steeply sloping hearing loss in the high frequencies. NLFC helps with clarity of speech, particularly because high-frequency consonants (e.g., /s/ and /f/) are very important in distinguishing between two otherwise similar sounding words (e.g., sat and fat).

However, some HA manufacturers automatically enable the NLFC in default, “first-fit” programming of nearly all losses, not just those that are steeply sloping. Therefore, NLFC may be over-utilized without validation in clinical populations (Shehorn et al., 2018b). Over-use of NLFC may not be detrimental to speech understanding for most HA listeners, but current studies are inconclusive on the effect of NLFC on music perception and enjoyment (Shehorn et al., 2018a). For example, Parsa and colleagues (2013) conducted a study of individuals with TH and hearing loss who listened to classical and contemporary music under varying NLFC schemes. Individuals with TH and hearing loss rated all conditions with NLFC poorer than the original recording, but those with hearing loss tended to rate more severe compression schemes (e.g., those with more frequencies transposed lower) as better than those with less severe NLFC compression.. However, other large-scale studies suggest preferences for removing NLFC for HA listeners to preserve the natural relationships between musical pitches (Crook et al., 2018). Until these discrepancies in both intensity and frequency compression are resolved, individuals with HAs may continue to listen to music in programming strategies tailored for speech, rather than music.

In today’s patient population, determining the appropriate settings for HA processing of music depends largely on clinician experience and patient preference. Some suggested models exist, such as the large scale studies emerging from the Music and Hearing Aids project (Crook et al., 2018). Strategies for music processing typically aim to make HAs rely on more linear processing, rather than processing that employs heavy use of either intensity or frequency compression. In the end, however, the patient’s preference for their HAs is what is most important. As seen in the first section about the production of music, many different types of music may rely on different instruments, chords, arrangements, tempos, and moods, so the patient's preferences for music programs in HAs are also likely to be informed by their musical preferences.

3.3 Peripheral Auditory Processing by CIs

In contrast to natural processing found in the typical peripheral auditory system and acoustic signal processing found in HAs, music processing by CIs involves yet another layer of complication. Though many sources of variability in music perception exist for CI listeners, this section will focus on three relatively well-researched areas of music perception with CIs: (a) placement of internal electrode; (b) rate of electrical stimulation by the electrode; and (c) signal processing limitations.

Typical peripheral processing of frequency information relies on the tonotopic organization of the cochlea in which each part of the cochlea responds best to a particular frequency or pitch. This tonotopic arrangement moves from high frequencies at the base of the cochlea to low frequencies at the apex of the cochlea. However, tonotopicity is disrupted with the placement of a CI.

The internal component of a CI is placed surgically into the cochlea, replacing its natural function, including the natural tonotopic response present in individuals with TH. The surgically implanted internal component, called the electrode array, includes many small electrodes that deliver electrical signals to the nerves underlying the portion of the cochlea upon which they rest. Most electrode arrays house 12-24 individual electrodes, depending on the brand and model of the internal component (Dhanasingh & Jolly, 2017). Each electrode typically stimulates a range of frequencies, but these do not necessarily fall upon the portion of the cochlea that would typically respond best to that frequency. In fact, some studies estimate that the electrodes are placed such that they are stimulating 1 to 2.2 octaves lower than the place in the cochlea that typically responds to that frequency, and that more variability is seen for lower frequency regions of the cochlea (Landsberger et al., 2015; Peters et al., 2019). This is typically because the insertion depth of the electrode does not reach deeply enough to stimulate the apical regions of the cochlea, where low frequencies are typically processed, though individual cochlear anatomy and surgical approaches can also contribute. An average cochlear duct is about 34 mm long, whereas internal electrode arrays can be anywhere from 15 mm to 31.5 mm long (Dhanasingh & Jolly, 2017). The result is a pitch mismatch between what the brain expects those neurons to correlate to in pitch and what pitches are being stimulated.

Another problem resulting from the placement of electrodes is that the 12-24 electrodes are attempting to replace the function of nearly 15,000-20,000 hair cells (LeMasurier & Gillespie, 2005). For this to happen, many input frequencies are often coded into one channel for processing, and each electrode is responsible for a portion of these channels. For adults, about 4-6 channels are needed to perceive speech in quiet and about 8 channels are needed to perceive speech in noise (Friesen et al., 2001). In contrast, music perception assessed by melody recognition improves incrementally through 20 active channels, the maximum number tested (Singh et al., 2009).

However, the relationship between channels and electrodes is not one-for-one; in some cases, “virtual channels” are used to stimulate an area between two electrodes by capitalizing on a phenomenon called “cross-channel interactions.” Typically, when two electrical bodies are situated in close proximity, there is the possibility that one electrical stimulation may “jump” to the next electrode, causing stimulation of both electrode sites along the cochlea (Landsberger et al., 2012). This phenomenon explains why adding more electrodes in closer proximity does not always lead to better performance on behavioral tasks (Noble et al., 2014; Zeng et al., 2015). However, CI manufacturers have developed ways to harness this problem and convert it to something useful: through the use of a process called "current steering," CIs can in fact stimulate an area between two electrodes, in theory utilizing a more natural place along the cochlea corresponding to the intended frequency (Choi & Hsu, 2008; Landsberger & Srinivasan, 2009).

Another way that the peripheral auditory system encodes pitch is through rate of stimulation. It is believed that for a small range of low frequencies, encoding of pitch is influenced by the firing rate and pattern of auditory neurons. This temporal theory of hearing is difficult to test in humans, due to the invasiveness of the recording measurements. From models of animal audition, researchers estimate that the auditory neurons can fire up to a maximum rate of 4,000 times per second, corresponding to a pitch perception of 4,000 Hz (Oxenham, 2013). This leaves approximately 16,000 Hz (from 4,000-20,000 Hz) unaccounted for in the temporal theory model, although researchers have proposed additional models (e.g., the Volley Theory) that could account for this discrepancy (Wever, 1939).

Similar to the typical auditory periphery, CIs utilize electrical stimulation to replace the dysfunctional hair cells and generate auditory nerve firings. The stimulation rates for CIs are typically left at a default dependent upon the manufacturer, but often range from 2,500-3,000 pulses per second per channel. CIs are better able to transmit pitch information via rate of stimulation at low frequencies, estimated to be intact through 300 Hz (Todd et al., 2017). Because most CI programming strategies extract the rate of stimulation from the envelope of the stimulus, rather than using the full fine structure information, the rate of stimulation may not be robust enough for CI listeners to reliably phase lock to the signal in the auditory periphery to extract pitch information (Limb & Roy, 2014). The ability of CI listeners to process temporal information about music likely relies at least partially upon the stimulation rate as well, but this skill set is not impeded in most CI listeners (Riley et al., 2018).

Finally, CI listeners are impeded in music processing among domains other than pitch. For example, CIs operate under different compression schemes than HAs, affecting their perception of loudness and timbre as well. CI listeners are able to perceive a range of 20 discrete steps of loudness compared to 120 steps of loudness that TH listeners are able to (Caldwell et al., 2017). When programming a CI, audiologists typically aim for their patient to have behavioral thresholds near 30 dB HL (Vaerenberg et al., 2014). This is somewhat counterintuitive, as this intentionally impairs an individual’s ability to detect the lowest intensity sounds, such as appliance noises and rustling leaves. However, the choice to set the threshold of this input dynamic range, or IDR, to a slightly louder level provides benefits. By focusing the IDR to a range of sounds deemed most important (i.e., sounds ranging from 30 dB to about 90 dB), the CI can preserve processing power while limiting access to distracting signal inputs (e.g., appliance noises). Because music can, and often does, exceed the limits of this IDR, the CI likely eliminates the lowest intensity sounds (i.e., the beginning of a *crescendo* or a soft snare drum) and distorts the most intense sounds (i.e., similar to “blowing out” a speaker by trying to play music too loudly).

In addition to loudness, CI listeners are unable to perceive the full range of sound quality that exists in music. This skill, often measured by an instrument identification task, suggests that

CI listeners are much poorer than TH listeners at identifying musical instruments (i.e., 47.1% compared to 86.9% correct) (Brockmeier et al., 2011). CI listeners rely primarily upon onset and offset cues to detect instruments, capitalizing on their intact temporal perception (Innes-Brown et al., 2013; Riley et al., 2018). To illustrate this concept, consider the gentle crescendo onset of a stringed instrument, created by the slow, low-pressure pulling of a bow across the string, compared to the blared onset of a trumpet, created by stopping the air pressure buildup at the mouthpiece with the player's tongue before releasing all the air pressure at once in a loud, crisp onset. Although individuals with CIs may not be able to distinguish the unique resonances of each instrument, they would be able to distinguish the temporal differences between the onset of these two instruments. While this is helpful for testing purposes, it may not translate to real-life perception and appreciation of complex musical arrangements, in which overlapping instruments may confuse the temporal signals available in single-instrument identification tasks.

Although much more could be covered about why CI listeners have difficulty perceiving all the elements of music accessible to the auditory systems of TH listeners, the above elements have yet to be resolved. The field will continue to develop other strategies that may improve music perception among CI listeners, such as surgical techniques, image-guided programming, and processing strategies and power, but current CI listeners require further study to determine how to capitalize on the strengths of their music perception to overcome some of the barriers inherent to listening to music.

3.4 Summary of Healthy Peripheral and Technological Processing of Music

Due to differences between TH listeners' peripheral auditory systems and the processing strategies of auditory technologies like HAs and CIs, one piece of music can be perceived in quite varied ways. These differences among listening experiences may be relatively consistent within one group, such as typical listeners' dynamic range falling around 120 dB; more often, however, each group has significant variability among all its members in music perception skills, such as the ability to recognize familiar melodies among listeners with auditory technology. By understanding these group differences and sources of individual variance, researchers can focus on improving aspects of music perception that affect most listeners within a particular group, and clinicians can target individualized music perception goals for each patient they encounter.

CHAPTER 4

NON-AUDITORY FACTORS IN MUSIC PERCEPTION AND APPRECIATION

Listeners with TH, HAs, and CIs may experience music in different ways. This is likely related to their auditory processing of music, whether through a typical periphery or technology. However, in groups of TH listeners, other non-auditory factors have been shown to contribute to the music perception and appreciation of participants. These factors include (a) history of musicianship, (b) familiarity and emotional responses to music, and (c) chronologic age. Thus far, sparse research relates these factors to music perception and appreciation among listeners with varying degrees of hearing abilities.

4.1 Musicianship

Musicianship has been studied extensively, but common definitions of musicianship are lacking. The definition of musicianship ranges from >10 years of formal musical training to the ability to read sheet music (Cogo-Moreira & Lamont, 2018). This makes cross-study comparisons hard. However, in general, formally trained musicians are more adept at most discrete skills (e.g., pitch difference limens and timbre judgments) related to music than those without formal musical training (Kaganovich et al., 2013; Kishon-Rabin et al., 2011; Liang et al., 2016). Not all studies show that musicians perform better than non-musicians. For example, one study assessed musicians’ and non-musicians’ abilities to discriminate melodic contours, which involves determining whether notes in a melodic sequence are higher or lower than the previous note. This study found no differences between the groups with musical training and without on these broader musical tasks (Bigand, 2003).

4.2 Familiarity

Familiarity of music affects an individual’s response to sound, both physiologically and emotionally. Pupillometry studies show that familiar music incites more pupil dilation in snippets of songs less than one second, suggesting an auditory pathway that allows for strong and rapid connections between hearing familiar songs and arousal of attention within areas of the brainstem such as the locus coeruleus and amygdala (Jagiello et al., 2018). Familiarity also leads to increased emotional responses to music, including judgements of emotional intensity and responses that participants “liked” the music stimuli with more familiarity (Ali & Peynircioğlu, 2010). Because of this reason, individuals who have never had access to a typical hearing system (i.e., prelingual listeners) might have a different sense of familiarity of melodies than who had TH from birth and acquired hearing loss later in life (i.e., postlingual listeners). Differences in familiarity of music have been found between children with pre- and postlingual deafness listening through CIs, such that those with postlingual deafness are more accurate at familiar melody identification than those with prelingual deafness (57.43% vs. 37.99%) (Olszewski et al., 2005).

4.3 Chronologic Age

Advanced chronologic age is well known to be associated with a decline in hearing thresholds, auditory processing skills, memory, and other cognitive processes. However, music perceptual skills often remain intact despite evidenced declines in other cognitive processes (Lagrois et al., 2018). In an extensive review of aging and music, older adults (≥ 60 years old) maintained performance on par with their younger counterparts (18-30 years old) across both simple and difficult musical tasks, such as determining similarities and differences in melodic contour and identifying “out of tune” notes in a sequence (Halpern & Bartlett, 2002). However, older adults perform poorer than the younger listeners on other types of processing tasks, such as identifying familiar tunes that have been sped up and long-term recognition of melodies (Halpern & Bartlett, 2002). Halpern and Bartlett (2002) could find no discrete pattern of aging and music processing, except to suggest that some musical tasks might be completed by more general cognitive resources – in these conditions, seniors were not at a disadvantage compared to their younger peers. Furthermore, though these studies showed no evidence of a compensatory mechanism for seniors to recruit additional cognitive resources to complete musically challenging tasks, there are likely accommodations that could be made to musical experiences for seniors, such as increased repetition of songs before a high degree of familiarity is achieved. Because music perceptual skills do not seem to decrease across the board with increased age in adults with TH, it is important to understand whether this will generalize to a group of older individuals with CIs.

In conjunction with a lack of aging effects in music perception, music appreciation reports suggest that age is a less important consideration for music appreciation. As individuals age, music becomes marginally less important in their lives, although it typically does not become unimportant (Bonneville-Roussy et al., 2013). Older individuals maintain a preference for music from their younger years throughout their lifespan (Schulkind et al., 1999), and familiar music from their younger years may aid adults in retrieving more emotionally robust autobiographical memories (Ford et al., 2016). Seniors may also perform cognitive tasks better with happier rather than negative music, a behavioral difference not seen in younger adults

(Vieillard & Bigand, 2014). Because older adults seem to maintain a strong, lifelong connection to music, the presence of hearing loss and the decrements in perception associated with auditory technology should be studied to determine strengths and weakness in music perception and appreciation in younger versus older populations.

4.4 Summary of Non-Auditory Factors Influencing Music Perception and Appreciation

Individuals’ current experiences with music likely differ based on a history of music performance, familiarity to musical stimuli, and chronologic age. While in many cases these factors affect primarily music perception, music appreciation may remain relatively constant among all groups of listeners, regardless of past music experiences.

CHAPTER 5

PURPOSE AND RESEARCH QUESTIONS

Music is a complex acoustic stimulus, featuring very quiet to very loud sounds, temporal patterns, extensive frequency ranges, complex melodic and harmonic relationships, and spectrotemporal qualities. While typical auditory systems are effective at perceiving, processing, and interpreting these acoustic cues, individuals with hearing loss listening via auditory technologies such as HAs and CIs experience these acoustic cues with degraded fidelity. At this time, researchers and clinicians have few successful strategies for remedying music perceptual difficulties, although emerging research is beginning to address music perception and appreciation. By including non-auditory factors such as musicianship, familiarity, and chronologic age in the current study, comparisons can be made to literature focusing on the TH population. By establishing baseline performance and methodological consistency, research about music perception and appreciation across this range of auditory and non-auditory factors can be extended.

5.1 Purpose and Research Questions

The purpose of this study is to compare music perception and appreciation of listeners based on three grouping variables: (a) auditory status (i.e., TH vs. HA vs. CI listeners); (b) categorization of onset of hearing loss (i.e., pre- vs. postlingual CI listeners); and (c) chronologic age (i.e., young vs. older CI listeners). To our knowledge, no study thus far has compared among all these groups in measures of both objective and subjective music perception and appreciation measures.

This study intends to answer the following research questions:

1. How do listeners with TH, HAs and CIs perform on objective measures of music perception (i.e., the Clinical Assessment of Music Perception) and subjective, self-report measures of music experiences (i.e., the Music-Related Quality of Life)?

    Hypothesis 1a. Listeners with TH will outperform those with HAs and CIs on objective measures of music perception and will rank subjective experiences of music abilities higher.

    Hypothesis 1b. HA listeners will perform better than CI listeners on objective measures of music perception.

    Hypothesis 1c. No significant group differences will be found on the subjective ratings of importance of music.

2. Does performance on objective measures of music differ between pre- and postlingual CI listeners?

    Hypothesis 2a. Prelingual CI listeners will recognize fewer familiar melodies than postlingual CI listeners, but the groups will discriminate similar numbers of unfamiliar melodies.

3. Does performance on objective measures of music differ between younger and older postlingual CI listeners?

    Hypothesis 3a. Younger adult CI listeners (i.e., 18-50 years) will outperform older adult CI listeners (i.e., 60-85 years) on all objective and subjective measures of music perception and appreciation.

4. Do objective and subjective measures have significant relationships to one another?

Hypothesis 4a. Objective measures on each of the four subtests with correlate with subjective evaluation of music abilities but not music importance.

Hypothesis 4b. Subjective measures of music abilities and importance will correlate.

Hypothesis 4c. Self-report of specific music abilities will be significantly correlated to their related objective measures.

This research fills a gap in the literature comparing groups of listeners on both objective and subjective measures of music perception and appreciation. By comparing these groups under one methodological approach, differences in performance and self-report can be elicited to better understand the musical experiences of individuals with hearing loss.

CHAPTER 6

METHODS

6.1 Consent and Ethical Approval

This study was approved by The University of Texas at Dallas's Institutional Review Board, Study 18-146. Written, informed consent or online consent was received from each participant.

6.2 Special Note Regarding COVID-19-Related Research Restrictions

After the conclusion of the pilot data collection phase of this study, in-person research was prohibited at our institution due to ethical concerns related to the COVID-19 pandemic. Therefore, a portion of this data collection reflects in-person research appointments, while the remainder reflects remote administration of the protocol over the secure videoconferencing software Microsoft Teams. Throughout the methodology, both in person and remote protocols are described.

6.3 Participants

Participants were 18-85 years old. Participants were grouped according to device status (i.e., TH, CI, or HA), onset of deafness (i.e., pre- or postlingual), and chronologic age (18-50 years or 60-85 years). Participants were excluded if they only had an electroacoustic device configuration (i.e., a non-traditional CI that includes both acoustic and electric hearing modalities within the same ear), and/or inability to complete the testing independently. Five groups of participants emerged. The first group (i.e., TH listeners) consisted of participants ages

18-50 with TH. The second group (i.e., young postlingual CI listeners) consisted of participants ages 18-50 with CIs who acquired hearing loss after the age of three years. The third group (i.e., young postlingual HA listeners) included participants ages 18-50 with HAs who acquired hearing loss after the age of three years. The fourth group (i.e., young prelingual CI listeners) included participants ages 18-50 with CIs who presented with congenital or acquired hearing loss before the age of three years. The final group (i.e., older postlingual CI listeners) included participants ages 60-85 years with CIs who acquired hearing loss after the age of three years.

Participants were recruited from local institutions in the Dallas-Fort Worth Metroplex, including The University of Texas at Dallas community, the University of Texas Southwestern Medical Center otolaryngology clinic, and the Callier Center for Communication Disorders. Additionally, participants were recruited from national online support groups, such as the Hearing Loss Association of America, the Association of Musicians with Hearing Loss, and the Association of Medical Professionals with Hearing Loss.

A priori power analysis for this study was calculated to detect differences among the three groups in the main study on the objective music measures using G*Power (Faul et al., 2007, 2009). Based on data from the original development and validation of the main objective music measure in this study, a large effect size was expected to emerge. In particular, TH participants scored much higher than CI listeners in pitch (Hedges' $g = .98$), familiar melody (Hedges' $g = 3.06$), and timbre (Hedges' $g = 3.31$) subtests (Kang et al., 2009). When taken in the context of music perception scores, Hedges' g values greater than .80 can be interpreted to be large effect sizes (Durlak, 2009). Thus, to achieve a power of .80 using $\alpha = .05$ in this main analysis, 10 participants per group were needed ($N = 50$).

6.4 Materials

6.4.1 Demographic and Audiologic Information

Demographic and audiologic characteristics were obtained from questionnaires delivered online or administered by the researcher. Demographic characteristics included age, gender, and musicianship status, (i.e., history of playing instrument and/or if they could read sheet music now or ever in their past). Audiologic characteristics (e.g., auditory device configuration) were obtained via self-report. Participants reporting TH completed a hearing evaluation in an audiometric suite using headphones. Participants reporting hearing loss were asked about the age at identification of their hearing loss, age at first HA, and age at first CI (if applicable). To confirm audiometric thresholds, in-person participants completed an aided hearing evaluation to ensure sufficient audibility of the stimuli. All audiometric thresholds were obtained using the modified Hughson-Westlake method by a trained researcher who was an audiologist or a graduate audiology student (Carhart & Jerger, 1959). Remote participants self-reported their degree of hearing loss in each ear with a visual aid that indicated where mild, moderate, severe, and profound hearing losses were located on the audiogram. To assess likelihood of up-to-date programming, remote participants were also asked when they had most recently visited the audiologist.

Participants with TH. Thresholds for in person participants were recorded at 250, 500, 1000, 2000, and 4000 Hz in each ear. Eighteen participants with TH completed this in-person hearing evaluation, and no participant had poorer than 25 dB HL threshold at any frequency in either ear. Two participants were tested remotely. These participants are licensed audiologists who completed a screen using the same criteria (25 dB HL in all frequencies) to confirm normal hearing thresholds.

Participants with HAs. No participants with HAs were recruited during the in person, pilot testing phase. Thus, no aided or unaided thresholds could be obtained for this group.

Participants with CIs. Participants with CIs were asked whether they were recipients of a hybrid or electroacoustic device. Participants who reported use of only these non-traditional CIs were excluded from the current data analysis. For participants who wore at least one traditional CI, regardless of contralateral device, aided thresholds using warbled tones in soundfield were recorded at 250, 500, 1000, 2000, and 4000 Hz in each ear with a CI. Eight participants with CI completed this in-person hearing evaluation, and no participant had poorer than 30 dB HL threshold at any frequency the ear(s) with CI.

Determining categorization of onset of hearing loss. Participants who reported an initial identification of hearing loss at younger than three years old were categorized as prelingual, while those who reported an initial identification of hearing loss at or after three years old were categorized as postlingual (Moran et al., 2016). Participants who used HAs who reported prelingual deafness were excluded from this data analysis.

6.4.2 Objective Evaluation of Music Perception

The objective evaluation of music perception included (a) three subtests of the Clinical Assessment of Music Perception (CAMP; Kang et al., 2009; Nimmons et al., 2008), which assessed behavioral perception of pitch, familiar melodies, and instrument identification; and (b) one subtest of the Profile of Musical Skills (PROMS; Law & Zentner, 2012), which evaluated behavioral perception of unfamiliar melodies. In their initial development, both the CAMP and the PROMS tests were taken by the participant at the computer, with the participant choosing their own responses. However, in the current study, the researcher administered the CAMP and the PROMS, while the participant reported their answers to the researcher who then selected that answer in the computer software for the participant.

CAMP. The CAMP test was developed to assess how listeners with CIs performed on measures of pitch direction, melody recognition, and timbre perception. It has been well-established that individuals with CIs can perform within normal limits on rhythm measures (Brockmeier et al., 2011; Cooper et al., 2008; Gfeller et al., 1997; Looi et al., 2008; Riley et al., 2018). For example, in early generation CIs, adult CI listeners scored between 83-85.5% correct on a rhythm task, while TH listeners scored 84.6% correct (Gfeller et al., 1997). This skill has persisted throughout the research literature, with more recent studies suggesting no significant differences between TH listeners and adult CI listeners in temporal music tasks. For example, in Brockmeier et al. (2011), TH listeners scored 84.0% correct on a rhythm task compared with CI listeners' average 78.8% correct. Therefore, measures of the temporal domains of rhythm and tempo have been left out of the CAMP and the current study.

Pitch discrimination. The first subtest of the CAMP measured how far apart in pitch two notes needed to be for listeners to detect that the tones were different. This threshold difference limen task was performed at three different base frequencies (i.e., 262 Hz, 330 Hz, and 394 Hz, corresponding to the middle C on a piano, E4 and G4[1]). This test employed a two-alternative forced choice paradigm: two pitches were presented, and the participant responded with which

---

[1] In music notation, E4 and G4 correspond to the E and G keys above middle C.

note was higher in pitch. Participants were given four practice trials before the test began with feedback on whether they responded correctly or incorrectly. During the experimental phase, no feedback on whether they were correct or incorrect was provided to the participant.

Possible scores on the pitch discrimination task ranged from 0.50 to 12, which represent the threshold in semitones (i.e., a half step, or the distance between a white key and its nearest black key on a piano) that listeners needed to determine that two sounds differed. Although the smallest interval tested was one semitone, participants received a score of 0.5 semitones if they were 100% correct at all presentations of the one semitone signal, suggesting an estimated threshold difference limen of less than one half step (Drennan et al., 2015; Kang et al., 2009; Nimmons et al., 2008). A score of 12 semitones indicated that listeners needed one octave or more difference between notes to detect two different pitches. Three previous studies using the CAMP with combined sample size of $N = 186$ suggested that adult CI listeners need anywhere from 2.9 to 11.5 semitones to detect a difference at a base frequency of 262 Hz, 2.59 to 9.0 semitones at 330 Hz, and 2.5 to 6.5 semitones at 394 Hz (Drennan et al., 2015; Kang et al., 2009; Nimmons et al., 2008).

Familiar melody recognition. The second subtest of the CAMP presented 12 childhood melodies (see Table 6.2) without their rhythms. This was a closed-set task, and participants were asked if they were familiar with all the melodies. In person, participants were provided a laminated card with the names of each of the melodies that were presented. Remotely, participants viewed the screen of the test, which included all the answer choices. Next, the researcher played each song for the participant twice, in the order listed in Table 6.1, with the

Table 6.1. Melodies and instruments tested in the Clinical Assessment of Music Perception.

Familiar Melodies	Instruments
• Frere Jacques / Are You Sleeping • Happy Birthday • Here Comes the Bride • Old MacDonald • Silent Night • Row, Row, Row Your Boat • Jingle Bells • Rock-a-Bye Baby • London Bridge • Mary Had a Little Lamb • Three Blind Mice • Twinkle Twinkle	• Cello • Clarinet • Flute • Guitar • Piano • Saxophone • Trumpet • Violin

researcher announcing which melody was being played. After this familiarization period, the experimental portion began. The participant was instructed to listen to the entire melody before responding and was encouraged to take their best guess if they were unsure.

The familiar melody subtest yielded a percent correct score. In previous studies with a combined total of *N* = 195 participants, average performance on this familiar melody recognition task was 23% to 26.2%, but participants scored between 0% to 94.4% correct across all the studies, suggesting wide variability in CI listeners' abilities on this task (Drennan et al., 2015; Kang et al., 2009; Nimmons et al., 2008).

Instrument identification. The final subtest of the CAMP requires participants to identify which of eight possible instruments played a melody (see Table 6.1). These instruments were live instruments, recorded in a professional recording studio, standardized to play at 82 beats per minute, with "the same intensity of mezzo forte, articulation (i.e., detached), and phrasing" (Kang et al., 2009, p. 4). It is worthwhile to note that many CI participants suspected that these instrumental recordings were synthesized, rather than live. This was a closed-set task, and participants were asked if they were familiar with all the instruments. In person, participants were provided a laminated card with the names and pictures of each of the instruments that were presented. Remotely, participants viewed the screen of the test, which included all the answer choices. Then, researchers familiarized participants to the stimuli by presenting each instrument playing the same five-tone melody twice in the order listed in Table 6.1. Then, the experimental portion began, and participants were instructed to let researchers know which instrument they thought was playing the same five-tone melody that was used during familiarization.

The instrument identification subtest yielded a percent correct score. In previous studies with a combined total of *N* = 195 participants, average performance on this instrument identification task was 43.2% to 49%, but participants scored between 12% to 87.5% correct across all the studies, suggesting wide variability in CI listeners' abilities on this task (Drennan et al., 2015; Kang et al., 2009; Nimmons et al., 2008).

PROMS. To account for the possibility that "familiarity" of melodies may differ among participants, specifically those who are pre- and postlingual CI listeners, a fourth subtest was included in the objective music perception battery. The full PROMS test encompasses nine subtests, but only one subtest (i.e., "melody") was used in the current study. To distinguish from this study's "familiar melody" test, the PROMS subtest is referred to as the "unfamiliar melody discrimination" subtest.

Unfamiliar melody discrimination. The unfamiliar melody discrimination task asked listeners to judge whether two melodies were the same or different. The participants listened to one practice trial with feedback provided by the researcher, and then the experimental portion began. In each presentation, the target melody was presented two times, and then a third melody was presented. The third melody was either the same as or different from the target melody. Participants were provided a laminated card (in-person) or viewed the screen (remotely) with their response choices, which were “Definitely same,” “Probably same,” “I don’t know,” “Probably different,” or “Definitely different.” The researcher verbally instructed the participant that many people are better at this task than they think they are, so they should try to avoid overusing “I don’t know” as a response option.

This test was scored in two ways, to accommodate the developers’ scoring methodology and to provide a score that is comparable to the familiar melodies subtest of the CAMP. For the developers’ scoring methodology, two points are assigned for choosing a correct response of “definitely same/different,” and one point is assigned for choosing a correct response of “probably same/different.” These points are summed and divided by two to yield the accuracy and confidence score. Because this test is not directly comparable to the percent correct scores generated by the CAMP, an additional score was made for this study by calculating the number of correct judgments, regardless of confidence of the response.

6.4.3 Subjective Music Questionnaire

MuRQoL. Subjective music experiences were measured using the Music-Related Quality of Life (MuRQoL; Dritsakis et al., 2017). The MuRQoL, a 36-item self-report questionnaire, was administered to assess subjective exposure to musical characteristics and situations and the relative importance of these music experiences (Dritsakis, 2017). For this study, data analysis was based on the two domains – Music Abilities and Music Importance –

Table 6.2. Domains, subscales, and examples from the Music-Related Quality of Life questionnaire.

Domain	Subscale	Definition	*n*	Example item
Music abilities	Ability-Perception	How well can the subject perceive musical characteristics	11	*Can you recognize the words in songs?*
	Ability-Engagement	How well can the subject engage with music across situations	7	*Do you choose to listen to new music (i.e., music that you have not heard before)?*
Music importance	Importance-Perception	How important is it for the subject to perceive music well	11	*How important is it for you to be able to recognize the words in songs?*
	Importance-Engagement	How important is it for the subject to engage with music across situations	7	*How important is it for you to be able to listen to new music (i.e., music that you have not heard before)?*

with higher scores representing more abilities or importance of music (see Table 6.2).

Music abilities. The first domain (referred to here as music abilities) combined scores from the first two subscales: ability-perception (i.e., subject's self-perceived music perception skills) and ability-engagement (i.e., subject's self-perceived ability to engage with music across situations). Response choices within music abilities range from never to always on a five-point scale.

Music importance. The second domain (referred to here as music importance) combines scores from the final two subscales: importance-perception (i.e., the subject's perception of how important it is to perceive music well) and importance-engagement (i.e., the subject's perception of how important it is to be able to engage with music across situations). Participants rate music importance on a five-point scale ranging from not important at all to extremely important.

Scoring. Responses to the MuRQoL are transposed from a one to five point scale to a 0 to 100 scale, with 0 representing never or not important at all and 100 representing always or extremely important. Further explanation of the subscales can be found in Table 6.2 or in the original development and validation paper (Dritsakis et al., 2017).

The 18 questions on the music abilities domain mirror the 18 questions on the music importance domain; for example, “Can you recognize the words in songs?” mirrors “How important is it for you to be able to recognize the words in songs?” The MuRQoL demonstrated adequate internal consistency (Cronbach’s $\alpha > .80$) and test-retest reliability (intra-correlation coefficients > .80) of the four subscales (see Dritsakis et al., 2017, p. 273) when tested with an initial sample of 147 adult CI listeners.

6.4.4 Validation and Calibration of In-Person and Remote Testing Procedures

The following section briefly describes the in-person and remote testing procedures, as well as calibration and validation efforts to ensure equivalency between the two measures. This process is fully described in the Remote Testing Wiki of the Acoustical Society of America (Fowler, 2020), and sections in long quotes are taken verbatim from this original writing.

In-person data collection procedure. During in person data collection, the CAMP and the PROMS were routed through the external inputs of the audiometer and presented via loudspeaker in the audiometric suite. Objective music tests were calibrated to 65 dBA using a NIOSH smartphone app on an iPhone or the dB Meter app on a single Android phone (Google Pixel). The CAMP provides a single calibration tone, while the PROMS provides a set of low-frequency percussive beats followed by high-frequency beats; therefore, calibration was performed using only the CAMP calibration tone and volume was not adjusted when switching from the CAMP to the PROMS test.

Remote data collection p**rocedure.** After confirming spectral equivalence and test-retest reliability of in person and remote data collection, the remote data collection phase began. During remote data collection, the CAMP and the PROMS were presented to the participant using screen sharing and the “Share System Audio” feature of the videoconferencing software Microsoft Teams. To ensure consistency among listeners, participants were instructed to remove any streaming capabilities of their devices to replicate the soundfield environment of the in person testing, except in the case that a participant did not have adequate computer speakers to perform the test. Because the objective music tests could not be calibrated remotely, participants were instructed to set their computers to a comfortable and audible level to listen to the stimuli. Test sentences included in the CAMP test were played to the participant as they adjusted their volume to ensure audibility and comfort.

In some early remote tests, the transmission of the computer’s audio would drop out unexpectedly, preventing the entire sound stimuli from being presented to the participant. Because the CAMP does not allow the opportunity to replay the presentation, participants were unable to accurately respond to these stimuli. For three participants, these stimuli were random and could not be confidently rejected. Therefore, these participants’ tests were excluded from the data analysis. To prevent this problem in the remaining tests, two solutions were implemented. First, the researcher tallied each presentation of each stimulus. Throughout the objective tests, after five stimuli presentations, the audio sharing was reset within Microsoft Teams. Second, because the researcher kept a tallied record of each presentation of the stimulus, if the audio did stop sharing unexpectedly, the researcher made a note of which stimulus was in error. The CAMP test provides an item record of stimuli and answers chosen, so the researcher went into the record and noted which presentations were in error and could correct accuracy scores to reflect only accurately presented items.

Calibration of remote and in person data collection. To ensure that stimuli delivered remotely via the videoconferencing software would not undergo undue spectral distortions, five lab members were invited to participate in the calibration study and were consented to the procedures. They were instructed to download the free sound analysis tool Audacity (Audacity Team, 2020).

> “The pitches were shared from the researcher’s computer (on campus) using Microsoft Teams and the “Share System Audio” feature while the participants recorded the sounds. Represented in this analysis are two Macbook Pros, two Macbook Airs, and one HP Envy X360. Four of five participants recorded the sounds directly into Audacity, while one participant recorded the sounds in QuickTime and converted the files into WAV files to be uploaded into Audacity” (Fowler, 2020).

> “Root mean squares were calculated for each of the 26 pitches included in the music test software. These tones range from 184 Hz to 783 Hz. With the exception of one pitch (659 Hz), all RMS were less than 5 Hz” (Fowler, 2020).

> "In classic psychoacoustic studies, frequency difference limens (DL) were tested as a function of intensity and frequency. Consistently, it was found that as frequency increased, DLs were larger (poorer), and as intensity increased, DLs were smaller (better) (Moore, 1973; Sek & Moore, 1995; Wier et al., 1977). In these studies, in the range of the frequencies presented here, participants had DLs typically around 2 Hz or less. While some of the RMS exceed this DL, the participants in these classic studies were highly trained (in some cases PIs and lab members of the studies with 20-30 hours of pitch discrimination training). These average DLs do not likely represent the whole untrained population, which are likely to be slightly larger in untrained normal hearing listeners. Thus, the above numbers presented here should not greatly affect the validity of the stimuli presented remotely" (Fowler, 2020).

Validation of equivalency of remote and in-person data collection. To ensure equivalency between in person and remote data collection, five of the original TH participants completed the objective music measures of pitch, familiar melody recognition, instrument identification, and unfamiliar melody again in the remote modality. *A priori,* a threshold of

Table 6.3. Test-retest correlation values between in-person and remote test administration.

Test	Correlation
Pitch Mean	-0.53
Familiar Melody	0.91
Timbre	0.78
PROMS Score	0.86
PROMS Percent	0.71

r = .70 was considered the acceptable value for a test-retest. Pearson's correlations were calculated for each of the five objective data points gathered in this study (see Table 6.3).

> "The correlations between the objective measures at time one and time two suggest that all measures meet a test-retest value of .70 or greater, except that of the pitch discrimination task. Three of five participants had mean pitch scores change by .02, one participant had mean pitch score change of .04, and one participant had a mean pitch score change of .10. The full range of scores possible is .50 to 12 semitones, with .50 being the best and 12 being the worst. Most typical hearing listeners can discriminate two pitches within one semitone, or one half-step. Therefore, a change of .10 is likely not a clinically significant difference" (Fowler, 2020).

> "Although the test-retest value of the mean pitch discrimination (*r* = -.53) is less than the predetermined .70 value, the aforementioned calibration study suggests that this is likely not due to remote administration of the objective measures. Because this calibration study suggested robust transmission of the pitches via the remote platform, and all other measures were above .70 test-retest, this validation study concludes that remote administration of the objective music tests mirrors that of the in-person data collection" (Fowler, 2020).

CHAPTER 7

RESULTS

7.1 Statistical Analyses

Six MANOVAs were run comparing objective music perception and subjective music appreciation scores among (a) the three groups by device status (i.e., TH, CI, and HA); (b) pre- and postlingual CI listeners; and (c) younger compared to older postlingual CI listeners. Correlations were run among the objective music perception scores and subjective data, showing whether relationships exist between the objective test scores and the domains of the MuRQoL, between the two domains of the MuRQoL, and between the objective test scores and their corresponding subjective questions (i.e., questions related to pitch, familiar and unfamiliar melody, and instrument identification). Reduced alpha values will be applied to account for alpha inflation during post-hoc testing.

7.2 Descriptive Statistics

Overall, 136 participants expressed interest in this study from recruitment efforts. Of these, 82 participated in data collection, and subsequently 22 of these participants were excluded from data analysis for testing errors ($n = 6$), not meeting age criteria ($n = 7$), not meeting technology criteria ($n = 3$), and not meeting auditory history criteria ($n = 6$). In total, 60 participants met criteria of age, technology, and auditory history, completed all study measures, and were included in data analysis. Descriptive statistics for each group are reported in Tables 7.1, 7.2, and 7.3.

Participants with TH (*n* = 20) had a mean age of 27.25 years and were slightly more female and musicians. They were tested primarily in person. Demographic and audiologic data are presented in Table 7.1. Only one participant reported any unfamiliarity with the melodies presented ("Three Blind Mice"). Results on objective and subjective measures are reported in Table 7.2 and 7.3, respectively. TH listeners were able to discriminate pitches less than one half step apart. They recognized most isochronous familiar melodies and instruments. In discriminating differences in unfamiliar melodies, they scored an average of 9.78 on the rating scale that considers both accuracy and confidence, which translated to a better-than-chance accuracy. On subjective measures of music abilities and importance, TH listeners rated their own abilities very high and the importance of music moderately high.

Table 7.1. Demographic and audiologic data of participants.

	TH (*n* = 20)	YPost CI (*n* = 10)	YPost HA (*n* = 10)	YPre CI (*n* = 10)	OPost CI (*n* = 10)
M Age, years (*SD*)	27.25 (4.59)	30.80 (8.42)	26.00 (5.08)	24.10 (4.09)	68.20 (5.83)
% Female	60%	70%	80%	70%	50%
% Remote	10%	70%	100%	50%	100%
% Musician	60%	50%	70%	50%	60%
Technology during test	N/A	5 Bi CI 5 Uni CI	10 Bi HA	6 Bi CI 4 Uni CI	5 Bi CI 5 Uni CI
M Age first HA, years (*SD*)*	N/A	13.43 (10.03)	10.00 (7.19)	0.75 (0.66)	33.30 (13.30)
M Age first CI, years (*SD*)	N/A	23.05 (12.31)	N/A	6.95 (9.84)	57.20 (11.54)

Note. TH = Typical hearing listeners; HA = Hearing aid; CI = Cochlear implant; YPost CI = Young postlingual CI listeners; YPost HA = Young postlingual HA listeners; YPre CI = Young prelingual CI listeners; OPost CI = Older postlingual CI listeners; Bi = Bilateral; Uni = Unilateral. *Mean age of first HA was reported by only three young prelingual CI participants and seven young postlingual CI participants.

Table 7.2. Means and standard deviations on objective measures of music perception.

	TH (*n* = 20)	YPost CI (*n* = 10)	YPost HA (*n* = 10)	YPre CI (*n* = 10)	OPost CI (*n* = 10)
M Pitch discrimination in semitones	0.69	2.11	0.68	2.56	1.88
(*SD*)	(0.27)	(1.10)	(0.17)	(1.51)	(1.75)
M Familiar melody %	81.81	44.44	70.75	18.66	25.28
(*SD*)	(18.48)	(31.40)	(26.00)	(25.25)	(13.76)
M Instrument %	87.71	51.66	70.42	46.67	37.08
(*SD*)	(12.38)	(21.17)	(17.00)	(15.09)	(14.76)
M Unfamiliar melody score	9.78	5.95	7.80	6.70	6.10
(*SD*)	(2.16)	(2.10)	(2.21)	(1.49)	(2.17)
M Unfamiliar melody %	67.50	45.00	56.67	51.67	47.22
(*SD*)	(10.08)	(8.86)	(15.00)	(9.09)	(14.41)

Note. TH = Typical hearing listeners; HA = Hearing aid; CI = Cochlear implant; YPost CI = Young postlingual CI listeners; YPost HA = Young postlingual HA listeners; YPre CI = Young prelingual CI listeners; OPost CI = Older postlingual CI listeners.

Table 7.3. Means and standard deviations on subjective measures of abilities and importance.

	TH (*n* = 20)	YPost CI (*n* = 10)	YPost HA (*n* = 10)	YPre CI (*n* = 10)	OPost CI (*n* = 10)
M Abilities	79.79	54.31	69.72	59.29	50.28
(*SD*)	(7.33)	(13.82)	(14.30)	(14.17)	(23.17)
M Importance	67.24	63.06	66.39	63.61	69.58
(*SD*)	(14.53)	(16.36)	(20.91)	(11.69)	(17.17)

Note. TH = Typical hearing listeners; HA = Hearing aid; CI = Cochlear implant; YPost CI = Young postlingual CI listeners; YPost HA = Young postlingual HA listeners; YPre CI = Young prelingual CI listeners; OPost CI = Older postlingual CI listeners.

Young participants with postlingual deafness who wore CIs (*n* = 10) had a mean age of 30.80 years. They were primarily female and evenly split between musicians and non-musicians. Their average age at first auditory technology was around 10 years and their average age at first CI was around 17 years. Demographic and audiologic data are presented in Table 7.1. They were tested primarily remotely, though the three participants tested in person passed the aided hearing screening, and the remainder of the participants had a recent audiology appointment within the past six months (*n* = 6) or one year (*n* = 1). Typically, five of these participants wore bilateral CIs, two wore unilateral CI, and one wore a bimodal arrangement. For testing, the bimodal participant wore only their CI and the rest wore their typical auditory technology configuration. One participant reported unfamiliarity with one of the childhood melodies (“Frere Jacques”); no other unfamiliarity was reported with the melodies or instruments presented in the test. Scores on objective and subjective measures are reflected in Tables 7.2 and 7.3, respectively. Participants who were postlingual wearing CIs were able to discriminate pitches slightly more than a whole step apart. They recognized fewer than half of isochronous familiar melodies and around half of the instruments. Average scores on discrimination of unfamiliar melodies was less than chance. On subjective measures of music abilities and importance, young postlingual CI listeners reported moderate abilities and greater than moderate importance of music.

Young participants with postlingual deafness who wore HAs (*n* = 10) had a mean age of 26.00 years. They were primarily female and musicians. Their average age at first HA was around 10 years old. All of these participants typically wore two HAs, and they also wore two HAs for testing. They were tested entirely remotely. Demographic and audiologic data are reported in Table 7.1. Because they were all tested remotely, no reliable aided hearing screening could be completed; however, most participants had been to the audiologist within the past six months (*n* = 8). No participants reported any unfamiliarity with the melodies or instruments presented in the test.

Postlingual HA listeners were able to discriminate pitches less than one half step apart. They recognized just under three-quarters of the isochronous familiar melodies and instruments. They scored slightly above chance accuracy on the unfamiliar melody discrimination task. On subjective measures of music abilities, participants ranked both their music abilities and the importance of music moderately high.

In the group of *young prelingual individuals who wore CIs* (*n* = 10), the average age was 24.10 years. They were primarily female and evenly split between musicians and non-musicians. For those who reported, their average age at first auditory technology was under two years and their average age at first CI was around seven years. The group was evenly split between those tested in person and remotely. Demographic and audiologic information is presented in Table 7.1. The five participants tested in person passed the aided hearing screening, and the remainder of the participants had a recent audiology appointment within the past six months (*n* = 4) or one and a half year (*n* = 1). Typically, six of these participants wore bilateral CIs and four wore a unilateral CI. For testing, all participants wore their typical auditory technology configuration, and one unilateral CI participant who did not have personal computer speakers used a streaming device. Five participants reported unfamiliarity with some of the melodies. “Frere Jacques” was unfamiliar to four participants, “Silent Night” and “London Bridge” were each unfamiliar to two participants; and “Rock-a-Bye Baby” and “Here Comes the Bride” were each unfamiliar to one participant. One participant reported unfamiliarity with four of the instruments presented (cello, clarinet, flute, and saxophone).

Participants with prelingual deafness wearing CIs were able to discriminate pitches with slightly more than a whole step apart. They recognized fewer than one-fifth of the isochronous familiar melodies and fewer than half of the instruments. Average score on discrimination of unfamiliar melodies was very slightly above chance accuracy. On subjective measures of music abilities and importance, prelingual CI listeners reported moderate abilities and greater than moderate importance of music.

In the final group of listeners, who were *older postlingual CI listeners*, participants (*n* = 10) were an average of 68.20 years. They were equally female and male and slightly more musicians than non-musicians. Their average age at first auditory technology was 33.30 years and their average age at first CI was about 20 years later. Demographic and audiologic data are presented in Table 7.1. They were tested entirely remotely. Because they were all tested remotely, no reliable aided hearing screening could be completed; most participants had been to the audiologist within the past six months (*n* = 7), two had been within the past year, and one had been within the last year and a half. One participant reported unfamiliarity with one of the melodies (“Frere Jacques”), but no other unfamiliarity was reported with either the melodies or instruments presented in the test. Typically, seven of these participants wore bilateral CIs, one participant wore a CI on one side and a CI with electroacoustic stimulation on the other, and one wore a bimodal arrangement. For testing, two participants who usually wore two CIs wore only one; the participant with both a traditional CI and a CI with electroacoustic stimulation wore only their traditional CI; the bimodal participant wore only their CI; and the rest wore their typical auditory technology configuration. One participant who did not have personal computer speakers enabled used a streaming device.

Older postlingual participants wearing CIs were able to discriminate pitches slightly less than a whole step apart. They recognized around one-quarter of the isochronous familiar melodies and just over one-third of the instruments. Average scores on discrimination of unfamiliar melodies were below chance accuracy. On subjective measures of music abilities and importance, older postlingual CI listeners reported moderate abilities and greater than moderate importance of music.

Four preliminary analyses were run to evaluate similarities and differences among the demographic data collected. First, an analysis was run to determine if age equivalence was as expected across the groups. A one-way ANOVA with age as the dependent variable and group as the independent variable was run with $\alpha = .05$. This ANOVA was significant, $F(4, 55) = 114.17$, $p < .001$. Post-hoc Tukey analyses with $\alpha = .01$ to correct for alpha inflation revealed that age was not significantly different among all the younger groups, but the older age group was significantly different than all younger groups ($p < .001$). Second, three contingency table analyses were run. Two Chi-square analyses were run to determine differences between the groups on gender and musicianship. The groups were similar in gender representation, χ^2 (4, N = 60) = 2.42, $p = .66$, and proportion of musicians, χ^2 (4, N = 60) = 1.17, $p = .88$. One Fisher's Exact Test was run (as some groups had zero observed for cell values) to determine differences in modality of testing. The groups differed significantly in the proportion of participants tested in person versus remote, Fisher's Exact Test = 36.60, $p < .001$.

7.3 Study 1: Group Differences Among Typical Hearing, Younger Postlingual CI and Younger Postlingual HA Listeners

This study compared listeners with TH to postlingual participants with either HAs or CIs on both objective measures and subjective measures using two MANOVAs with an $\alpha = .05$. Post-hoc Tukey testing with a value of $\alpha = .01$ to correct for alpha inflation was used to find specific group differences.

7.3.1 Objective Tests.

In the first MANOVA, mean score on pitch discrimination, familiar melody accuracy, instrument identification accuracy, and unfamiliar melody discrimination accuracy were entered as dependent variables and grouping variable was entered as the independent variable. This MANOVA resulted in significant group differences, $F\ (8, 68) = 7.56$, $p < .001$; Wilk's $\Lambda = 0.28$, with significant differences found in all four entered objective music measures.

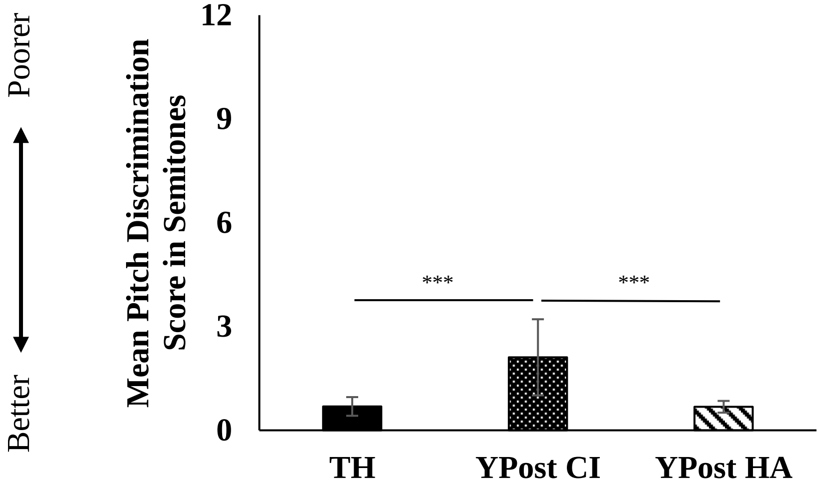


Figure 7.1. Mean scores on pitch discrimination among typical hearing, young postlingual CI and young postlingual HA listeners.

Note: TH = Typical hearing listeners; YPostCI = Young postlingual cochlear implant listeners; YPost HA = Young postlingual hearing aid listeners. Error bars represent standard deviation. Young postlingual CI listeners need more difference in frequency between two notes to determine that they were different pitches compared to listeners with TH and young postlingual HA listeners.
$^{***}p < .001$

In the pitch subtest, TH listeners and young postlingual HA listeners discriminated pitches closer together than young postlingual CI listeners (*p* < .001; see Figure 7.1). Effect sizes show a large effect size in both comparisons, Hedges' *g* = 2.14 and Hedges' *g* = 1.82, respectively. No other significant differences in pitch performance were found.

In the familiar melody recognition subtest, TH listeners recognized more isochronous familiar melodies than young postlingual CI listeners (*p* < .001; see Figure 7.2). The effect size is large, Hedges' *g* = 1.60. No other significant differences were found.

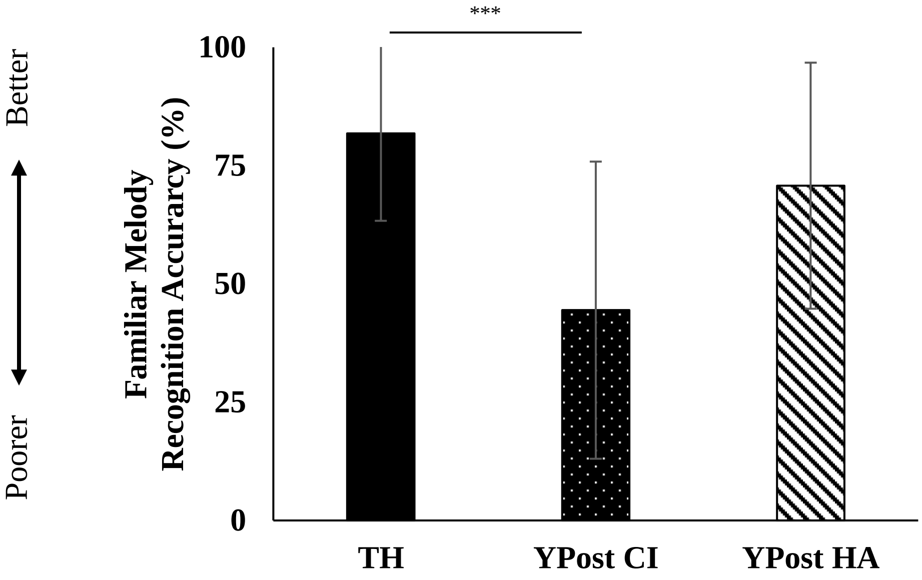


Figure 7.2. Mean familiar melody recognition accuracy among typical hearing, young postlingual CI and young postlingual HA listeners.

Note: TH = Typical hearing listeners; YPostCI = Young postlingual cochlear implant listeners; YPost HA = Young postlingual hearing aid listeners. Error bars represent standard deviation. Listeners with TH recognized significantly more isochronous familiar melodies than young postlingual listeners with CIs. No significant differences were found between young postlingual listeners with HAs and those with TH or CIs.
$^{***}p < .001$

In the instrument identification task, TH listeners recognized significantly more instruments than young postlingual CI listeners (*p* < .001; See Figure 7.3). This comparison has a large effect size, Hedges' *g* = 2.29. No other significant differences were found among the groups in accuracy of instrument identification.

In the unfamiliar melody discrimination task, young TH listeners correctly discriminated significantly more melodies than young postlingual CI listeners (*p* < .001; see Figure 7.4). This effect was large, Hedges' *g* = 2.32. No other significant differences emerged.

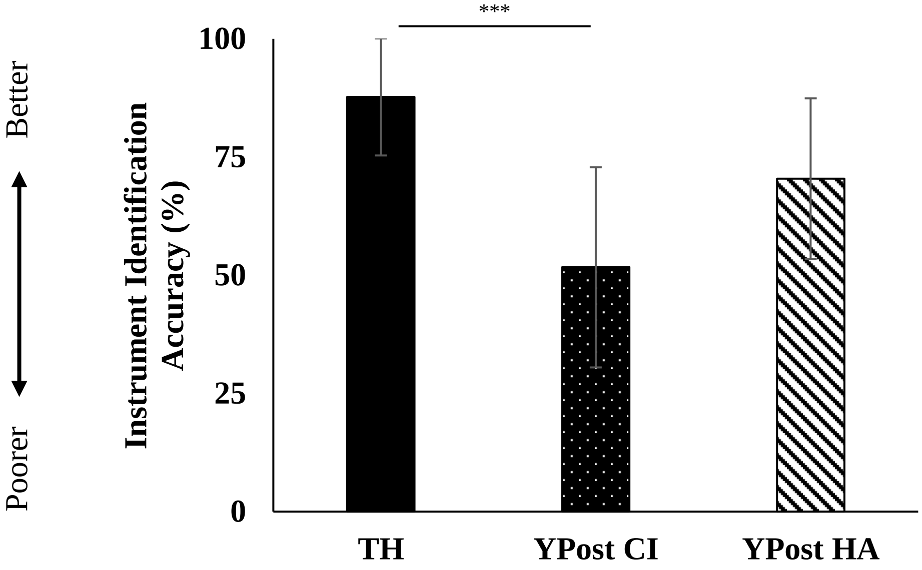


Figure 7.3. Mean instrument identification accuracy among typical hearing, young postlingual CI and young postlingual HA listeners.

Note: TH = Typical hearing listeners; YPostCI = Young postlingual cochlear implant listeners; YPost HA = Young postlingual hearing aid listeners. Error bars represent standard deviation. Listeners with TH identified significantly more instruments than young postlingual listeners with CIs. Young postlingual listeners with HAs identified similar numbers of instruments compared to TH and young postlingual CI listeners.
$^{***}p < .001$

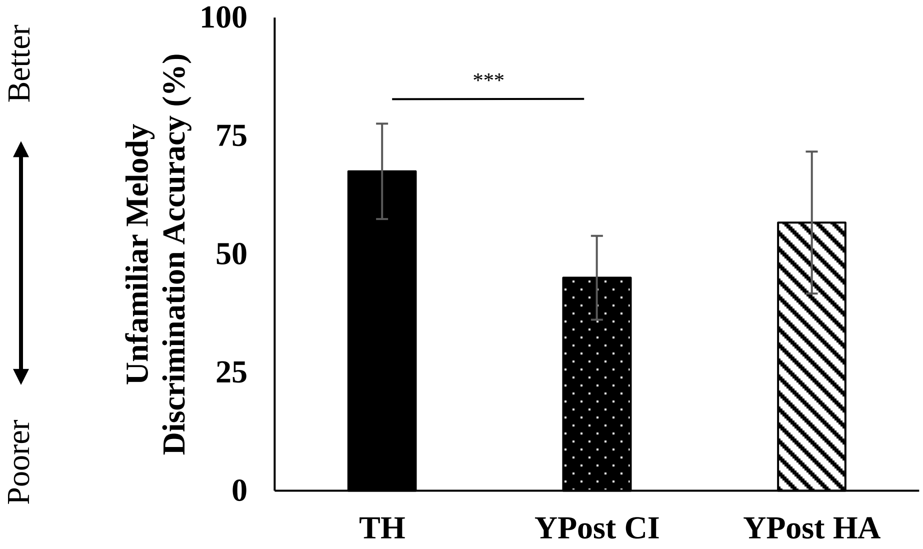


Figure 7.4. Mean unfamiliar melody discrimination accuracy among typical hearing, young postlingual CI, and young postlingual HA listeners.

Note: TH = Typical hearing listeners; YPostCI = Young postlingual cochlear implant listeners; YPost HA = Young postlingual hearing aid listeners. Error bars represent standard deviation. TH listeners discriminated differences in unfamiliar melodies significantly more than young postlingual CI listeners, but no significant differences emerged between young postlingual listeners with HAs and TH or young postlingual listeners with CIs.
$^{***}p < .001$

7.3.2 Subjective Reports.

In the second MANOVA, mean scores on music abilities and music importance were entered as dependent variables and grouping variable was entered as the independent variable. This MANOVA resulted in significant group differences, F (4, 72) = 8.12, $p < .001$; Wilk's Λ = 0.48, with significant differences found in only the subjective rating of music abilities.

In the subjective rating of music abilities, young TH listeners and young postlingual HA listeners ranked themselves higher than young postlingual CI listeners ($p < .001$ and $p = .01$,

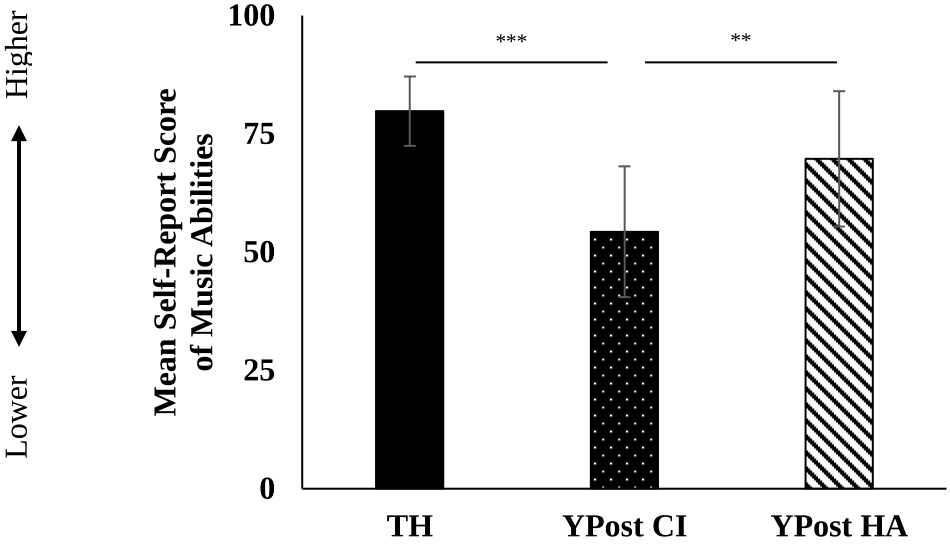


Figure 7.5. Mean self-report of music abilities among typical hearing, young postlingual CI, and young postlingual HA listeners.

Note: TH = Typical hearing listeners; YPostCI = Young postlingual cochlear implant listeners; YPost HA = Young postlingual hearing aid listeners. Error bars represent standard deviation. Young postlingual CI listeners rated themselves significantly poorer in music abilities than peers with TH and young postlingual HA listeners.
$^{**}p < .01$; $^{***}p < .001$

respectively; see Figure 7.5). The effect sizes are large, with Hedges' *g* = 2.58 and Hedges' *g* = 1.10, respectively.

In ratings of importance, no significant differences emerged, with young TH listeners, young postlingual CI listeners and young postlingual HA listeners reporting similar levels of music importance (see Figure 7.6). These effects are small, with Hedges' *g* = 0.28 between TH and postlingual CI listeners; Hedges' *g* = 0.05 between TH and postlingual HA listeners; and Hedges' *g* = 0.18 between postlingual CI and HA listeners.

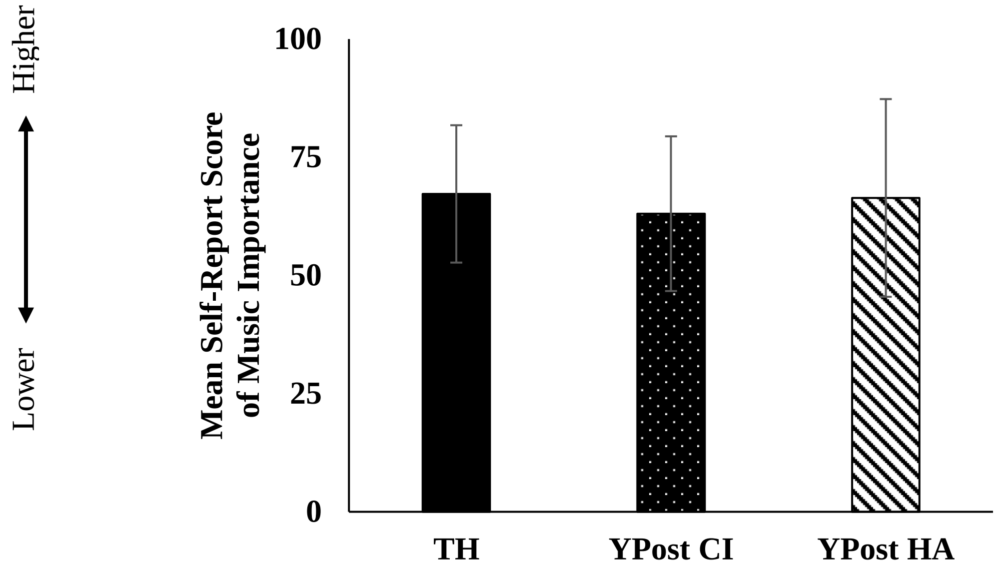


Figure 7.6. Mean self-report of music importance among TH, YPost CI, and YPost HA listeners.

Note: TH = Typical hearing listeners; YPostCI = Young postlingual cochlear implant listeners; YPost HA = Young postlingual hearing aid listeners. Error bars represent standard deviation. All groups rated music as similarly important, with an average score corresponding to the value of "somewhat" to "very" important.

7.4 Study 2: Group Differences between Younger Postlingual CI vs. Younger Prelingual CI Listeners

This study compared postlingual and prelingual participants with CIs on both objective measures and subjective measures using two MANOVAs with an $\alpha = .05$. Between-subjects effects were measured at an $\alpha = .01$ to adjust for alpha inflation.

7.4.1 Objective Tests.

In the first MANOVA, mean score on pitch discrimination, familiar melody recognition, instrument identification, and unfamiliar melody discrimination accuracy were entered as dependent variables and grouping variable was entered as the independent variable. This

MANOVA revealed no significant group differences, *F* (4, 15) = 2.22, *p* =.11 Wilk's Λ = 0.63, and no significant differences emerged at the between-subjects level. Though no significant findings emerged, effect sizes are reported below.

In the pitch subtest, postlingual CI listeners and prelingual CI listeners discriminated pitches similarly, more than a whole step apart. Slightly more variability was observed in the prelingual CI group. Effect size was small, Hedges' *g* = 0.34. In the familiar melody recognition subtest, postlingual CI listeners recognized on average more isochronous familiar melodies than young prelingual CI listeners, but this finding was not significant. Similar variability was found in both groups. The effect size is large, Hedges' *g* = 0.90. In the instrument identification task, postlingual CI listeners and prelingual CI listeners recognized approximately the same number of instruments; this comparison was not significant. The effect size in this comparison is very small, with Hedges' *g* = 0.27. In the unfamiliar melody discrimination task, postlingual CI listeners and prelingual CI listeners discriminated a similar number of melodies. Though insignificant, the effect was medium, Hedges' *g* = 0.74.

7.4.2 Subjective Reports.

In the second MANOVA, mean score on music abilities and music importance were entered as dependent variables and grouping variable was entered as the independent variable. This MANOVA resulted in no significant group differences, *F* (2, 17) = 0.34, *p* = .72; Wilk's Λ = 0.96, and no significant differences emerged at the between-subjects level. Though no significant findings emerged, effect sizes are reported below.

In the subjective rating of music abilities, young postlingual CI listeners and young prelingual CI listeners self-reported similar moderate levels of music abilities across perceptual skills and engagement activities. The effect size for this comparison was small, Hedges' *g* = 0.36. In the subjective rating of music importance, no significant differences emerged, with young postlingual CI listeners and young prelingual CI listeners reporting nearly the same levels of music importance. This effect is small, Hedges' *g* = 0.04.

7.5 Study 3: Group Differences between Younger Postlingual CI vs. Older Postlingual CI Listeners

This study compared postlingual participants who were either younger or older on both objective measures and subjective measures using two MANOVAs with an α = .05. Between-subjects effects were measured at an α = .01 to adjust for alpha inflation.

7.5.1 Objective Tests.

In the first MANOVA, mean score on pitch discrimination, familiar melody recognition, instrument identification, and unfamiliar melody discrimination accuracy were entered as dependent variables and grouping variable was entered as the independent variable. This MANOVA resulted in no significant group differences, *F* (4, 15) = 1.29, *p* = .32; Wilk's Λ = .74. Though no significant findings emerged, effect sizes are reported below.

In the pitch subtest, younger postlingual CI listeners and older postlingual CI listeners discriminated approximately the same distances in pitch. The effect size was small, Hedges' *g* = 0.16. In the familiar melody recognition subtest, younger postlingual CI listeners and older postlingual CI listeners recognized similar levels of isochronous familiar melodies. In both groups, the variability on this task was quite large. The effect size was medium, Hedges' *g* = 0.79. In the instrument identification task, younger postlingual CI listeners and older postlingual

CI listeners correctly recognized similar numbers of instruments. The effect size was medium, Hedges' *g* = 0.80. In the unfamiliar melody discrimination task, younger postlingual CI listeners and older postlingual CI listeners correctly discriminated a similar number of melodies. The effect size was small, Hedges' *g* = 0.19.

7.5.2 Subjective Reports.

In the second MANOVA, mean score on music abilities and music importance were entered as dependent variables and grouping variable was entered as the independent variable. This MANOVA resulted in no significant group differences, *F* (2, 17) = 0.88, *p* = .43; Wilk's Λ = 0.91. Though no significant findings emerged, effect sizes are reported below.

In the subjective rating of music abilities, younger postlingual CI listeners and older postlingual CI listeners ranked themselves similarly. The effect size was small, Hedges' *g* = 0.21. In the subjective rating of music importance, no significant differences emerged, with younger postlingual CI listeners and older postlingual CI listeners reporting similar levels of music importance. This effect is medium, Hedges' *g* = 0.39.

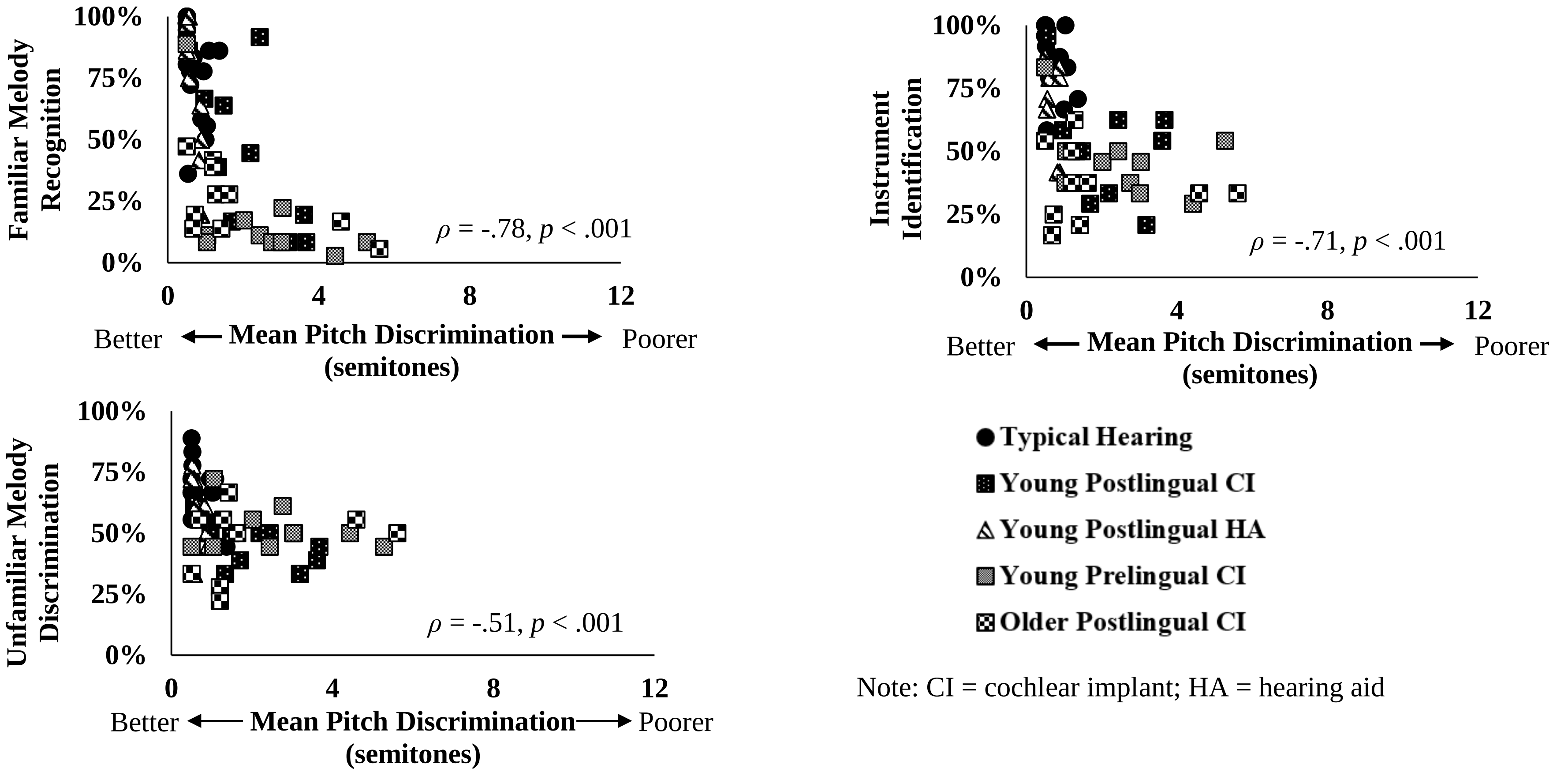
7.6 Study 4: Correlations Between Objective and Subjective Measures

For the five groups combined and within each of the five groups, correlations were run among the objective music perception scores and subjective data, showing whether relationships exist between the objective test scores and the domains of the MuRQoL and between the objective test scores and their corresponding subjective questions (i.e., questions related to pitch, familiar and unfamiliar melody, and instrument identification). To account for unequal variances, Spearman's ρ was used, and to account for alpha inflation, α = .01

7.6.1 Objective Tests and Subjective Reports.

Across all participants, mean pitch score was found to be significantly correlated to accuracy on familiar melody recognition ($\rho = -.78$, $p < .001$), accuracy on instrument identification ($\rho = -.71$, $p < .001$), accuracy on unfamiliar melody discrimination ($\rho = -.51$, $p < .001$), and subjective rating of music abilities ($\rho = -.53$, $p < .001$); see Figure 7.7 and 7.9. Accuracy on familiar melody was found to be significantly related to accuracy on pitch discrimination, instrument identification ($\rho = .82$, $p < .001$), accuracy on unfamiliar melody discrimination ($\rho = .53$, $p < .001$), and subjective rating of music abilities ($\rho = .54$, $p < .001$); see Figures 7.8 and 7.9. Accuracy on instrument identification was significantly related to pitch discrimination, familiar melody recognition, unfamiliar melody discrimination ($\rho = .56$, $p < .001$), and subjective rating of music abilities ($\rho = .66$, $p < .001$); see Figures 7.8 and 7.9. Accuracy on unfamiliar melody discrimination was significantly related to pitch discrimination, accuracy on familiar melody recognition, accuracy on instrument identification, and subjective rating of music abilities ($\rho = .51$, $p < .001$), see Figure 7.9. Subjective rating of music abilities was significantly related to subjective importance of music for all groups ($\rho = .36$, $p = .004$), see Figure 7.10.

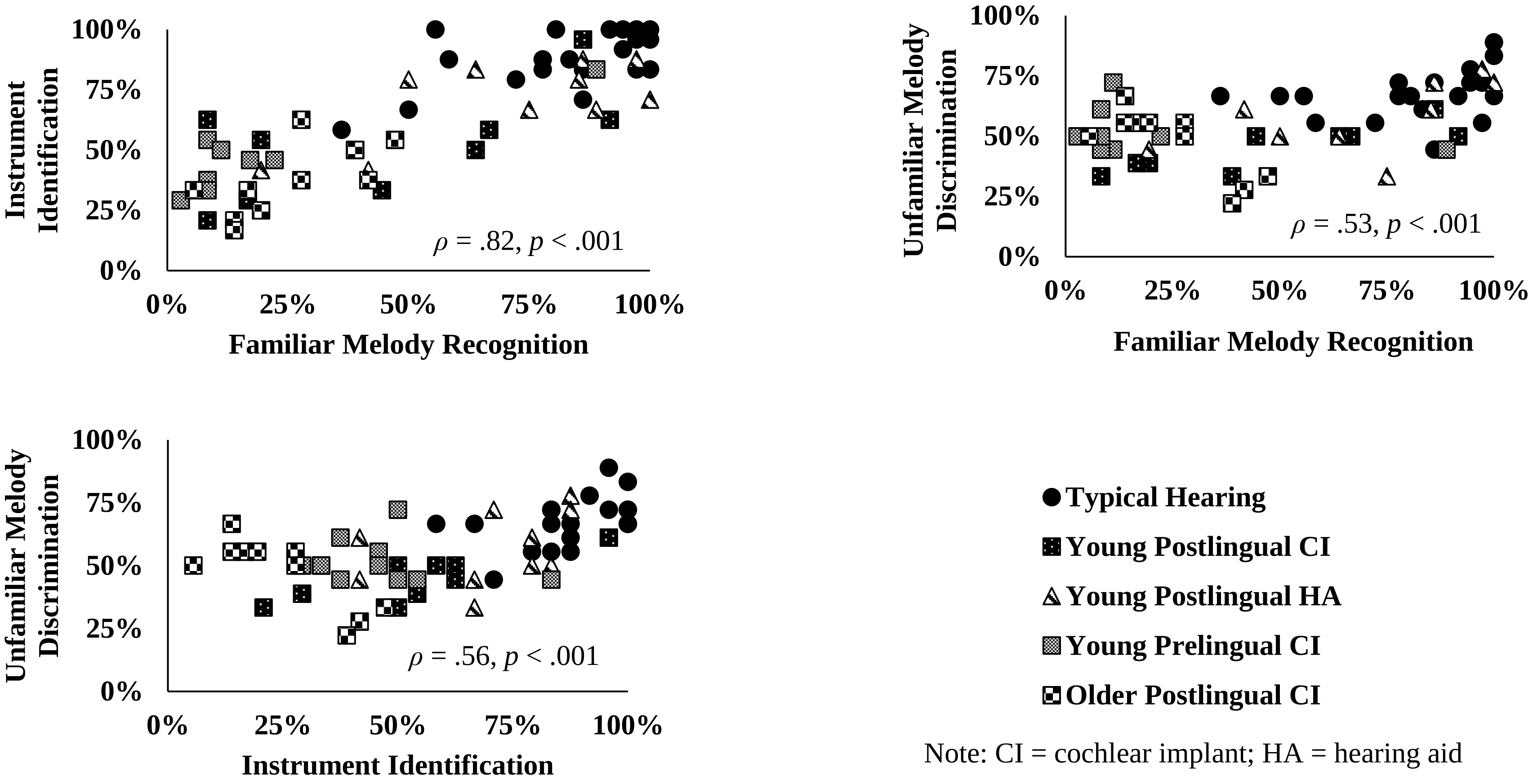
For young participants with TH, the correlations between objective and subjective measures revealed two significant relationships. Mean score on pitch discrimination was significantly related to both accuracy on familiar melody recognition ($\rho = -.64$, $p = .005$) and instrument identification ($\rho = -.60$, $p = .005$). In both cases, this relationship was moderate and negative, with lower (i.e., better) values on the pitch discrimination subtest relating to higher



Note: CI = cochlear implant; HA = hearing aid

Figure 7.7. Scatter plots of pitch discrimination compared to all objective measures.

In each graph, correlations reference the values found for all groups combined. Across all groups, pitch discrimination was significantly related to familiar melody recognition, instrument identification, and unfamiliar melody discrimination. While these relationships were not found within the CI groups when stratified by group, this may have been due to truncated performance on some of the objective measures.



Note: CI = cochlear implant; HA = hearing aid

Figure 7.8. Scatter plots of accuracy-scored objective measures.

In each graph, correlations reference the values found for all groups combined. Across all groups, familiar melody recognition, instrument identification, and unfamiliar melody were all significantly related each other. When stratified by group, this trend only held true for young postlingual CI listeners when comparing the familiar and unfamiliar melody tasks. No other groups maintained significant correlations, which may have been due to truncated performance within each group.

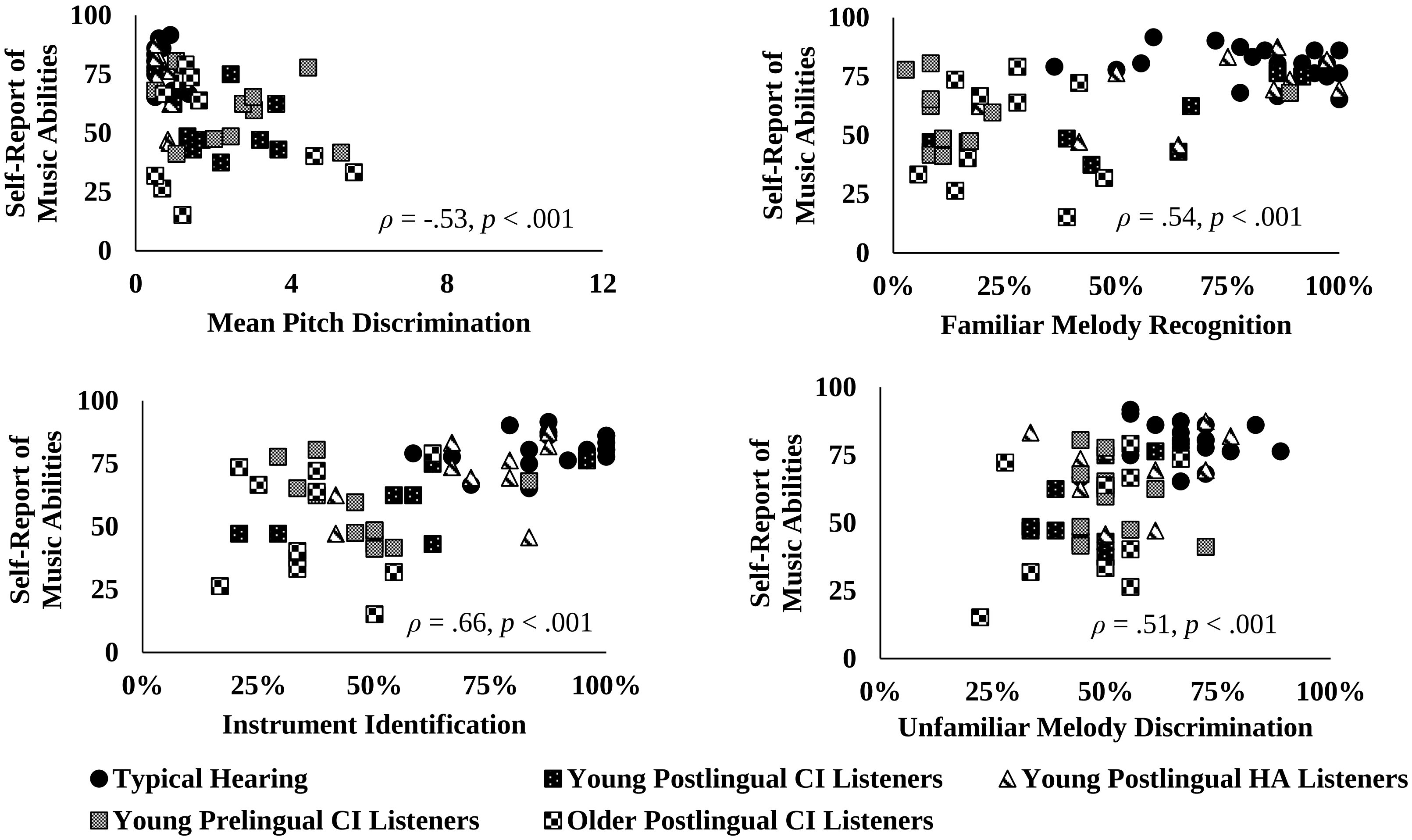


Figure 7.9. Scatter plots of objective measures to subjective self-report of music abilities.

Note: CI = Cochlear implant; HA = Hearing aid. In each graph, correlations reference the values found for all groups combined. Across all groups, pitch discrimination, familiar melody recognition, instrument identification, and unfamiliar melody were all significantly related to self-reported music abilities.

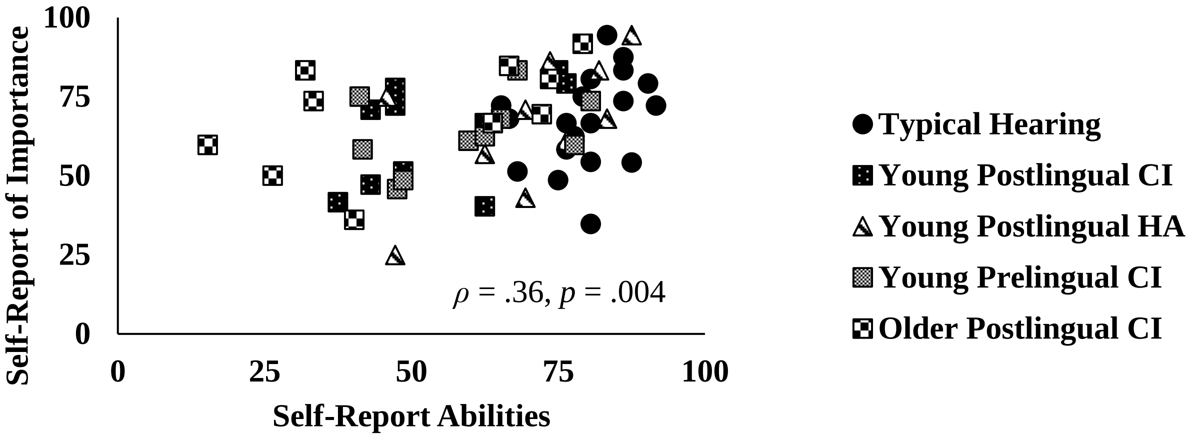


Figure 7.10. Scatter plot of self-report of music abilities compared music importance.

Note: CI = Cochlear implant; HA = Hearing aid. The correlation references the value for all groups combined. Self-reported abilities and importance were significantly related when combined across all listeners.

(i.e., better) scores on the familiar melody recognition and instrument identification tasks. For younger postlingual HA listeners, mean score on pitch discrimination was significantly related to accuracy on familiar melody recognition (*ρ* = -.77, *p* = .009). This relationship was moderately negative, with lower (i.e., better) values on the pitch discrimination subtest relating to higher (i.e., better) scores on the familiar melody recognition. For younger postlingual CI listeners, accuracy on familiar melodies was strongly, positively correlated with accuracy on the unfamiliar melody discrimination task (*ρ* = .78, *p* = .008). For younger prelingual CI and older postlingual CI listeners, no significant correlations emerged among any objective and subjective measures.

7.6.2 Self-Report of Specific Music Abilities.

For the second correlation, self-reported scores on the ability and importance of discriminating pitches, recognizing familiar melodies, recognizing instruments, and following the tune of a melody were correlated with their respective objective measure. This was first done among all participants, and then within each group for further analysis.

For all participants, mean pitch discrimination score was weakly, negatively correlated with self-reported ability to recognize pitches (ρ = -.53, p < .001) such that lower (i.e., better) performance on the pitch discrimination task was related to higher (i.e., better) self-report of ability of these tasks (see Figure 7.11). Self-report of pitch discrimination abilities was also weakly, positively correlated with the importance of recognizing different pitches (ρ = .36, p = .004), such that self-reported higher abilities related to self-reported higher importance of discriminating pitches. Accuracy of isochronous familiar melody recognition was weakly, positively correlated with self-reported recognition of familiar melodies (ρ = .39, p = .002; see Figure 7.12), but not significantly related to its importance (ρ = -.02, p = .89). Accuracy of instrument identification was moderately, positively correlated with self-reported recognition of instruments (ρ = .57, p < .001; see Figure 7.13), but not significantly related to its importance (ρ = .18, p = .18). For instrument identification, self-report and importance of the skill were weakly, positively correlated (ρ = .33, p = .008; see Figure 7.14). Accuracy of unfamiliar melody discrimination was weakly, positively correlated with the self-reported ability to follow a melody (ρ = .46, p < .001; see Figure 7.15), but not significantly related to its importance (ρ = .20, p = .12); however, this self- reported skill was moderately, positively correlated to its importance (ρ = .49, p < .001).

Finally, each group was analyzed independently in the same fashion. TH listeners had a significant correlation between correctly identifying instruments and the self-reported ability to do so ($\rho = .66$, $p = .002$), as did postlingual HA listeners ($\rho = .86$, $p = .001$). No other significant relationships between objective scores and self-report of ability or importance were found.

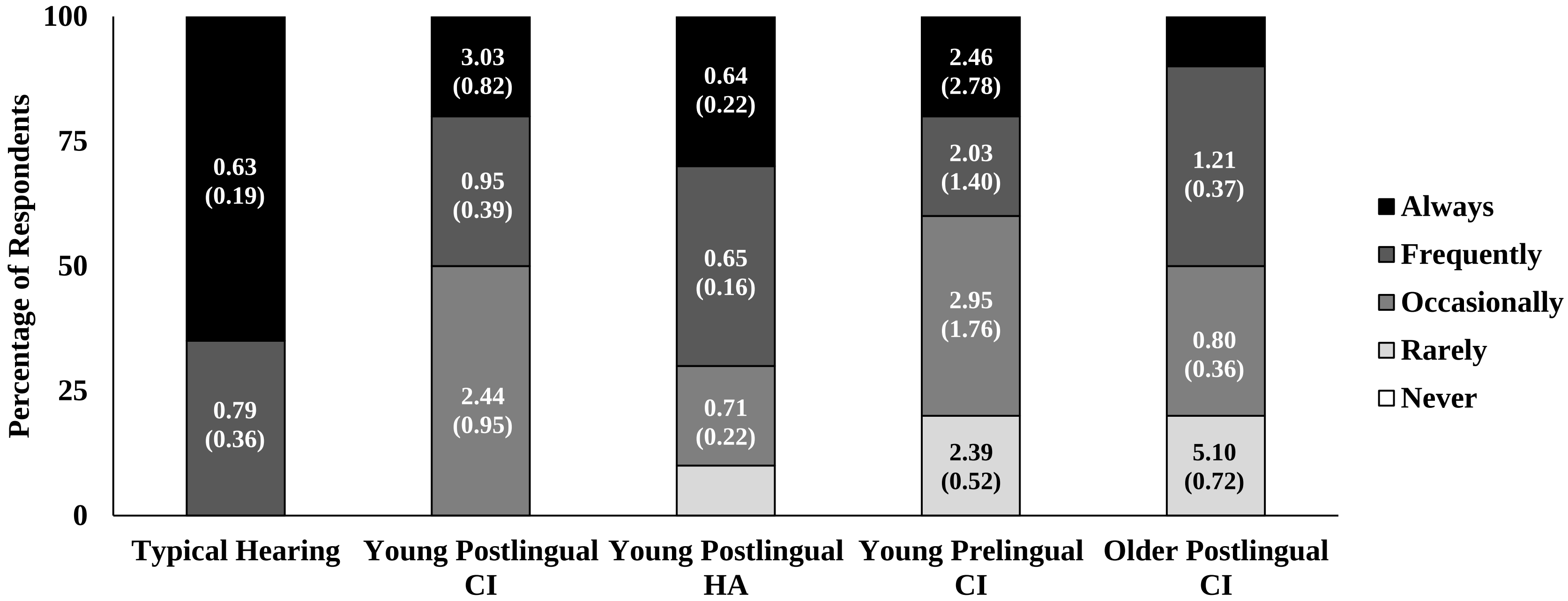


Figure 7.11. Scores on objective pitch discrimination for each group, broken out by response to self-report of pitch discrimination.

Note: CI = Cochlear implant; HA = Hearing aid. In the figure above, participants are stratified first by their grouping variable (accounting for age, auditory status, and onset of hearing loss). The proportion of responses (represented by the gradations of black) reflect how often they reported being able to discriminate pitches, on a scale from never to always. Within each bar, the values for mean and standard deviation (in parentheses) are displayed, except when only one participant answered that choice. For participants with typical hearing and HAs, self-report of pitch skills is relatively intact; for individuals with CIs, self-report of pitch skills and actual pitch discrimination were quite variable.

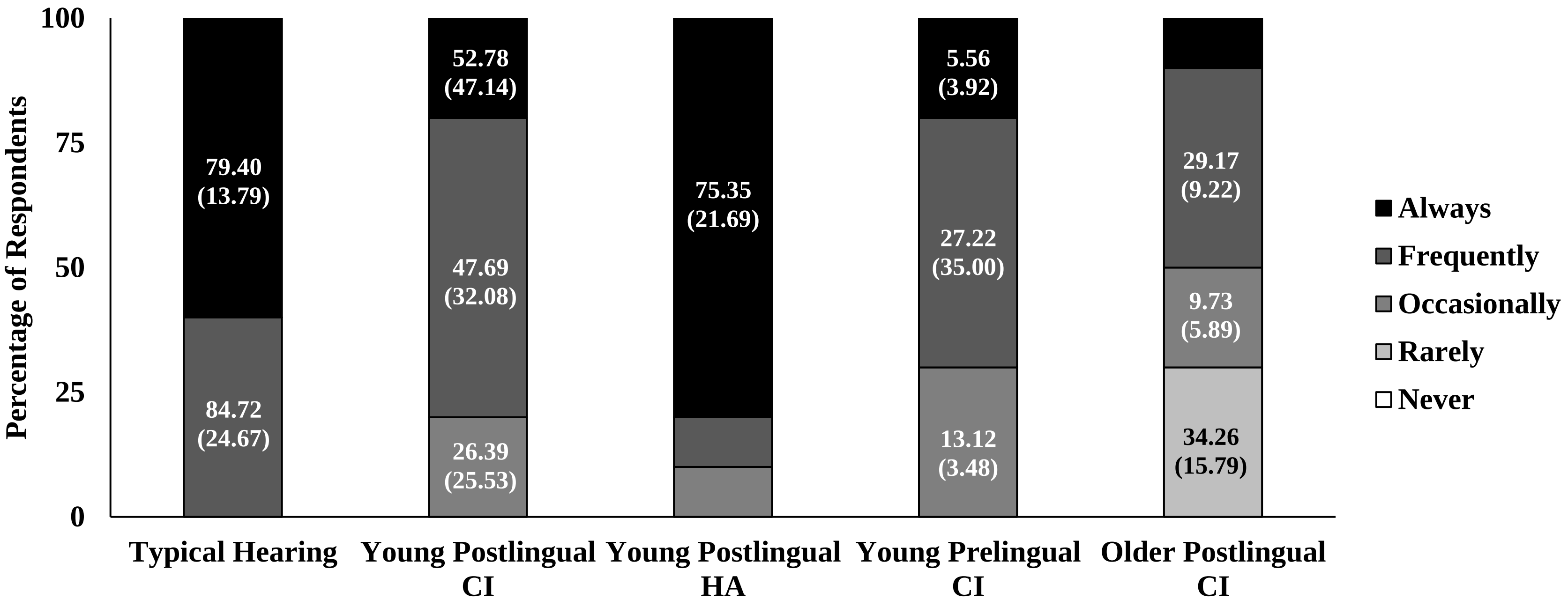


Figure 7.12. Scores on familiar melody recognition for each group, broken out by self-report of familiar melody recognition.

Note: CI = Cochlear implant; HA = Hearing aid. In the figure above, participants are stratified first by their grouping variable (accounting for age, auditory status, and onset of hearing loss). The proportion of responses (represented by the gradations of black) reflect how often they reported being able to recognize familiar melodies, on a scale from never to always. Within each bar, the values for mean and standard deviation (in parentheses) are displayed, except when only one participant answered that choice. For this measure, large discrepancies were found in prelingual CI listeners and older postlingual CI listeners, whose self-report of recognizing familiar melody was inaccurately captured by this measure of isochronous familiar melody recognition.

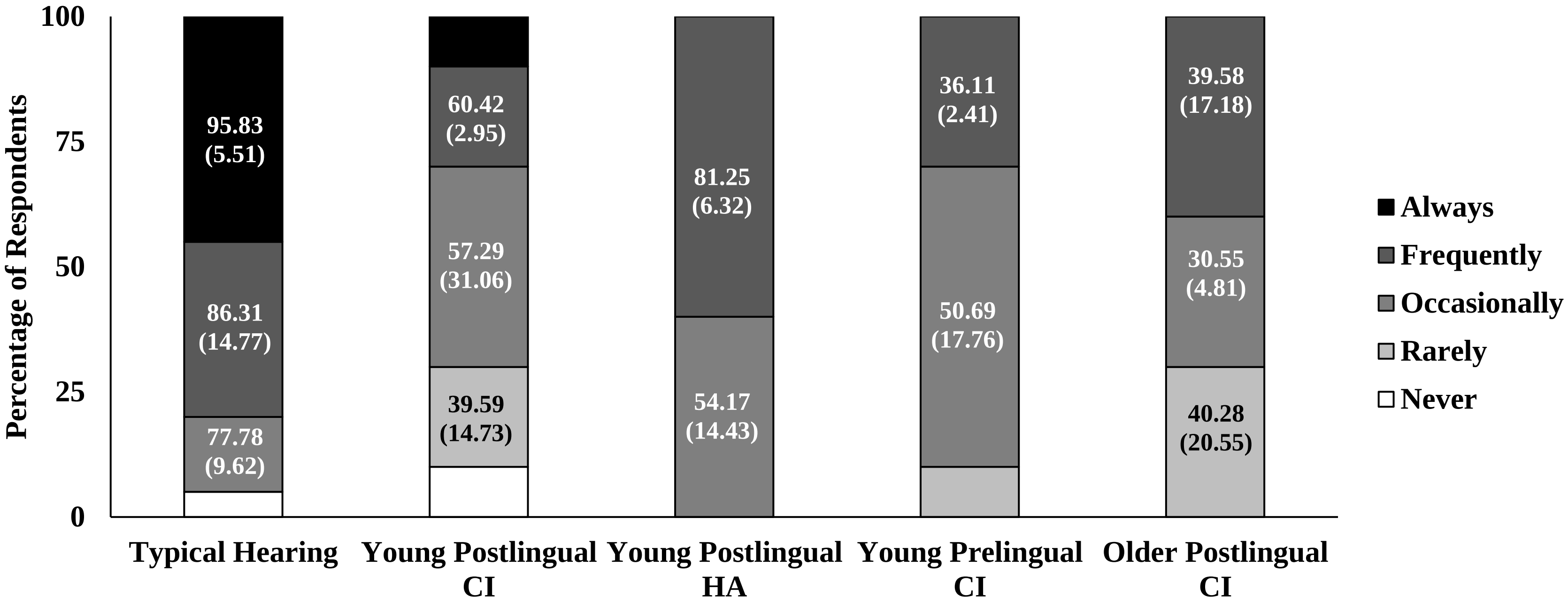


Figure 7.13. Scores on objective instrument identification for each group, broken out by response to self-report of instrument identification.

Note: CI = Cochlear implant; HA = Hearing aid. In the figure above, participants are stratified first by their grouping variable (accounting for age, auditory status, and onset of hearing loss). The proportion of responses (represented by the gradations of black) reflect how often they reported being able to identify instruments, on a scale from never to always. Within each bar, the values for mean and standard deviation (in parentheses) are displayed, except when only one participant answered that choice. For participants with typical hearing, HA listeners, and postlingual CI listeners, self-report of instrument identification is relatively intact; for prelingual CI listeners, self-report of instrument identification was less accurate.

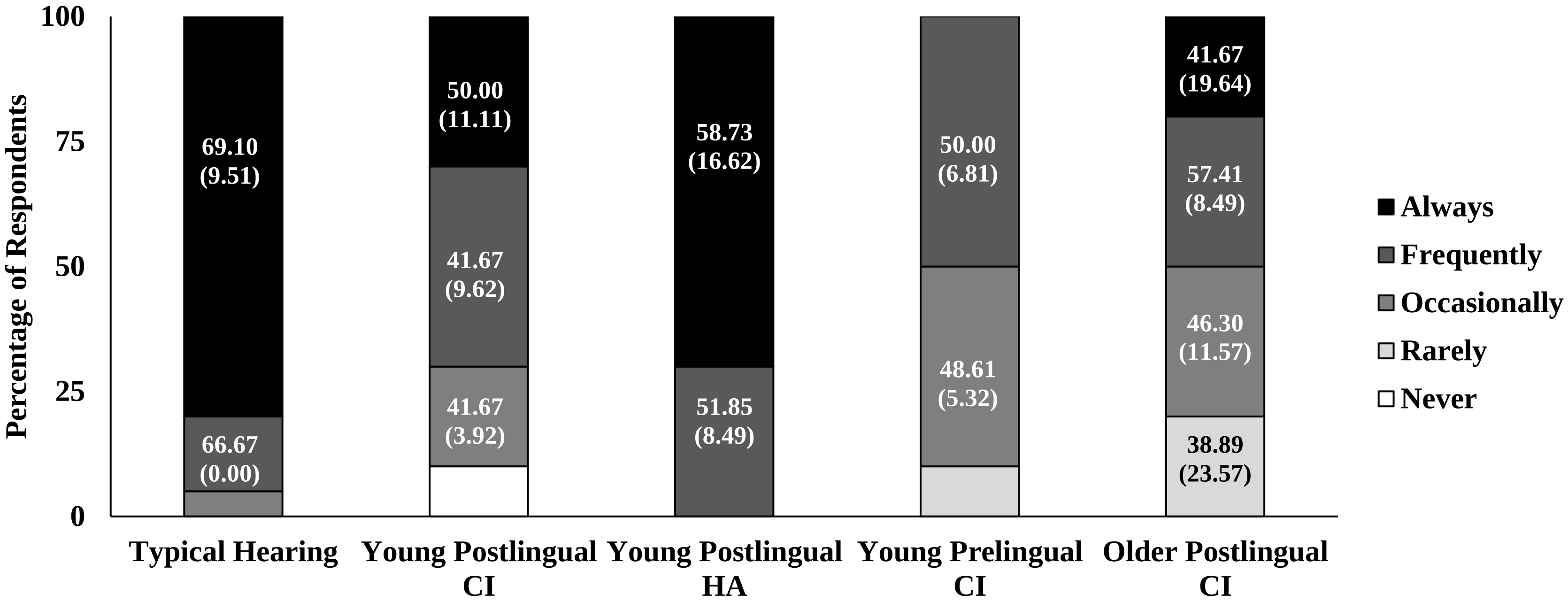


Figure 7.14. Scores on unfamiliar melody discrimination for each group, broken out by response to self-report of following a tune.

Note: CI = Cochlear implant; HA = Hearing aid. In the figure above, participants are stratified first by their grouping variable (accounting for age, auditory status, and onset of hearing loss). The proportion of responses (represented by the gradations of black) reflect how often they reported being able to follow a tune, on a scale from never to always. Within each bar, the values for mean and standard deviation (in parentheses) of unfamiliar melody discrimination are displayed, except when only one participant answered that choice. For all participants, self-report of following a tune is ineffectively captured by this measure of unfamiliar melody discrimination, due most likely to truncated data sets.

CHAPTER 8

DISCUSSION

This research expands upon existing literature in two ways. First, each group is distinct, with clear delineations among the groups in age at first auditory technology and in type of technology used during testing, and with appropriate similarities within each intended age group. Furthermore, each group had similar proportions of gender and musicianship present. While the testing modality significantly differed between the two groups, this was unavoidable due to our priority to complete research in the safest way for participants during COVID-19 human subjects research restrictions.

Second, this research contributes both objective and subjective data on each group, allowing for a fuller picture of participants' experiences with music. While available studies do investigate either objective (e.g., Gfeller et al., 2002; Looi et al., 2008) or subjective data (e.g., Dritsakis et al., 2017; Gfeller et al., 2000; Looi & She, 2010) in a wide variety of TH, HA, and CI listeners, rarely are they combined within one study. When both objective and subjective data have been collected within one study (e.g., Drennan et al., 2015), the undertaking typically excludes the collection of data in comparison groups. The result is a collection of studies that offer valuable insights into how music is perceived in the lives of individuals with hearing loss, but which lack similar methodologies that allow for comparison across groups of listeners or types of musical experiences.

The current study provides objective and subjective scores on readily available, clinically feasible music measures for five of many possible groups of interest to the audiology community. These data provide support to clinical audiologists, surgeons, speech pathologists, and other interested professionals who are routinely faced with the musical concerns of patients with hearing loss. The following sections summarize the research findings, explore the implications of these findings, detail the limitations of the study, and explain the possible future directions in this topic area.

8.1 Summary of Findings

In the first research aim, listeners with TH were compared to their peers with postlingual hearing loss listening via either HAs or CIs on both objective and subjective measures. The first hypothesis for this aim was partially supported. TH participants had better pitch discrimination, isochronous familiar melody recognition, instrument identification, unfamiliar melody discrimination and self-report of musical abilities than their postlingual CI peers. However, contrary to the hypothesis, TH listeners and postlingual HA listeners were markedly similar in all objective measures. The second hypothesis for this aim was partially supported. While it was expected that younger postlingual HA listeners would perform better than postlingual CI peers on all objective measures of music, this was only true on the outcome of pitch discrimination. The third hypothesis for this aim was supported, which found no significant differences among TH, postlingual CI and postlingual HA listeners on subjective ratings of music importance.

In the second research aim, CI listeners with postlingual and prelingual deafness were compared on the objective and subjective measures. This aim had one hypothesis, which was not supported. Postlingual and prelingual CI listeners did not perform significantly differently on any musical tasks, though it was expected that there would be differences in tests related to familiar and unfamiliar melody identification. While no significant differences emerged, effect size estimates suggest that there may be large differences in how these groups perceive melodies.

Post-hoc power analyses were conducted to determine what power was actually achieved with the given effect sizes and given sample sizes at $\alpha = .05$. In the familiar melody task, a power of .61 was achieved, and in the unfamiliar melody discrimination subtest, a power of .48 was achieved. This suggests that future studies with more power might detect significant differences, if they exist. Additionally, the wide variability of duration of device use may have played a factor here. The postlingual listeners had an average CI device use of 7.75 years (*SD* = 6.67), while the prelingual CI listeners had an average of 17.15 years of CI use, with an *SD* of 8.73. Performance on the melody measures may have been explained by these differences in experience with the CIs.

In the third research aim, objective and subjective measures were compared between older and younger postlingual CI listeners. The hypothesis here was not supported, with younger postlingual CI listeners and older postlingual CI listeners scoring nearly the same on most objective and subjective music measures. Effect sizes for this group comparison on all measures were medium or small. Again, the wide variability of duration of device use may have played a factor here. The older postlingual listeners had an average CI device use of 11.00 years (*SD* = 7.64). Performance on the objective measures may have been explained by these differences in experience with the CIs.

In the final research aim, objective and subjective measures were correlated. The first hypothesis was partially supported when considering all participants together, such that objective measures correlated with self-reported music abilities in the expected direction. However, when broken down into distinct groups, significant relationships emerged only in the TH, HA and young postlingual CI groups. In the TH group, pitch discrimination was significantly related to familiar melody identification and instrument identification. In the HA group, pitch discrimination was significantly related to only familiar melody identification. In the young postlingual CI group, accuracy on familiar melody recognition was significantly related to accuracy on unfamiliar melody discrimination. No relationships between objective measures or subjective measures emerged in the other two CI groups. The second hypothesis was supported when considering all participants as a whole, such that a significant relationship between self-reported abilities and self-reported importance emerged. However, no relationships emerged between the two subjective scales (abilities and importance) when correlations were run within each of the groups. Finally, the third hypothesis was partially supported. Among all listeners, self-reported ability of discrete musical skills significantly correlated with the objective score on those music perception tasks. When separated by group, only TH listeners and HA listeners were able to self-report how well they could identify instruments. This was not the case for other musical skills or other groups of listeners.

8.2 Implication of Findings

This research demonstrates that listeners with varying age of diagnosis of hearing loss and technology arrangements find music as important as their peers with TH, though there are differences in how listeners with hearing loss perceive musical characteristics and self-report their abilities relating to music.

8.2.1 Objective Tests

Pitch detection and discrimination is foundational to music perception, and the relationships between two pitches (i.e., musical intervals) form the basis of what is “in tune” or “out of tune” in Western music (Limb & Roy, 2014). For TH and HA listeners, this skill was intact, with both groups able to detect very small differences in pitch. For the CI groups, this skill was impaired, with more distance needed between two pitches to determine they were different. This was true for the pitches tested in this study (i.e., <800 Hz), but other patterns may emerge at higher frequencies, such as those that would be affected by HA frequency transposition technology. This data, while not entirely new, does show that HA listeners are more like TH listeners in pitch than their CI counterparts, and that CI individuals have difficulty with this task, even when stratified by age and onset of hearing loss. Thus, it is likely the CI device rather than the hearing loss of the patient that decreases one’s ability to discriminate between two pitches.

Familiar melody recognition was one of the musical abilities brought up in conversation by many of our participants with hearing loss. In some instances, the first time individuals felt hopeful about their relationship to music post-CI was when they first recognized a familiar melody without context or without significant effort. In the test presented here, familiar melody recognition may not have been representative of real-world melody recognition skills due to the manipulation of the rhythmic cues to isolate melodies. While some participants suggested that after a few repetitions of the stimuli, the melody would “click” in their brain and start to sound like the song it was intended to be, many participants reported a more analytical approach to this task, such as counting the number of notes that they perceived to be the same at the beginning or end of each song to use as their reference point for which choice to make. Finally, participants with CIs, particularly those who were prelingual, reported being unfamiliar with some of the songs in this task, such that the benefit of “familiarity” intended in this task was not necessarily true for them.

Because of these limitations, it is difficult to draw broad conclusions about our participants' abilities with familiar melodies. TH listeners did as expected and similar to participants in prior studies on this measure (Fowler et al., 2021; Jung et al., 2010; Kang et al., 2009), recognizing more than 80% of the melodies. HA listeners did nearly as well at around 70% accuracy. CI listeners recognized only about a third of the melodies in the highest performing group (i.e., young postlingual CI listeners), and the other CI listeners performed less accurately. Furthermore, in the case of eight individuals with CIs (five of whom were prelingual), only chance or poorer recognition of the melodies was achieved. In comparison to previous groups of CI listeners tested with this battery, the young postlingual CI listeners in the current study scored slightly better, though the young prelingual and older postlingual CI listeners scored in line with prior results, near 25% accuracy. (Drennan et al., 2015; Fowler et al., 2021; Jung et al., 2010; Kang et al., 2009; Nimmons et al., 2008).

Instrument identification was a surprisingly straightforward task, considering that existing research on timbre suggests it is complex combination of spectral and temporal information (Limb & Roy, 2014). Despite this, all groups identified instruments better than they recognized familiar melodies, and no individual scored at or below chance on instrument identification. In line with previous studies, TH listeners were nearly 90% accurate compared to CI listeners who were around 40% accurate (Drennan et al., 2015; Fowler et al., 2021; Jung et al., 2010; Kang et al., 2009; Nimmons et al., 2008).

Finally, the unfamiliar melody discrimination task was revealed to be only marginally beneficial. Though it was intended to determine if perception of melodies was different after considering familiarity of melodies, this task was approached in a novel way that may not have been appropriate for listeners with hearing loss. First, no published studies report administering these tasks to participants with hearing loss. Second, the conversion of these scores from an accuracy and confidence score to a purely accuracy score established the chance accuracy at 50%. Only three groups (TH, young postlingual HA, and young prelingual CI) averaged above chance, and 27 participants total scored at or below chance (one in the TH group, 90% of the young postlingual CI group, 50% of the young postlingual HA group, 70% of the young prelingual CI group, and 50% of the old postlingual CI group). It is surprising that the best average score among the three CI groups was the young prelingual CI listeners, who are disadvantaged in many ways due to lack of TH experiences in their lifetime.

The relationship between any two objective measures revealed only limited conclusions. Better pitch discrimination abilities correlated with higher familiar melody recognition for only TH listeners, and with instrument recognition for both TH and HA listeners. It is surprising that relationships between pitch and other measures did not emerge in the groups of listeners with CIs, because pitch is generally discussed as the foundational missing component for listeners with CIs (e.g., Limb & Roy, 2014). This research suggests that even if pitch scores are near perfect in this measure, CI listeners may still have difficulties in perceiving other musical characteristics on par with their TH and HA peers. Notably, one correlation between two objective measures did emerge as significant for one group of CI listeners. Young postlingual CI listeners who recognized more familiar melodies also tended to discriminate unfamiliar melody differences better.

8.2.2 Subjective Tests

Two general conclusions can be drawn from the inclusion of subjective tests in our study. First, our research concurs with the general understanding that music perception and appreciation are not related within groups of individuals with hearing loss, such that individuals with hearing loss still have vibrant musical lives despite impairments in some or all musical perception skills (Gfeller et al., 2008; Wright & Uchanski, 2012). Indeed, when asked about their motivation to join the current research project, many participants said they actively play an instrument professionally or semi-professionally; they have children involved in musical performances; they love to listen to music and dance with their spouse; or they simply listen to music as a way of relaxing or engaging with a larger social network. This study contributes unique data comparisons, which suggests that within discrete groups of listeners, these self-reported abilities are not correlated to importance of music.

Second, self-report of these perceptual skills and their actual performance on the tasks measured here do not seem to match. This may indicate that participants with hearing loss do not accurately self-report their ability to discriminate between two pitches, recognize familiar melodies, recognize instruments, or follow a melody. If this were true, it might suggest that individuals with hearing loss “don’t know what they don’t know.” On the other hand, this finding could reflect a methodological issue in measuring music perceptual skills such that the chosen measures for this study may not represent real-life perception of music. Further support is given to this second explanation when considering that the lack of significant relationship between self-report and objectively measured abilities persists within the group of TH listeners, who would be the most likely candidates to accurately self-report their musical skills. In fact, in research with a large set of TH listeners (*N* > 100,000), objective tests on rhythm and melodic memory were significantly associated with self-reported musical abilities (Müllensiefen et al., 2014). Although the current study did not directly test either rhythmic elements or musical memory, the ability to self-report in one domain may extend to other domains as well.

8.3 Limitations

While this research presents a firm foundation of objective and subjective scores collected on the same measures for five groups of listeners, there are some limitations.

First and foremost, to comply with safety measures related to COVID-19, these data were collected both in person and remotely, and the proportion of participants tested in each modality was significantly different. While efforts were made to calibrate testing stimuli and validate test-retest equivalency between the two methods, there was inevitable variability introduced by combining the two modalities. While participants tested in person were in a soundproof room with a standardized 65 dBA calibrated signal coming from loudspeakers intended for high-quality clinical testing, participants tested remotely were subject to ambient noises in their own home, distractions from pets and other household members, varying quality of computer speakers, and varying quality of personal internet connectivity. This was mitigated in four ways. The researcher requested participants find a quiet space to complete testing. The researcher observed most encounters with participants through videoconferencing so that stimuli could be paused when distracting interruptions arose. The researcher requested feedback on loudness and clarity of computer speakers and allowed those without the capability to complete testing via computer speakers to use streaming devices. Finally, the researcher's computer was always connected to a hard ethernet connection to prevent internet connectivity issues emerging on the researcher's side. While these efforts likely mitigated some of the variability in remote testing setups, error is inherent in these circumstances and likely still contributed to some of the variability found.

Beyond the remote testing, participants were categorized as either pre- or postlingual by asking what age their hearing loss was diagnosed. It is possible that in some instances, participants were delayed in their diagnosis of hearing loss, or that some hearing loss was present from birth but undetected until it fell to a noticeable level after age three, and thus our questions may not have gotten to the true nature of their emergence of hearing loss.

The measures used had limitations as well, and results on these measures may not fully represent real-world experiences with music. First, no rhythm abilities were measured in this test, a conscious choice made to save time in test administration and with the understanding that rhythm skills are known to be intact for most listeners using auditory devices (Brockmeier et al., 2011; Kang et al., 2009). However, by not including a subset of temporal-based tests, the full picture of musical strengths and weaknesses is not apparent in this research.

Second, the pitch discrimination measure tested only three base frequencies surrounding middle C. The pitches tested ranged from 184 Hz to 783 Hz. This truncated range does not encompass the full spectrum of pitches that participants' devices are processing (which extends to 8,000 or 10,000 Hz in some cases), and therefore pitch discrimination differences may emerge at higher frequencies.

Third, the familiar melody test was predicated on an idea that melodies were familiar, which was not entirely true in our sample. While most participants who were queried reported being familiar with the melodies presented, participants with hearing loss, especially those who were prelingually deafened, reported not being familiar with “Frere Jacques,” “Silent Night,” “Here Comes the Bride,” “Rock-a-Bye Baby,” and “London Bridge.” It is worthwhile to note here that inclusion of two relatively religious holiday-based songs (i.e., “Silent Night” and “Jingle Bells”) in this test is particularly problematic for participants from diverse backgrounds who may not celebrate Christmas.

Similarly, familiarity with the instruments presented, while not as necessary to the assumptions of the instrument identification task, was not uniform among all participants, with one prelingual CI listener unfamiliar with four of the instruments, and some participants reporting varying levels of familiarity from recognition of what the instrument is to intimate familiarity emerging from playing that instrument.

To address some of the limitations of the familiar melody task, the measure of unfamiliar melody discrimination was added. It was not developed for or validated on participants with hearing loss, and so its applicability to this population was unknown before this study. Because it relied on some small and some large pitch differences to create differences in the melodies, those individuals with poor pitch discrimination may have been at an inherent disadvantage for detecting these differences within the melody.

While the subjective measure of music perception, the MuRQoL, is relatively new, it was chosen for the clinical feasibility and distinction between abilities and importance of music. Dritsakis and colleagues developed this measure by interviewing individuals with CIs to determine their musical concerns (2017). In the current study, this measure was also given to individuals with HAs, though in conversation with the first author of the measure, it was revealed that their group determined the questionnaire to be unsuitable for individuals with HAs and suggested that a similar focus-group-based methodology should be undertaken to develop a corresponding measure for individuals with HAs (G. Dritsakis, personal communication, October 2020).

Finally, limitations may have emerged in statistical analyses. Though participant groups were kept as distinct as possible, some participants were not tested using their typical auditory arrangement, particularly those who were bimodal. Anecdotally, however, many of these participants reported finding little benefit from their HA ear beyond sound localization, which concurs with the severity of hearing loss reported by these participants. Additionally, while enough participants were collected to satisfy the power requirements to detect large effect sizes, there may have been smaller effect sizes that emerged that needed more participants in order to detect, particularly in the secondary analyses (studies 2, 3, and 4). Lastly, there may have been a problem detecting correlations among the measures within each group due to truncated data on the objective measures.

These limitations form a foundation from which to develop more psychometrically valid studies that address real-life musical concerns of participants with hearing loss, with an emphasis on the development of short, informative, clinically feasible measures of objective and/or subjective musical experiences rather than discrete musical characteristics.

8.4 Future Directions

The present analyses suggest that while abilities with music differ, music appreciation (as measured by the music importance domain) is the same for all groups of listeners, regardless of auditory status (i.e., TH, HA listeners, and CI listeners), onset of hearing loss (i.e., postlingual or prelingual), or age (i.e., younger vs. older). Because of the self-reported importance of music in the lives of these individuals, this auditory signal needs additional attention in translational research.

Collaboration between researchers and clinicians promises a path forward for better addressing patient experiences with music, though further developments in understanding and training are certainly needed. Researchers' understanding of music experiences is still limited, especially in the expectations for longitudinal trajectories for development of music abilities and in pre-implantation, surgical, and post-implantation interventions. On the other hand, clinicians often lack training in counseling their patients with hearing loss on musical experiences and they are even less trained on best practices in music optimization with auditory devices. Future research from this lab will address the above points.

8.4.1 Development of Objective and Subjective Music Measures

First and foremost, development of improved measures will be paramount to tracking baseline music perception and appreciation, as well as changes due to time and other interventions. With the goal of translational research in mind, measures should be feasible for clinical implementation, as well as sensitive to group and individual changes and representative of real-world experiences. In this study, we tested using the shortest available, comprehensive objective measure, which was estimated to take about 45 minutes. While this estimate was relatively accurate, even this timeframe is a bit long for a clinical measure when compared to other robust measures with wide clinical adoption (e.g., speech-in-noise measures). The objective measure is sensitive to group differences, at least for large effects, but it may not be sensitive to within-subjects changes over time or as a result of intervention, as published longitudinal data are unavailable. Further, it may not be representative of real-life music perception abilities because self-reported experiences were not reflected in the perceptual measures of discrete characteristics of music. This trend also persisted in the control group without hearing loss.

We also tested using a very short, clinically feasible subjective measure, which took participants less than 10 minutes to complete. The MuRQoL is unique among questionnaires about music due to its methodology in development (i.e., focus groups with many listeners with CIs) and robust psychometric validation efforts. It was sensitive to some group differences with expected large effect sizes (i.e., CI compared to TH listeners). However, its ability for use as a proxy for actual objective measures is called into question because it did not result in strong, significant correlations between objective scores and self-report of these skills within groups of listeners with hearing loss. On the other hand, this may be the case for any questionnaire that asks listeners to self-report their own music perceptual abilities.

With the aforementioned considerations in mind for a translational approach to future research (i.e., clinic feasibility and robustness for tracking group and individual data), there remains much work to do in development of optimal objective and subjective measures. Input from patients with diverse and representative backgrounds, such as via focus group and other qualitative methodology, may increase the real-world applicability of these measures. Input from interdisciplinary professionals, such as audiologists, speech pathologists, physicians, psychologists, and music cognition scientists could lead to a cohesive set of tests to answer a range of questions in the research, clinical, and overlapping domains.

8.4.2 Longitudinal Data

Available research does not offer an understanding of how long it will take an individual with hearing loss to achieve satisfaction of music experiences. This is the case for listeners with HAs and CIs. Some questionnaires (e.g., the Munich Music Questionnaire, Brockmeier, n.d.) make an attempt to answer this question by asking participants to compare their post-implantation music experiences to their pre-implantation experiences (e.g., how much did you listen to music before/after your implant?) or by reporting how long after cochlear implantation they began to listen to music again. However, this approach relies on appropriate estimation of musical experiences and is susceptible to both recall bias and overestimation of reported numbers. Overestimation is seen in other areas of auditory research; for example, parents and patients are poor reporters on the average consistency of device use when compared to objective datalogging measures (Walker et al., 2015). This overestimation of numerical data could be overcome with more robust measures not susceptible to recall bias.

A more reliable approach will be to gather longitudinal data, particularly with participants who are transitioning from HAs to CIs. These longitudinal data could have implications for understanding that the development of “easier” skills (e.g., closed-set speech recognition, open-set speech recognition in quiet) will precede the development of more complex skills (e.g., open-set word recognition in noise and discrete musical skills) for which devices are still not yet optimized (B. Ingrao, personal communication, October 2020).

8.4.3 Interventional Studies

Future research should also determine which interventions may yield improved musical skills or appreciation. On the one hand, participants already report that music is important to them, that they listen to it regularly, and that they appreciate having music in their lives, despite evidence that these reports are uncorrelated to both their subjective and objective musical abilities. As such, music appreciation does not seem to depend on any of the measures often used in our research. Therefore, it is unclear if musical training activities that target the discrete musical skills tested in objective music measures will yield better self-reported abilities or appreciation. While app- and other computer-based musical training programs abound from both manufacturers of auditory devices and non-audiologically affiliated groups, the generalizability of these training programs to real-life experiences is not yet clear. As such, future research evaluating these concerns and diverse approaches to interventions beyond the realm of musical training should be investigated.

By emphasizing musical experiences preemptively, such as musical training recommendations for individuals before the progression of their hearing loss, we could potentially begin to understand how "musicianship" could be a protective factor against musical decline with hearing loss. However, the differences that emerge between individuals who are musicians versus those who are not is still elusive, likely because of the way musicianship is defined in the literature (Cogo-Moreira & Lamont, 2018) and due to differences in length and intensity of training, type of instrument used, and time since musical training.

Because many limitations are introduced by the device implanted itself, device and surgical factors should also be considered a major component of our possible intervention strategies. Device factors could include the length of the electrode chosen and the capabilities of the associated external processor (e.g., fine structure processing). Additional surgical factors, like emerging hearing preservation techniques, could lend even better possibilities for post-implant musical abilities.

Finally, post-implantation interventions, which are being developed by researchers and implant companies around the world, often focus on app-based development of music perceptual skills. While this is highly important in engaging patients and keeping them motivated on their journey to reclaim music, other interventions that participants may be seeking on their own could be evaluated and combined with training for better outcomes. Individuals in this study were often engaged in peer-to-peer support within musicianship communities. Some were highly motivated to learn about music, hearing loss and the intersection of the two. Post-implantation interventions could also focus on more individualized MAPping strategies that account for the device placement within the tonotopic cochlea, such as the emerging image-guided MAPping techniques (Noble et al., 2014; CAScination AG, n.d.), and may thus optimize the devices for music perception.

8.4.4 Clinical Counseling Considerations

Currently, audiologists may not be engaged with patients on musical experiences due to lack of training on this matter. In fact, Greasley and colleagues report that no audiology curriculum requires musical training, and only 63% of audiologists had received training in terms of music and HAs (2019) in the form of conference presentations and continuing education. Audiologists who do feel confident discussing music with patients may have been musicians themselves. Furthermore, in conversations with our participants, many agreed with our hypothesis that their audiologists never brought up the topic of music, and that most conversations about music, when they did happen, were initiated by the patient. Survey data would lead to better understanding of most audiologists', surgeons', and speech-pathologists' approach to music counseling with their patients.

8.5 Conclusion

As one participant said, music is the holy grail for listeners with hearing loss. With devices optimized for robust speech perception over the past half-century and an emphasis on communication, music has been largely ignored as an integral component of our auditory environment. This research emphasizes that music is a vital part of the lives of all listeners, regardless of hearing loss, and that invested researchers, manufacturers, audiologists and other health care professionals must overcome the challenge to allow patients access to the music in their lives.

REFERENCES

Ali, S. O., & Peynircioğlu, Z. F. (2010). Intensity of emotions conveyed and elicited by familiar and unfamiliar music. *Music Perception*, *27*(3), 177–182. https://doi.org/10.1525/mp.2010.27.3.177

Audacity Team. (2020). *Audacity: Free Audio Editor and Recorder* (2.4.2) [Computer software]. https://audacityteam.org/

Bigand, E. (2003). More about the musical expertise of musically untrained listeners. *Annals of the New York Academy of Sciences*, *999*, 304–312.

Blanchfield, B. B., Feldman, J. J., Dunbar, J. L., & Gardner, E. N. (2001). The severely to profoundly hearing-impaired population in the United States: Prevalence estimates and demographics. *Journal of the American Academy of Audiology, 12*, 183–189.

Bonneville-Roussy, A., Rentfrow, P. J., Xu, M. K., & Potter, J. (2013). Music through the ages: Trends in musical engagement and preferences from adolescence through middle adulthood. *Journal of Personality and Social Psychology*, *105*(4), 703–717. https://doi.org/10.1037/a0033770

Brockmeier, S. J. (n.d.). *Munich Music Questionnaire*. https://s3.medel.com/downloadmanager/downloads/bridge_us/Resources/en-US/Munich_Music_Questionnaire.pdf

Brockmeier, S. J., Fitzgerald, D., Searle, O., Fitzgerald, H., Grasmeder, M., Hilbig, S., Vermiere, K., Peterreins, M., Heydner, S., & Arnold, W. (2011). The MuSIC perception test: A novel battery for testing music perception of cochlear implant users. *Cochlear Implants International*, *12*(1), 10–20. https://doi.org/10.1179/146701010X12677899497236

Caldwell, M. T., Jiam, N. T., & Limb, C. J. (2017). Assessment and improvement of sound quality in cochlear implant users. *Laryngoscope Investigative Otolaryngology*, *2*(3), 119–124. https://doi.org/10.1002/lio2.71

Caldwell, M. T., Jiradejvong, P., & Limb, C. J. (2016). Impaired perception of sensory consonance and dissonance in cochlear implant users. *Otology & Neurotology*, *37*(3), 229–234. https://doi.org/10.1097/MAO.0000000000000960

Carhart, R., & Jerger, J. F. (1959). Preferred Method For Clinical Determination Of Pure-Tone Thresholds. *Journal of Speech and Hearing Disorders*, *24*(4), 330–345. https://doi.org/10.1044/jshd.2404.330

Chasin, M., & Russo, F. A. (2004). Hearing aids and music. *Trends in Amplification*, *8*(2), 35–47. https://doi.org/10.1177/108471380400800202

Choi, C. T. M., & Hsu, C.-H. (2008). Conditions for generating virtual channels in cochlear prosthesis systems. *Annals of Biomedical Engineering*, *37*(3), 614. https://doi.org/10.1007/s10439-008-9622-9

Clarke, E. F. (1999). Rhythm and timing in music. *The Psychology of Music*, 473–500.

Cogo-Moreira, H., & Lamont, A. (2018). Multidimensional measurement of exposure to music in childhood: Beyond the musician/non-musician dichotomy. *Psychology of Music*, *46*(4), 459–472. https://doi.org/10.1177/0305735617710322

Cooper, W. B., Tobey, E., & Loizou, P. C. (2008). Music perception by cochlear implant and normal hearing listeners as measured by the Montreal Battery for Evaluation of Amusia. *Ear and Hearing*, *29*(4), 618–626. https://doi.org/10.1097/AUD.0b013e318174e787

Crook, H., Greasley, A. E., & Beeston, A. V. (2018). *Music counselling and fitting: A guide for audiologists* (Version 1.0). https://musicandhearingaids.org/wp-content/uploads/sites/35/2018/09/Music-counselling-and-fitting-a-guide-for-audiologists-Version-1.0-24-Sept-2018.pdf

Dhanasingh, A., & Jolly, C. (2017). An overview of cochlear implant electrode array designs. *Hearing Research*, *356*, 93–103. https://doi.org/10.1016/j.heares.2017.10.005

Ding, N., Patel, A. D., Chen, L., Butler, H., Luo, C., & Poeppel, D. (2017). Temporal modulations in speech and music. *Neuroscience & Biobehavioral Reviews, 81,* 181–187. https://doi.org/10.1016/j.neubiorev.2017.02.011

Drennan, Ward. R., Oleson, J. J., Gfeller, K., Crosson, J., Driscoll, V. D., Won, J. H., Anderson, E. S., & Rubinstein, J. T. (2015). Clinical evaluation of music perception, appraisal and experience in cochlear implant users. *International Journal of Audiology*, *54*(2), 114–123. https://doi.org/10.3109/14992027.2014.948219

Dritsakis, G., van Besouw, R. M., Kitterick, P., & Verschuur, C. A. (2017). A Music-Related Quality of Life measure to guide music rehabilitation for adult cochlear implant users. *American Journal of Audiology*, *26*(3), 268–282. https://doi.org/10.1044/2017_AJA-16-0120

Durlak, J. A. (2009). How to select, calculate, and interpret effect sizes. *Journal of Pediatric Psychology*, *34*(9), 917–928. https://doi.org/10.1093/jpepsy/jsp004

Eargle, J. (2003). *Handbook of Recording Engineering* (4th ed.). Springer Science+Business Media, Inc.

Elliott, T. M., Hamilton, L. S., & Theunissen, F. E. (2013). Acoustic structure of the five perceptual dimensions of timbre in orchestral instrument tones. *The Journal of the Acoustical Society of America*, *133*(1), 389–404. https://doi.org/10.1121/1.4770244

Fant, G. (1960). *Acoustic theory of speech production: With calculations based on X-ray studies of Russian articulations*. Mouton.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Feldman, A. S. (1963). Maximum air-conduction hearing loss. *Journal of Speech and Hearing Research*, *6*(2), 157–163. https://doi.org/10.1044/jshr.0602.157

Ford, J. H., Rubin, D. C., & Giovanello, K. S. (2016). The effects of song familiarity and age on phenomenological characteristics and neural recruitment during autobiographical memory retrieval. *Psychomusicology: Music, Mind, and Brain*, *26*(3), 199–210. https://doi.org/10.1037/pmu0000152

Fowler, S. L. (2020). *Testing Music Perception Through Microsoft Teams*. Remote Testing Wiki. https://www.spatialhearing.org/remotetesting/Examples/ExampleMusicPerceptionThroughTeams

Fowler, S. L., Calhoun, H., & Warner-Czyz, A. D. (2021). Music perception and speech-in-noise skills of typical hearing and cochlear implant listeners. *American Journal of Audiology*.

Friesen, L. M., Shannon, R. V., Baskent, D., & Wang, X. (2001). Speech recognition in noise as a function of the number of spectral channels: Comparison of acoustic hearing and cochlear implants. *The Journal of the Acoustical Society of America*, *110*(2), 1150–1163. https://doi.org/10.1121/1.1381538

Furuya, S., Aoki, T., Nakahara, H., & Kinoshita, H. (2012). Individual differences in the biomechanical effect of loudness and tempo on upper-limb movements during repetitive piano keystrokes. *Human Movement Science*, *31*(1), 26–39. https://doi.org/10.1016/j.humov.2011.01.002

Gasser, N. (2019). *Why you like it: The science and culture of musical taste*. Flatiron Books.

Gelfand, S. A. (2009). *Hearing: An introduction to psychological and physiological acoustics*. CRC Press LLC. http://ebookcentral.proquest.com/lib/utd/detail.action?docID=1407439

Gfeller, K., Oleson, J., Knutson, J. F., Breheny, P., Driscoll, V., & Olszewski, C. (2008). Multivariate Predictors of Music Perception and Appraisal by Adult Cochlear Implant Users. *Journal of the American Academy of Audiology, 19*(02), 120–134. https://doi.org/10.3766/jaaa.19.2.3

Gfeller, K., Turner, C., Mehr, M., Woodworth, G., Fearn, R., Knutson, J. F., Witt, S., & Stordahl, J. (2002). Recognition of familiar melodies by adult cochlear implant recipients and normal-hearing adults. *Cochlear Implants International*, *3*(1), 29–53. https://doi.org/10.1179/cim.2002.3.1.29

Gfeller, K., Witt, S. A., Spencer, L. J., Stordahl, J., & Tomblin, B. (2000). Musical involvement and enjoyment of children who use cochlear implants. *The Volta Review*, *100*(4), 213–233.

Gfeller, K., Woodworth, G., Robin, D. A., Witt, S., & Knutson, J. F. (1997). Perception of rhythmic and sequential pitch patterns by normally hearing adults and adult cochlear implant users. *Ear & Hearing*, *18*(3), 252–260.

Ghitza, O. (2013). The theta-syllable: A unit of speech information defined by cortical function. *Frontiers in Psychology*, *4*. https://doi.org/10.3389/fpsyg.2013.00138

Greasley, A. E., Crook, H., & Beeston, A. V. (2019). *Hearing Aids for Music: Findings and recommendations for hearing aid users, audiologists, manufacturers and researchers* [Final Report of the AHRC-funding Hearing Aids for Music Project]. https://musicandhearingaids.org/wp-content/uploads/sites/35/2019/04/Hearing-aids-for-music-findings-and-recommendations-25-April-2019.pdf

Grey, J. M. (1977). Multidimensional perceptual scaling of musical timbres. *The Journal of the Acoustical Society of America*, *61*(5), 1270–1277. https://doi.org/10.1121/1.381428

Grinn, S. K., & Le Prell, C. G. (2019). Noise-dose estimated with and without pre-cochlear amplification. *The Journal of the Acoustical Society of America*, *146*(5), 3967–3977. https://doi.org/10.1121/1.5132546

Halpern, A. R., & Bartlett, J. C. (2002). Aging and memory for music: A review. *Psychomusicology: A Journal of Research in Music Cognition*, *18*(1–2), 10–27. https://doi.org/10.1037/h0094054

Hockley, N. S., Bahlmann, F., & Fulton, B. (2012). Analog-to-digital conversion to accommodate the dynamics of live music in hearing instruments. *Trends in Amplification*, *16*(3), 146–158. https://doi.org/10.1177/1084713812471906

Homma, K., Du, Y., Shimizu, Y., & Puria, S. (2009). Ossicular resonance modes of the human middle ear for bone and air conduction. *The Journal of the Acoustical Society of America*, *125*(2), 968–979. https://doi.org/10.1121/1.3056564

Innes-Brown, H., Marozeau, J. P., Storey, C. M., & Blamey, P. J. (2013). Tone, rhythm, and timbre perception in school-age children using cochlear implants and hearing aids. *Journal of the American Academy of Audiology*, *24*(9), 789–806. https://doi.org/10.3766/jaaa.24.9.4

Jagiello, R., Pomper, U., Yoneya, M., Zhao, S., & Chait, M. (2018). *Rapid brain responses to familiar vs. Unfamiliar music – an EEG and pupillometry study* [Preprint]. Neuroscience. https://doi.org/10.1101/466359

Jung, K. H., Cho, Y.-S., Cho, J. K., Park, G. Y., Kim, E. Y., Hong, S. H., Chung, W.-H., Won, J. H., & Rubinstein, J. T. (2010). Clinical assessment of music perception in Korean cochlear implant listeners. *Acta Oto-Laryngologica*, *130*(6), 716–723. https://doi.org/10.3109/00016480903380521

Kaganovich, N., Kim, J., Herring, C., Schumaker, J., MacPherson, M., & Weber-Fox, C. (2013). Musicians show general enhancement of complex sound encoding and better inhibition of irrelevant auditory change in music: An ERP study. *European Journal of Neuroscience*, *37*(8), 1295–1307. https://doi.org/10.1111/ejn.12110

Kang, R., Nimmons, G. L., Drennan, W., Longnion, J., Ruffin, C., Nie, K., Won, J. H., Worman, T., Yueh, B., & Rubinstein, J. (2009). Development and validation of the University of Washington Clinical Assessment of Music Perception Test. *Ear and Hearing*, *30*(4), 411–418. https://doi.org/10.1097/AUD.0b013e3181a61bc0

Killion, M. C. (2009). What special hearing aid properties do performing musicians require? *The Hearing Review*, 20–31.

Kirchberger, M., & Russo, F. A. (2016). Dynamic range across music genres and the perception of dynamic compression in hearing-impaired listeners. *Trends in Hearing*, *20*, 233121651663054. https://doi.org/10.1177/2331216516630549

Kishon-Rabin, L., Amir, O., Vexler, Y., & Zaltz, Y. (2011). Pitch discrimination: Are professional musicians better than non-musicians? *Journal of Basic and Clinical Physiology and Pharmacology*, *12*(2), 125–144. https://doi.org/10.1515/JBCPP.2001.12.2.125

Lagrois, M.-É., Peretz, I., & Zendel, B. R. (2018). Neurophysiological and behavioral differences between older and younger adults when processing violations of tonal structure in music. *Frontiers in Neuroscience*, *12*, 54. https://doi.org/10.3389/fnins.2018.00054

Landsberger, D. M., Padilla, M., & Srinivasan, A. G. (2012). Reducing current spread using current focusing in cochlear implant users. *Hearing Research*, *284*(1–2), 16–24. https://doi.org/10.1016/j.heares.2011.12.009

Landsberger, D. M., & Srinivasan, A. G. (2009). Virtual channel discrimination is improved by current focusing in cochlear implant recipients. *Hearing Research*, *254*(1–2), 34–41. https://doi.org/10.1016/j.heares.2009.04.007

Landsberger, D. M., Svrakic, S., Roland, J. T., & Svirsky, M. (2015). The relationship between insertion angles, default frequency allocations, and spiral ganglion place pitch in cochlear implants. *Ear and Hearing*, *36*(5), e207–e213. https://doi.org/10.1097/AUD.0000000000000163

Law, L. N. C., & Zentner, M. (2012). Assessing musical abilities objectively: Construction and validation of the Profile of Music Perception Skills. *PLoS ONE*, *7*(12), e52508. https://doi.org/10.1371/journal.pone.0052508

LeMasurier, M., & Gillespie, P. G. (2005). Hair-cell mechanotransduction and cochlear amplification. *Neuron*, *48*(3), 403–415. https://doi.org/10.1016/j.neuron.2005.10.017

Levitin, D. J., McAdams, S., & Adams, R. L. (2002). Control parameters for musical instruments: A foundation for new mappings of gesture to sound. *Organised Sound*, *7*(2), 171–189. https://doi.org/10.1017/S135577180200208X

Liang, C., Earl, B., Thompson, I., Whitaker, K., Cahn, S., Xiang, J., Fu, Q.-J., & Zhang, F. (2016). Musicians are better than non-musicians in frequency change detection: Behavioral and electrophysiological evidence. *Frontiers in Neuroscience*, *10*. https://doi.org/10.3389/fnins.2016.00464

Limb, C. J., & Roy, A. T. (2014). Technological, biological, and acoustical constraints to music perception in cochlear implant users. *Hearing Research*, *308*, 13–26. https://doi.org/10.1016/j.heares.2013.04.009

Lin, F. R., Niparko, J. K., & Ferrucci, L. (2011). Hearing loss prevalence in the United States. *Archives of Internal Medicine*, *171*(20), 2.

Looi, V., McDermott, H., McKay, C., & Hickson, L. (2008). Music perception of cochlear implant users compared with that of hearing aid users. *Ear and Hearing*, *29*(3), 421–434. https://doi.org/10.1097/AUD.0b013e31816a0d0b

Looi, V., & She, J. (2010). Music perception of cochlear implant users: A questionnaire, and its implications for a music training program. *International Journal of Audiology*, *49*(2), 116–128. https://doi.org/10.3109/14992020903405987

Madsen, S. M. K., & Moore, B. C. J. (2014). Music and hearing aids. *Trends in Hearing*, *18*. https://doi.org/10.1177/2331216514558271

Mehra, S., Eavey, R. D., & Keamy, D. G. (2009). The epidemiology of hearing impairment in the United States: Newborns, children, and adolescents. *Otolaryngology–Head and Neck Surgery*, *140*(4), 461–472. https://doi.org/10.1016/j.otohns.2008.12.022

Moore, B. C. J. (1973). Frequency difference limens for short-duration tones. *The Journal of the Acoustical Society of America*, *54*(3), 610–619. https://doi.org/10.1121/1.1913640

Moran, M., Rousset, A., & Looi, V. (2016). Music appreciation and music listening in prelingual and postlingually deaf adult cochlear implant recipients. *International Journal of Audiology*, *55*(sup2), S57–S63. https://doi.org/10.3109/14992027.2016.1157630

Müllensiefen, D., Gingras, B., Musil, J., & Stewart, L. (2014). The Musicality of Non-Musicians: An Index for Assessing Musical Sophistication in the General Population. *PLOS ONE*, *9*(2), e89642. https://doi.org/10.1371/journal.pone.0089642

National Institute on Deafness and Other Communication Disorders. (2016). *Quick statistics about hearing*. National Institute on Deafness and Other Communication Disorders. https://www.nidcd.nih.gov/health/statistics/quick-statistics-hearing

Nimmons, G. L., Kang, R. S., Drennan, W. R., Longnion, J., Ruffin, C., Worman, T., Yueh, B., & Rubinstein, J. T. (2008). Clinical Assessment of Music Perception in cochlear implant listeners. *Otology & Neurotology*, *29*(2), 149–155. https://doi.org/10.1097/mao.0b013e31812f7244

Niskar, A. S., Kieszak, S. M., Holmes, A., Esteban, E., Rubin, C., & Brody, D. J. (1998). Prevalence of hearing loss among children 6 to 19 years of age: The Third National Health and Nutrition Examination Survey. *JAMA*, *279*(14), 1071. https://doi.org/10.1001/jama.279.14.1071

Noble, J. H., Gifford, R. H., Hedley-Williams, A. J., Dawant, B. M., & Labadie, R. F. (2014). Clinical evaluation of an image-guided cochlear implant programming strategy. *Audiology and Neurotology*, *19*(6), 400–411. https://doi.org/10.1159/000365273

Olszewski, C., Gfeller, K., Froman, R., Stordahl, J., & Tomblin, B. (2005). Familiar melody recognition by children and adults using cochlear implants and normal hearing children. *Cochlear Implants International*, *6*(3), 123–140. https://doi.org/10.1002/cii.5

Oxenham, A. J. (2013). Revisiting place and temporal theories of pitch. *Acoustical Science and Technology / Edited by the Acoustical Society of Japan*, *34*(6), 388–396.

Oxenham, A. J. (2018). How we hear: The perception and neural coding of sound. *Annual Review of Psychology*, *69*, 27–50. https://doi.org/10.1146/annurev-psych-122216-011635

Parsa, V., Scollie, S., Glista, D., & Seelisch, A. (2013). Nonlinear frequency compression: Effects on sound quality ratings of speech and music. *Trends in Amplification*, *17*(1), 54–68. https://doi.org/10.1177/1084713813480856

Peters, J. P. M., Bennink, E., & van Zanten, G. A. (2019). Comparison of place-versus-pitch mismatch between a perimodiolar and lateral wall cochlear implant electrode array in patients with single-sided deafness and a cochlear implant. *Audiology and Neurotology*, *24*(1), 38–48. https://doi.org/10.1159/000499154

Plyler, P. N., Easterday, M., & Behrens, T. (2019). The effects of extended input dynamic range on laboratory and field-trial evaluations in adult hearing aid users. *Journal of the American Academy of Audiology*, *30*(7), 634–648. https://doi.org/10.3766/jaaa.18003

Riley, P. E., Ruhl, D. S., Camacho, M., & Tolisano, A. M. (2018). Music appreciation after cochlear implantation in adult patients: A systematic review. *Otolaryngology–Head and Neck Surgery*, *158*(6), 1002–1010. https://doi.org/10.1177/0194599818760559

Rosengard, P. S., Payton, K. L., & Braida, L. D. (2005). Effect of slow-acting wide dynamic range compression on measures of intelligibility and ratings of speech quality in simulated-loss listeners. *Journal of Speech, Language & Hearing Research*, *48*(3), 702–714. https://doi.org/10.1044/1092-4388(2005/048)

Schulkind, M. D., Hennis, L. K., & Rubin, D. C. (1999). Music, emotion, and autobiographical memory: They're playing your song. *Memory & Cognition*, *27*(6), 948–955. https://doi.org/10.3758/BF03201225

Sek, A., & Moore, B. C. J. (1995). Frequency discrimination as a function of frequency, measured in several ways. *The Journal of the Acoustical Society of America*, *97*(4), 2479–2486. https://doi.org/10.1121/1.411968

Shehorn, J., Marrone, N., & Muller, T. (2018a). Speech perception in noise and listening effort of older adults with nonlinear frequency compression hearing aids. *Ear and Hearing*, *39*(2), 215–225. https://doi.org/10.1097/AUD.0000000000000481

Shehorn, J., Marrone, N., & Muller, T. (2018b). Benefits of non-linear frequency compression hearing aids. *The Hearing Journal*, *71*(7), 10. https://doi.org/10.1097/01.HJ.0000542421.93431.24

Singh, S., Kong, Y.-Y., & Zeng, F.-G. (2009). Cochlear implant melody recognition as a function of melody frequency range, harmonicity, and number of electrodes. *Ear and Hearing*, *30*(2), 160–168. https://doi.org/10.1097/AUD.0b013e31819342b9

Todd, A. E., Mertens, G., Van de Heyning, P., & Landsberger, D. M. (2017). Encoding a melody using only temporal information for cochlear-implant and normal-hearing listeners. *Trends in Hearing*, *21*. https://doi.org/10.1177/2331216517739745

Vaerenberg, B., Smits, C., De Ceulaer, G., Zir, E., Harman, S., Jaspers, N., Tam, Y., Dillon, M., Wesarg, T., Martin-Bonniot, D., Gärtner, L., Cozma, S., Kosaner, J., Prentiss, S., Sasidharan, P., Briaire, J. J., Bradley, J., Debruyne, J., Hollow, R., … Govaerts, P. J. (2014). Cochlear implant programming: A global survey on the state of the art. *The Scientific World Journal*, *2014*, 1–12. https://doi.org/10.1155/2014/501738

Van Dyck, E., Moens, B., Buhmann, J., Demey, M., Coorevits, E., Dalla Bella, S., & Leman, M. (2015). Spontaneous entrainment of running cadence to music tempo. *Sports Medicine - Open*, *1*(1), 15. https://doi.org/10.1186/s40798-015-0025-9

Vieillard, S., & Bigand, E. (2014). Distinct effects of positive and negative music on older adults' auditory target identification performances. *The Quarterly Journal of Experimental Psychology*, *67*(11), 2225–2238. https://doi.org/10.1080/17470218.2014.914548

Walker, E. A., McCreery, R. W., Spratford, M., Oleson, J. J., Van Buren, J., Bentler, R., Roush, P., & Moeller, M. P. (2015). Trends and Predictors of Longitudinal Hearing Aid Use for Children Who Are Hard of Hearing. *Ear & Hearing*, *36*(Supplement 1), 38S-47S.

Watson, P. J., & Schlauch, R. S. (2008). The effect of fundamental frequency on the intelligibility of speech with flattened intonation contours. *American Journal of Speech-Language Pathology*, *17*, 348-. Gale OneFile: Health and Medicine.

Wever, E. G. (1939). The electrical responses of the ear. *Psychological Bulletin*, *36*(3), 143–187. https://doi.org/10.1037/h0055507

Wier, C. C., Jesteadt, W., & Green, D. M. (1977). Frequency discrimination as a function of frequency and sensation level. *The Journal of the Acoustical Society of America*, *61*(1), 178–184. https://doi.org/10.1121/1.381251

Wright, R., & Uchanski, R. M. (2012). Music Perception and Appraisal: Cochlear Implant Users and Simulated Cochlear Implant Listening. *Journal of the American Academy of Audiology*, *23*(05), 350–365. https://doi.org/10.3766/jaaa.23.5.6

Zeng, F.-G., Rebscher, S. J., Fu, Q.-J., Chen, H., Sun, X., Yin, L., Ping, L., Feng, H., Yang, S., Gong, S., Yang, B., Kang, H.-Y., Gao, N., & Chi, F. (2015). Development and evaluation of the Nurotron 26-electrode cochlear implant system. *Hearing Research*, *322*, 188–199. https://doi.org/10.1016/j.heares.2014.09.013

BIOGRAPHICAL SKETCH

Stephanie L. Fowler earned her BA in Communication Sciences and Disorders with departmental honors and a minor in English Language and Literature from Wichita State University. She earned her AuD from The University of Texas at Dallas. Concurrently with her AuD, she was motivated to pursue her PhD to enhance her participation in translational research. In addition to her research, she was able to work closely on the clinical education of graduate students, implementing novel simulated assignments and managing relationships with on- and off-site audiologists serving as clinical preceptors. She is active with her national and state professional audiology organizations, particularly on student engagement initiatives. While she no longer considers herself a musician, her research emerges from her experiences playing the viola, a passion for listening to music, and a dedication to serving patients' complex auditory and socioemotional needs.

CURRICULUM VITAE

STEPHANIE L. FOWLER, AuD

Education

PhD, Communication Sciences and Disorders | May 2021 | The University of Texas at Dallas, Dallas, TX

> Dissertation: The effect of auditory device, onset of hearing loss, and chronologic age on music perception and appreciation among adult listeners
> Advisor: Andrea D. Warner-Czyz, PhD

AuD | May 2020 | The University of Texas at Dallas, Dallas, TX

> Capstone: Effect of sound on heart rate in adults with typical hearing
> Advisor: Andrea D. Warner-Czyz, PhD

BA, Communication Sciences and Disorders | May 2014 | Wichita State University, Wichita, KS

> Emory Lindquist Honors Program | Departmental Honors
> Capstone: Effect of race on hearing screening failure rates in a newborn, well-baby unit
> Advisor: David Downs, PhD

Employment

Teaching Assistant | Fall 2017 – May 2021 | The University of Texas at Dallas, Dallas, TX
Audiology Extern | Fall 2018 – Spring 2020 | Callier Center for Communication Disorders; Plano ISD/RDSPD | Dallas, Richardson, and Plano, TX
Graduate Assistant | Fall 2015 – Summer 2017 | The University of Texas at Dallas, Dallas, TX

Professional Recognitions and Honors

1. President's Award for Excellence in Teaching by a Teaching Assistant | Nominee | February 2020
2. 1st Annual Future Leaders of Audiology Student Conference (FLASC) | Attendee | June 2016

Professional Memberships

Memberships

American Auditory Society | 2021 – present
Association for Research in Otolaryngology | 2021 – present
American Cochlear Implant Alliance | 2016 – present
American Academy of Audiology | 2015 – present
Texas Academy of Audiology | 2016 – present

Certification and Licensure

Audiologist License | Texas Department of Licensing and Regulation | June 2020

Question, Persuade, Respond (QPR) Suicide Prevention Training | The University of Texas at Dallas | March 2020

Advanced Graduate Teaching Certificate | The University of Texas at Dallas | December 2019

Graduate Teaching Certificate | The University of Texas at Dallas | September 2018

Achievements in Original Investigation

Articles in Non-Refereed Journals

Fowler, S. L., Jackson, S., Gohmert, A., & Cokely, C. (2020). Planning effective remote clinical education. *Audiology Today*.

Books/Articles Accepted for Publication

Fowler, S. L., Calhoun, H., & Warner-Czyz, A.D. Music perception and speech-in-noise skills of typical hearing and cochlear implant listeners. Accepted to American Journal of Audiology, December 2020.

Invited or Refereed Presentations to Seminar or Colloquia Assemblies

Fowler, S. L. "Music Experiences of Adolescents with Cochlear Implants." FLASH Lecture Series in Communication Disorders, School of Behavioral and Brain Sciences, The University of Texas at Dallas, Dallas, TX, October 2019.

Fowler, S. L. and Warner-Czyz, A. D. "Eyes Open, Ears On: Fatigue in school-aged children with hearing loss." Brown Bag presentation at Cook Children's Rehabilitation Hospital, Mansfield, TX, July 2017.

Refereed Oral Presentations to Professional Meetings

Fowler, S. L. & Warner-Czyz, A. D. "Group differences among CI users in objective and subjective measures of music." Podium presentation at the American Cochlear Implant Alliance Conference, Virtual, April 2021.

Fowler, S. L., Tolisano, A. M., Saadeh, C., Robbins, K., Hunter, J. B., & Warner-Czyz, A. D. "Music-Related Quality of Life in Adults with Cochlear Implants: Relationships Among Demographic Factors, Musicianship, and Audiological Factors." Podium presentation at the American Cochlear Implant Alliance Conference, Virtual, April 2021.

Fowler, S. L., Tolisano, A. M., Saadeh, C., Robbins, K., Hunter, J. B., & Warner-Czyz, A. D. "Music-Related Quality of Life in Adults with Cochlear Implants: Relationships Among Demographic Factors, Musicianship, and Audiological Factors." Poster highlight session at the American Cochlear Implant Alliance Conference, Orlando, FL, March 2020. (Conference cancelled).

Fowler, S. L., Tolisano, A. M., Hunter, J. B., & Warner-Czyz, A. D. "Music-Related Quality of Life and Generic Quality of Life in Adolescents with Cochlear Implants." Poster highlight session at the American Cochlear Implant Alliance Conference, Hollywood, FL, July 2019.

Refereed Poster Presentations at Professional Meetings

Fowler, S. L., Hunter, J. B., Brinkley, T., Kronenberger, K., & Warner-Czyz, A. D. "Data-driven considerations for counseling CI users on music-related experiences." Poster presentation at the American Cochlear Implant Alliance Conference, Virtual, April 2021.

Fowler, S. L., Tolisano, A. M., Saadeh, C., Robbins, K., Hunter, J. B., & Warner-Czyz, A. D. "Music-Related Quality of Life in Adults with Cochlear Implants: Relationships Among Demographic Factors, Musicianship, and Audiological Factors." Poster presentation at the American Cochlear Implant Alliance Conference, Orlando, FL, March 2020. (Conference cancelled).

Fowler, S. L., Tolisano, A. M., Hunter, J. B., and Warner-Czyz, A. D. "Music-Related Quality of Life and Generic Quality of Life in Adolescents with Cochlear Implants." Poster presentation at the American Cochlear Implant Alliance Conference, Hollywood, FL, July 2019.

Wiseman, K., Warner-Czyz, A. D., Kwon, S., Fiorentino, K., **Fowler, S. L.**, and Tolstyka, D. "Daily device use in pediatric cochlear implant users over time." Poster presentation at the American Cochlear Implant Alliance Conference, Washington D.C., March 2018.

Contributed (Unrefereed) Oral Presentations at Professional Meeting

Fowler, S. L., Fiorentino, K., and Warner-Czyz, A. D. "Impact of Music on the Social and Emotional Well-Being of Adolescents with Hearing Loss." Oral presentation at the Texas Academy of Audiology Conference, The Woodlands, TX, October 2018.

Contributed (Unrefereed) Poster Presentations at Professional Meeting

Saadeh, C., **Fowler, S. L.**, Warner-Czyz, A. D., & Hunter, J. B. "Music-Related Quality of Life Among Cochlear Implant Users." Presentation given by C. Saadeh at Graduation Talk for UT Southwestern Medical Center, Dallas, TX. June 2020.

Fowler, S. L., Warner-Czyz, A. D., Loy, B., and Evans, C. S. "Extracurricular activities in children with and without hearing loss." Poster presentation at the Texas Academy of Audiology Conference, The Woodlands, TX, October 2018.

Fowler, S. L., Warner-Czyz, A. D., Loy, B., and Evans, C. S. "Extracurricular activities in children with and without hearing loss." Poster presentation at the American Academy of Audiology Conference, Nashville, TN, April 2018.

Fowler, S. L., Warner-Czyz, A. D., Loy, B., and Evans, C. S. "Extracurricular activities in children with and without hearing loss." Poster presentation at the Promotion of Academic and Clinical Excellence (P.A.C.E.), The University of Texas at Dallas, Dallas, TX, February 2018.

Fowler, S. L., Warner-Czyz, A. D., and Wiseman, K. B. "Effect of sound on heart rate in adults with typical hearing." Poster presentation at AudiologyNOW, the annual convention of the American Academy of Audiology, Indianapolis, IN, April 2017.

Funding

External

$250 | Craig Dunckel Scholarship | Scott Haug Foundation | October 2019
$425 | Scholarship | American Cochlear Implant Alliance | July 2019

Internal

$1000 | Travel Award | School of Behavioral and Brain Sciences | March 2020 (Conference cancelled)
$1000 | Travel Award | School of Behavioral and Brain Sciences | July 2019
$1000 | Travel Award | School of Behavioral and Brain Sciences | April 2018
$1000 | Travel Award | School of Behavioral and Brain Sciences | April 2017

Teaching

Teaching Assistantships

AUD 7280 – Doctoral Practicum in Audiology | Spring 2021 | Carol Cokely, PhD
AUD 7280 – Doctoral Practicum in Audiology | Fall 2020 | Carol Cokely, PhD
AUD 7280 – Doctoral Practicum in Audiology | Summer 2020 | Carol Cokely, PhD
AUD 6216 – Audiologic Rehabilitation for Adults | Summer 2020 | Carol Cokely, PhD
AUD 7280 – Doctoral Practicum in Audiology | Spring 2020 | Carol Cokely, PhD
AUD 7388 – Research in Audiology | Fall 2019 | Carol Cokely, PhD
AUD 6318 – Pediatric Audiology | Spring 2019 | Andrea Warner-Czyz, PhD
AUD 6v20 – Laboratory Procedures – Vestibular | Spring 2019 | Andrea Gohmert, AuD
AUD 7338 – Research in Audiology | Fall 2018 | Carol Cokely, PhD
AUD 6305 – Anatomy & Physiology – Audition | Fall 2018 | Colleen Le Prell, PhD
AUD 6314 – Instrumentation | Summer 2018 | Jeffrey Martin, PhD
SPAU 3341 – Introduction to Audiology | Fall 2017 | Jeffrey Martin, PhD

Service

Reviewing, refereeing, and administrative work for journals

Cochlear Implants International | 2019 – present
PLOS One | 2020 – present
American Journal of Audiology | 2020 – present
Annals of Otolaryngology and Rhinology | 2018 – present
International Journal of Audiology | 2016 – present

Professional Organization Service

Appointed Board Member, Student Engagement | Texas Academy of Audiology | 2021
Elected by Board of Directors to coordinate student poster submissions and presentations, Texas Academy of Audiology Annual Conference | October 2020 | Virtual
Advocacy Chairperson, Student Academy of Audiology, The University of Texas at Dallas | 2016-2017 | Dallas, TX

University Committees

BBS School Representative – Graduate Student Assembly | The University of Texas at Dallas | 2019-2020 | Dallas, TX
Inaugural Member, Graduate Student Assembly | The University of Texas at Dallas | 2018 | Dallas, TX

Community Service

Metro Dallas Homeless Alliance Point-in-Time Count | January 2020 | Dallas, TX
Dallas Audiology Society’s Senior Source Partnership | October 2018 | Dallas, TX
Commemorative Air Force WWII Air Show | October 2018 | Dallas, TX
National Day at Your State Capitol Day | March 2017 | Austin, TX
World Hearing Day | March 2017 | Dallas, TX
Brother Bill’s Helping Hands | January 2016 – Present | Dallas, TX
Center of Hope | July 2016 – Present | Dallas, TX
Agape Clinic | August 2016 – Present | Dallas, TX