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The Effect of Low Frequency Sound on Listening Level

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UNIVERSITY OF NORTHERN COLORADO

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The Graduate School

THE EFFECT OF LOW FREQUENCY SOUND ON LISTENING LEVEL

A Doctoral Scholarly Project Submitted in Partial Fulfillment
of the Requirements for the Degree of
Doctor of Audiology

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College of Natural and Health Sciences
Department of Communication Sciences and Disorders
Audiology

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This Doctoral Scholarly Project by: Samuel E. Pennington

Entitled: *The Effect of Low Frequency Sound on Listening Level*

has been approved as meeting the requirement for the Degree of Doctor of Audiology in the College of Natural and Health Sciences in the Department of Communication Sciences and Disorders, Program of Audiology.

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ABSTRACT

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A listener's preferred listening level (PLL) for music under headphones has been found to be related to factors such as music genre, external noise, and headphone fit. The purpose of this study was to investigate the relationship between a listener's PLL and the amount of low frequency sound in music. The study also investigated the relationship between a listener's PLL, their music preference, and familiarity with the songs used in the experiment. For the study, 44 participants aged 18 to 35 years old with normal hearing were recruited from a university population. Participants completed listening tasks comprised of 16 experimental stimuli representing the pop, rock, and classical genres, as well as a self-selected song of their preference. High-pass filtering with corner frequencies of 100, 173, and 300 Hz was applied to 12 of the stimuli while 4 stimuli remained unfiltered. Participants adjusted the volume setting to their preference for each stimulus. A post-test survey was administered to rate the participants' familiarity with the songs used in the listening task. A two-way repeated measures ANOVA analysis demonstrated that there were significant differences between the songs (p = 0.009) and the filter settings that removed low frequency sound (p = 0.009), as well as interaction effects between these groups (p = 0.018). A post-hoc analysis revealed that the PLLs for the classical song were significantly lower than the other 3 songs, and only the 300 Hz high-pass filter setting was significantly higher in PLL than the baseline "no filter" setting. No significant correlation was found between participant ranking of song familiarity and volume setting for that song. The use of a preferred or familiar song did not have a significant effect when measuring a listener’s PLL in this study. These results demonstrate that the absence of low frequency sound can lead to an increase in listener PLL for music. However, observations from the data revealed that this trend may not be true for all listeners. The real-implications of these findings suggest that a transducer with poor low-frequency response may lead to higher listener PLLs. Similar future studies should consider other methods to further clarify the influence of low frequency sound on PLL and how other known influences on PLL (i.e., environmental noise) may interact.

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LIST OF ABBREVIATIONS

AN	auditory nerve
BM	basilar membrane
CF	corner frequency
cVEMP	cervical-vestibular evoked myogenic potential
dB	decibel
dBFS	decibel full scale
DL	difference limen
DRC	damage risk criteria
HL	hearing level
HRTF	head-related transfer function
Hz	Hertz
IE	in-ear
IHC	inner hair cell
KEMAR	Knowles Electronic Manikin for Acoustic Research
MAP	minimum audible pressure
MIHL	music-induced hearing loss
MIRE	microphone-in-real-ear
OE	open ear
OHC	outer hair cell

oVEMP	ocular-vestibular evoked myogenic potential
PFS	percent full scale
PLD	personal listening device
PLL	preferred listening level
SL	sensation level
SPL	sound pressure level
TFOE	transfer function of the outer ear
TM	tympanic membrane
TW	traveling wave
VEMP	vestibular evoked myogenic potential

CHAPTER I

INTRODUCTION

Statement of the Problem

Since their rise in popular use over the last 40 years, personal listening devices (PLD) and headphones have been the focus of researchers who have expressed interest in how these devices are used and what factors determine the listener's experience. Early research reported that PLDs could be potentially damaging to hearing given long enough listening sessions (Catalano & Levin, 1985; Meyer-Bisch, 1996). The output levels for PLDs and various headphones were also shown to have the potential to exceed National Institute for Occupational Safety and Health (NIOSH) damage risk criteria (DRC) for noise exposure within just 1 hour at 70% of the max volume setting (Fligor & Cox, 2004). However, whether those who routinely use PLD's are at risk for hearing loss depends on factors related to the human auditory system, the technology involved, and the habits associated with PLD use.

In comparison to the entire frequency range of human hearing (20 to 20,000 Hz), low frequency sounds (i.e., below 300 Hz) are not easily detectable by the human auditory system. The sound pressure levels (SPL) required to reach the hearing threshold for frequencies below 300 Hz are greater than for higher frequencies in normal hearing individuals (Fletcher & Munson, 1933). Regardless, listener preference for varying degrees of audibility of low frequencies in music has been suggested by research in headphone design (Olive & Welti, 2015), live music (i.e., Dibble, 1995), and vestibular function (Todd & Cody, 2000). Given listener preference for bass audibility, changes in the low frequencies of a signal such as music could produce differences in preferred listening level (PLL).

Consumer headphone design considers several parameters for optimal live sound reproduction and listener experience including comfort, aesthetics, and effects from the external ear canal in addition to sound quality (Breebaart, 2017; Olive et al., 2013; Toole, 1984). The optimal headphone calibration for frequency response has been an issue of ongoing debate with more recent evidence showing listener preference for headphones calibrated to the response of a speaker in a listening room (Olive et al., 2013). The type of headphone (for example, circum-aural, supra-aural, or in-the-ear headphones) may change how much sound intensity reaches the eardrum as well as the frequency response of the signal (Fligor & Ives, 2006). Research has also shown that listeners, particularly males under the age of 35, prefer a stronger bass to treble balance (Olive & Welti, 2015). The relationship between bass response and PLL has only been explored briefly for in-ear headphones and the significance of the effect from lack or presence of bass has not been reported (Olive et al., 2016).

Listening environment, the fit of the headphone, and genre preference may also affect PLLs. Olive et al. (2016) demonstrated that increased leakage in a sealing in-the-ear headphone correlated with a loss in low frequency information and higher average PLLs. Leakage from a poor seal or non-sealing earbud-style headphones additionally leaves the listener more exposed to environmental noise (Olive et al., 2016). Therefore, PLLs will generally increase along with increasing levels of environmental noise and loss of signal intensity through the inadequate headphone seal (Hodgetts et al., 2007, 2009; Portnuff et al., 2011). Any research investigating changes to PLL must take these acoustical factors into account and necessarily eliminate any potential effect from variables outside those being measured. While many researchers have considered whether genre preference correlates to higher PLLs (i.e., Fligor et al., 2014; Portnuff et al., 2011), only one has tested the genre effect specifically and found no significant evidence for increased PLLs for a preferred song when heard in quiet (Almeida et al., 2020).

While there is evidence that headphone quality and fit can affect the amount of low frequency sound in the signal and PLL, there has been no evidence that demonstrates the gradation of this effect. Factors such as human sensitivity to low frequencies, headphone fit, and background noise must also be considered when making PLL measurements. The results of this study have implications for educating users about the effect of low frequencies on their PLL. The outcome may also provide further evidence for consideration of genre preference when making PLL measurements.

Purpose

The purpose of this study was to investigate the relationship between a listener's PLL and the amount of low frequency sound in music. The study also investigated the relationship between a listener's PLL, their music preference, and familiarity with the songs used in the experiment.

Research Questions

Q1 Is there a significant relationship between listeners' volume setting for music and the low frequency response of the signal?

Q2 Does a listener's preferred song result in higher volume settings compared to the experimental songs?

Q3 Is a listener's rating of familiarity of a song associated with listener preferred volume setting for that song?

CHAPTER II

REVIEW OF THE LITERATURE

For music to be played through headphones and heard by the listener, several stages of sound transduction must take place using various types of devices known as transducers. The devices typically used for sound transduction are microphones, amplifiers, loudspeakers, and headphones. For the purposes of this review, headphones were used as a general term and type of headphone were specified as circum-aural (around-the-ear), supra-aural (on-the-ear), in-the-ear (sealing the ear canal), or simply earbud (non-sealing and resting in the concha).

Transducers

Understanding how listeners interact with music devices would first require background knowledge of the technology behind those devices and how technology has developed to improve listener experience. Firstly, accurate reproduction of sound through a speaker system requires careful consideration of the three basic characteristics of sound: time, frequency, and amplitude. Sound is usually depicted as a waveform, which is generated by the compression and rarefactions of pressure changes travelling through a physical medium over time. Frequency represents the number of oscillations that occur within one second, expressed in Hertz (Hz). Amplitude represents the amount of energy present in a waveform and can be expressed both linearly and logarithmically. Sound transduction occurs when physical variations in air pressure are converted into an electric signal by a microphone or converted from an electrical signal to air pressure variations by a loudspeaker. The signal changes in various ways as it passes through the electrical system. For example, an amplifier signal gain, or a filter may alter the frequency composition of the waveform. The electric signal can then be transduced back into sound pressure by passing electricity through a wire around a magnetic coil whose magnetic field excites the diaphragm of a loudspeaker or headphone and produces sound (Beranek & Mellow, 2012b; McCarthy, 2016a).

Specifications for Microphones, Amplifiers, Loudspeakers, and Headphones

Sound transduction is further complicated by the need to factor for the characteristics of each transducer. Microphones, amplifiers, loudspeakers, and headphones have physical limitations that determine how accurately a sound is converted and reproduced to match the range of human hearing. For instance, because very low (i.e., 20 Hz) and very high (i.e., 20,000 Hz) frequencies are difficult to reproduce, transducers are labeled with a specified frequency range for operation. Frequencies in a signal outside this range are severely attenuated. Moreover, frequencies within the system’s frequency range may be amplified or attenuated due to the physical properties of the transducers and electrical wiring. Inertia, electrical resistance, gauge and insulation of wiring, impedance, and loudspeaker construction are just a few examples of characteristics that can change the output gain of certain frequencies. A “flat” frequency response from a transducer indicates minimal changes (i.e., +/- 3 decibels [dB]) across the frequency range compared to the original signal prior to the transduction process. Another specification related to frequency output response is harmonic distortion, which generates frequencies that are integer multiples of the input frequency. Every system will also output self-generated noise, known as the system’s noise floor (McCarthy, 2016c; Whitlock, 2013).

Additional specifications of transducers denote the amplitude of the input signal. All devices have a maximum amplitude level in volts and the signal will be clipped beyond the maximum level, resulting in distortion. Speakers also specify their power handling capability, which defines the maximum power that an amplifier can output to the speaker. Dynamic range describes the range of transmissible voltage levels between the noise floor and maximum amplitude level. Sensitivity denotes the relationship between a device's input and output levels that changes depending on the transducer. For instance, a microphone with high sensitivity will produce more output voltage in response to a weak acoustic signal (Beranek & Mellow, 2012a; McCarthy, 2016b; Whitlock, 2013).

Impedance is another important specification for transducers. Any electrical circuit has resistance or opposition to electrical current, expressed in ohms. However, in a circuit with sinusoidal current, including audio circuits, the frequency of the current creates additional factors for resistance called capacitance and inductance. These two factors act respectively as high-pass and low-pass filters that may alter the transmission of a signal depending on its frequency. Low-pass and high-pass filters respectively act as attenuators of high and low frequencies while not affecting others depending on their cutoff frequency (Floyd & Buchla, 2019). Impedance is a term that refers to the combination of resistance, capacitance, and inductance. In a circuit with multiple devices, as in an audio circuit with an amplifier and loudspeaker, the devices are typically matched for impedance. If there is an impedance mismatch between devices, the electrical signal from the source, or the amplifier in this case, could be reflected by the electric load of the loudspeaker, thus, attenuating the source signal (Beranek & Mellow, 2012a; McCarthy, 2016a).

Loudspeaker Construction

Loudspeakers must be designed to produce sound at high enough intensities to deliver the full range of sound to an entire room or outdoor space rather than just the listener's ear canal. Therefore, loudspeaker listening creates a unique experience with speaker design and room-related factors that must be considered in contrast to headphones. Loudspeaker systems are typically composed of several types of single transducer elements called drivers, which can produce sound at high intensity levels given a powerful enough input signal, typically generated by an amplifier. However, drivers have limitations for the frequencies that they can produce due to their construction and physical properties. Loudspeaker construction often involves two or three drivers that form an array to best reproduce a larger frequency range. A typical three-way driver array is composed of a tweeter that best operates in the high frequency range, a mid-frequency range driver, and a woofer or sub-woofer for the low-frequency bass range. Because each driver best responds to just a piece of the total frequency range, crossover filters are implemented to split the signal and deliver specific frequency components to the appropriate driver (Beranek & Mellow, 2012b; McCarthy, 2016b; Mitchell, 2013).

Drivers are seldom implemented in isolation; rather, they are typically mounted flush to a surface that may also use an enclosure to contain the rear-facing half of the driver. The space behind the driver or the volume of the enclosure is a factor in the overall frequency response and efficiency of the system. The volume of the space has resonance characteristics that can be manipulated to better reproduce low frequencies. For example, an unenclosed ceiling mounted driver will have a very large volume of space behind it, also called an "infinite baffle," that is a poor resonator of the desired low frequencies for sound reproduction. On the other hand, a box-type enclosure can act as an efficient resonator of low frequencies depending on the volume and shape of the enclosure design. Resonance can be further controlled by the inclusion of a specially designed vent or port, which also will resonate at a specific frequency and is designed in tandem with the enclosure to create a system that is more linear or predictable (McCarthy, 2016a; Mitchell, 2013).

Room Acoustics and Loudspeaker Quality

Regardless of speaker construction and calibration, the ultimate frequency response will be determined by how the sound interacts with space. Therefore, room acoustics are a vital component to consider in speaker design. The typical box-shaped room has six flat surfaces that are made of hard, sound-reflecting materials. Because of the impedance mismatch between the air and the walls, very little sound energy is transmitted through the wall and more energy reflects within the room. Particularly in an empty room, there are a multitude of reflection points for sound to reverberate, which leads to distortion of the source signal played through the loudspeaker. This is often described as the “comb filter” effect, where reflections cause a phase-shift in the signal delivery resulting in the attenuation and amplification of certain frequencies (Toole, 2006). In smaller rooms, constructive and destructive interference generates standing waves at low frequencies where the wavelength is twice the length of the room. Therefore, a listener may hear more or less bass in a signal depending on their location in the room and where the sound waves are amplified or attenuated (Fuchs, 2013).

Consequently, room construction and materials greatly influence the perceived sound quality of a loudspeaker (Olive & Martens, 2007). One typical strategy to reduce low frequency resonances in concert halls is to design the room with walls that radiate out from the sound source at angles beyond 90 degrees, thus altering the room shape that would cause resonance. Any protruding objects, such as balconies in a concert hall or chairs in a living room, are points of reflection and may cause dissonance (Beranek & Mellow, 2012c). Furthermore, the material composition of surfaces will vary in impedance value and lead to higher reflection or absorbance for certain frequencies. For example, a church with wooden pews would reflect high frequencies and cause the room to sound reverberant, whereas a concert hall with padded seats would absorb more of the high frequencies and reduce sound reflection. However, there is a balance for sound absorption that must be achieved to avoid over-attenuating high frequencies and creating a “dull” sounding room. Other factors such as speaker placement, balcony design, and surface materials of walls or sound absorbing panels must also be considered to deliver sound uniformly to all points in the listening space and with as little distortion as possible (Jones, 2013; Long, 2014).

Headphone Construction

Given all the factors for loudspeaker design and sound quality, the design becomes further complicated when these devices are reduced in size and coupled directly to the ear. In a review of headphone design and performance, Toole (1984) pointed out that headphone design must consider comfort and aesthetics in addition to sound quality. Furthermore, headphones disrupt binaural listening, and their design must factor for psychoacoustical aspects such as localization. Toole (1984) also acknowledged that the human ear canal affects the frequency response of sound from a headphone and, therefore, there is a need to account for individual differences in the external ear transfer functions of each listener and each ear.

Just as with loudspeakers, headphones are also drivers that are contained within enclosures. Therefore, the design properties of the enclosure or the “cup” of the headphone, as well as how the headphone fits on the wearer, are of concern for the optimization of the low frequency response. The volume of a closed headphone cup will change the output sensitivity of the system, with the greatest sensitivity achieved with essentially zero volume outside of the wearer’s ear canal, a designed exemplified by the in-the-ear style of headphone. However, given that over-the-ear headphones must contain the wearer’s pinna, a design with optimal sensitivity will allow for as little volume in the cup as possible while still comfortably covering the pinna. Venting also becomes an issue in headphone enclosure design since the fit of the headphone or the design of the headphone cushion may not always allow for complete enclosure. In essence, an unintended vent is created through the cushion or improper fit, which alters the response and sensitivity of the system. This can be controlled by the intentional inclusion of a vent in the outward-facing portion of the headphone cup, also known as a “open-back” headphone design. Although, it should be noted that the open-back design has its own disadvantages, including reduced overall sensitivity, reduced low frequency emphasis that necessitates compensations by the voltage input of the signal or the driver, and the loss of external sound attenuation by the cup (Avis & Kelly, 2006).

Psychological Factors for Judging the Sound Quality of Loudspeakers

Apart from the physical aspects of loudspeaker listening, many researchers have attempted to identify and quantify the psychological factors for categorizing subjective judgments of loudspeaker sound quality. Gabrielsson and Sjögren (1979) conducted an experiment in which participants identified adjectives that best described the sound quality of recorded music and voice played through loudspeakers, headphones, and hearing aids. From their data, the researchers concluded that there were seven perceptual dimensions consistently used by experienced listeners for describing sound quality: loudness, clarity, fullness, spaciousness, brightness, softness, and nearness (Gabrielsson & Sjögren, 1979). In a later experiment, Gabrielsson et al. (1990) also explored how these perceptual dimensions related to changes in the frequency response of a loudspeaker system. They applied four different filters to the signal: a flat response filter, a low-pass filter with a 200 Hz cutoff frequency, a mid-high filter centered around 1,000 Hz, and a high-pass filter centered around 4,000 Hz. Listeners were asked to rate each perceptual category and overall fidelity in the case of each type of filtered signal. Their results showed that the low-pass filter correlated with increased scores in loudness and fullness and decreased scores in spaciousness, brightness, and overall fidelity. The high-pass filter correlated with increased loudness and clarity scores (Gabrielsson et al., 1990).

Other researchers have expanded on the relationship between frequency response and perceived sound quality. Zielinski et al. (2005) surveyed a panel of experienced listeners after having them listen to various audio signals that had been degraded in either timbral or spatial fidelity. Timbral fidelity in this case refers to the “trueness” of the reproduction of the frequency characteristics of the original sound. Spatial fidelity refers to how well the sound is perceived to be coming from both left and right speakers, rather than just the left or right speaker. The researchers also defined “basic audio quality” as a generic rating of any notable differences between a reference signal and the signal being judged. The listeners’ subjective ratings for each condition revealed that timbral fidelity was more correlated with higher scores for basic audio quality than spatial fidelity (Zielinski et al., 2005). Lavandier et al. (2008) further supported the importance of timbral fidelity in an experiment asking listeners to make dissimilarity judgements between loudspeakers with different inherent qualities. The qualities that were most salient to listeners were bass and treble balance, or how “flat” the frequency response was, and amplification in the medium frequency range from 355 Hz to 1,120 Hz (Lavandier et al., 2008).

Experienced and Unexperienced Listener Judgements

Regarding the validity of these experiments, some have questioned the inclusion of experienced listeners and how related their judgements are to the broader public. Rumsey et al. (2005) considered the issue in depth by eliciting naïve listener judgements and comparing them with those of experienced listeners to investigate whether one set of results could be used to predict the other. Experienced listeners were defined as those who had received academic or studio training in audio engineering and naïve listeners were college students without any prior training. Rumsey et al. (2005) reported that the judgements of naïve listeners were less predictable than that of experienced listeners' scores, whereas experienced listeners were more consistent and could be extrapolated to predict scores among the broader public (Rumsey et al., 2005). Olive (2003) also found that experienced and naïve listeners came to similar subjective conclusions about speaker performance. Michaud et al. (2015) additionally questioned whether including a large number of music stimuli in these studies may affect listeners ability to make reliable judgements of dissimilarity from a reference stimulus. After performing a listening experiment with the number of stimuli presented to each listener ranging from 10 to 50, they concluded that there was no effect from the number of stimuli on listeners ability to make dissimilarity judgements (Michaud et al., 2015).

Overall, perceived loudspeaker sound quality is subject to factors as basic as the construction of the drivers and as minute as the padding of chairs in the listening space. Moreover, researchers have demonstrated that, while describing sound quality is a subjective process, there are ways of consistently relating subjective judgments to quantifiable changes in a signal using experienced listeners. Even naïve listeners are sensitive to changes in the low, middle, and high frequency ranges, although it should be noted that naïve listener judgements can be variable from person to person. However, it remains unknown how listeners' subjective awareness of sound quality affects their listening behavior and preferred listening volumes. Hearing status is also of concern when asking listeners to make judgements. The previously discussed experiments either excluded participants with hearing loss or assumed their listeners had normal auditory function.

Headphone Design and the Target Response Curve

Because headphone speakers couple directly on the ear, they also do not have the same spatial quality from room acoustics and need to be calibrated to have a similar sound quality to a loudspeaker. The two primary methods used to achieve this effect are free-field and diffuse-field design. Free-field design matches the headphone frequency response to the real-ear response measured from a loudspeaker directly in front of the listener in an anechoic chamber or room designed to limit effects on the sound from the room itself. On the other hand, diffuse-field design matches the frequency response for a loudspeaker played in a typical listening room that does produce room acoustics (H. Møller et al., 1995). Theile (1985) argued that free-field calibration measured with a speaker at zero degrees azimuth produces a response that will give a listener localization cues, as no other directional information from reflection is included. Therefore, a diffuse-field calibration was suggested for best performance and spatial fidelity (Theile, 1985). Diffuse-field calibration has since become the international standard for headphone design (IEC 60268-7:2010; International Electrotechnical Commission, 2010). There have been many authors who have argued that adjustments to this formula lead to better subjective ratings of sound quality (i.e., Lorho, 2009; H. Møller et al., 1995; Olive & Welti, 2012). Olive et al. (2013) proposed the alternative Harman Target Response Curve after demonstrating listener preference for calibration performed in a listening room with reduced reverberation compared to the standard used in prior diffuse-field measurements. Interestingly, despite extensive research into the best calibration methods, recent market research by Breebaart (2017) showed that there is no correlation between the frequency response and price of headphones.

Regardless of how accurately headphones are designed for a natural sounding frequency response, the ear canal is distinct and alters the final response properties (Toole, 1984). As described by Shaw (1974), there are several physical features that shape the frequency response of sound before it reaches the eardrum. At low frequencies, there is very little change in the signal with a small amplitude increase generated by the head, neck, and torso from 250 Hz up to approximately 1,000 Hz. The pinna flange, concha, and ear canal each contribute resonant peaks around 3,000 Hz, 5,000 Hz, and 2,500 Hz, respectively. The concha and ear canal each contribute up to 10 dB SPL around their resonant frequency, while the pinna flange only contributes around 3 dB SPL at its resonant peak. The frequency response characteristics of physiological resonance measured at the eardrum is referred to as the head-related transfer function (HRTF), which includes torso and head-related effects on resonance (Shaw, 1974).

Headphone design has addressed the issue of the HRTF and its effect on sound quality. Hammershoi and Møller (1996) attempted to measure the individual HRTF's under headphones for 12 participants using probe mic measurements. They found that the response was relatively flat from 200 Hz up to 2,000 Hz and highly variable above 2,000 Hz between subjects. Because no headphone has a truly flat frequency response, equalization must be applied to account for the response properties of each design as it is measured on human ears. The researchers concluded that headphones would ideally equalize to every listener's unique HRTF. However, realistic limitations in headphone design led the researchers to propose a sound power averaging technique that minimizes peaks and dips caused by ear canal resonance (Hammershoi & Møller, 1996). More recently, Celestinos et al. (2019) proposed a method for calculating a personalized equalization using a near-field microphone. The microphone is located near the driver to measure the fundamental frequency of the listener's ear and the volume of the ear to predict their personal ear canal resonances (Celestinos et al. (2019).

Schärer and Lindau (2009) studied the issue of equalization for the HRTF and came to a similar conclusion, that minimizing high-frequency variables through high-pass filtering yielded the best results. However, the researchers also take into consideration the positioning of the headphone on the ear and its effects on the HRTF. They found that repositioning had significant effects on the high-frequency responses of open and closed-back headphones. The low frequency response of closed-back headphones can also be affected by position on the ear and bass leakage through the coupler (Schärer & Lindau, 2009). Masiero and Fels (2011) reported that variability in the frequency response of the signal could be reduced in experiments by allowing subjects to place the headphones in the position they found most comfortable.

While these researchers considered the design and performance optimization for circum-aural headphones, little research had been done on the frequency response and design of in-ear (IE) headphones (Olive et al., 2016). Olive et al. (2016) compared the performance of IE headphones with previously studied designs of open-ear (OE) circum-aural headphones to see what frequency response is preferred for IE headphones and whether a difference in occlusion affects user listening volumes. Their results showed that IE headphone listeners preferred a frequency response with approximately 5 dB SPL more in the bass filter (20-1,000 Hz) compared to OE headphone measures. Additionally, using a microphone monitoring system inside the headphone, the researchers showed that a poor acoustic seal in the ear could result in losses of up to 30 dB SPL below 500 Hz. Olive et al. (2016) suggested that this finding attributed to listener volume levels that were up to 2 dBA higher in test conditions where an acoustic seal was not verified.

Overall, the effects of coupling a sound source to the ear are numerous. Designers must compensate for a lack of room acoustics and the individual response of each listener’s ear canal. Furthermore, the speaker housing and earpad change the nature of the headphone frequency response and perceived sound quality. While Olive et al. (2016) suggested that not controlling for bass leakage was a factor that led listeners to choose volumes up to 2 dBA higher~~,~~ their experiment did not verify exactly how much bass signal was reaching listeners’ ear drums or lost to leakage. Therefore, the exact correlation between bass response and chosen listener volume remains unknown and requires further investigation.

Physiological and Psychoacoustic Processing of Low Frequency Sound

The human auditory system and auditory cortex introduce many factors for interpreting frequency specific information in a soundwave. Auditory physiology is responsible for transducing sound into electrical neural signals while psychoacoustic processing describes how the brain ultimately perceives the sound.

Physiological Processing of Low Frequency Sound

To understand how low frequency sound affects listener behavior, it is first important to establish how sound is processed by the auditory system and the physiological aspects that are unique to low frequencies. Von Békésy (1953) and Von Békésy and Wever (1960) were the first to describe the travelling wave (TW) that leads to the tonotopic organization of the inner ear. As sound enters the ear canal, it strikes the tympanic membrane and is transmitted through the three connected ossicles in the middle ear space. The footplate of the third ossicle, the stapes, oscillates on the oval window at the base of the cochlea. The oscillation patterns vary according to the intensity and frequency of the stimulus. The motion of the stapes creates pressure differences between the oval window and round window opening at the opposite end of the fluid-filled cochlea and initiates the TW. The TW describes the envelope of displacement along the basilar membrane (BM), which reaches its maximum amplitude at the place along the BM that corresponds to the critical frequency information in the sound. The BM is arranged such that the base is thinner and more rigid while the apex is wider and less rigid. The resulting mass and stiffness characteristics cause the BM to respond best to high frequencies at the base and low frequencies at the apex. Therefore, the place of maximum displacement on the BM is attributed to the mass and stiffness characteristics that correlate to the resonant frequency of the sound (Pickles, 1988). Furthermore, Zwislocki (2002) showed that the TW moves twice as fast at the base compared to the apex and the amplitude of maximum displacement at the apex is 10x that of the base.

The TW described by Bekesy did not fully account for the frequency discrimination capability of the human ear. In later experiments by other researchers, it was discovered that the active components of the BM were contributing to high sensitivity and sharp frequency tuning. This effect, termed the cochlear amplifier, was attributed to the contraction and expansion of the outer hair cells (OHC). Nonetheless, the increased tuning ability of the cochlear amplifier is most effective at lower intensities and loses its influence at higher intensities (Ashmore et al., 2010). The effect of the cochlear amplifier led many researchers to describe the BM as having a compression effect where there is more “gain” or sensitivity for low intensity sounds and less for high intensity sounds (Ruggero, 1992). Furthermore, the cochlear amplifier can be disrupted by damage to the OHC’s, resulting in reduced frequency selectivity, poorer audiometric hearing thresholds, and intolerance for high-level sound (Oxenham & Bacon, 2003). It has also been shown that the compression effect is greater for higher frequencies than lower frequencies (Rhode & Cooper, 1996).

The tonotopic organization of the BM is maintained as the signal is transferred to higher-level components of the auditory system. As the BM oscillates upward and downward in response to the compressions and rarefactions generated by the stapes, the stereocilia of the inner hair cells (IHC) move laterally in a shearing motion. This causes the depolarization of the hair cell and begins the mechano-chemical transduction process in the auditory nerve (AN). Attached to the base of IHC’s are afferent AN fibers which compose up to 95% of the AN (Spoendlin, 1972). As the IHC’s are depolarized by the shearing motion of the BM, neurotransmitters are released, which results in firing the fibers of the AN (Dallos et al., 1972).

It is known that frequency coding in the AN is related to two factors: the place of neural activation on the BM and the timing of neural activity. Firstly, each fiber connected to the IHC’s has a characteristic frequency to which it best responds, and which correlates to the location of the fiber on the BM. Additionally, the ability of the nerve to fire at the same rate as the frequency, also known as phase-locking, is said to contribute to frequency coding. The maximum firing rate of the auditory nerve fibers is 800 times per second, which would seem to limit the ability of the nerve to code any frequency beyond 800 Hz. However, it has been shown that the AN response can include some degree of alternating current or phase-locked response up to around 5,000 Hz (Johnson, 1978). To explain high frequency coding, it was theorized that multiple nerve fibers would be recruited to phase-lock to the signal frequency in alternating patterns. This has become known as the volley theory of frequency coding (Hanekom & Krüger, 2001).

Tonotopic organization is maintained as frequency-specific information is transmitted by the AN to the brainstem and higher-level central processing areas of the auditory system. However, the exact nature of frequency representation becomes less clear as the signal approaches the auditory cortex. First, the AN delivers the signal to the cochlear nucleus, whose three sub-divisions each maintain their own tonotopicity. High frequency and low frequency processing are respectively found in the posterior and anterior sections of the dorsal, posterior ventral, and anterior ventral cochlear nuclei. The superior olivary complex also represents high and low frequencies in a spatial pattern from dorsal to ventral areas in the lateral superior olive and peripheral to medial areas in the medial superior olive. Further up, the lateral lemniscus and medial geniculate body are less organized and tuning curves tend to be broad or irregular (Morel et al., 1987). At the level of the auditory cortex contained within Heschl's Gyrus, tonotopic organization is symmetric and mirrored with low frequencies being represented laterally to the gyrus and high frequencies being represented both anteriorly and posteriorly to the low frequency region. Tuning curves can be measured in the auditory cortex and may be sharp or flat irrespective of frequency (Humphries et al., 2010).

Vestibular Sensitivity to Low Frequencies

The vestibular organs, the utricle and saccule, have also been shown to play a role in the processing of sound. In particular, the vestibular organs have been shown to be sensitive to low frequencies and their function has been proposed as one explanation for preference for high-level sound. The acoustic sensitivity of the saccule and utricle has been studied using sound-dependent effects such as nystagmus or vestibular evoked myogenic potentials (VEMP) where vestibular stimulation correlates with muscle activation in the eyes (ocular VEMP or oVEMP) or sternocleidomastoid muscle (cervical VEMP or cVEMP; Todd et al., 2014). Colebatch et al. (1994) first demonstrated the existence of cVEMP's using 75 to 100 dB SPL clicks. Using 110 dB SPL air-conducted (AC) tone pips, Todd et al. (2007) reported that vestibular activation by AC sound is most sensitive in the 400 to 800 Hz range. Furthermore, their research showed another sensitivity peak at 100 Hz using mastoid vibration (Todd et al., 2007). Comparative testing later led researchers to conclude that the 500 and 100 Hz sensitivity were respectively related to the properties of the saccule and utricle (Todd et al., 2009). Moreover, thresholds for activation differed depending on the mode of sound transduction, with AC thresholds at 80 dB sensation level (SL) and bone conducted or vibration thresholds at -15 dB SL. The low threshold for vibration was considered evidence for the high sensitivity in humans to low frequency noise or infrasound (sound consisting of frequencies below the human frequency range for hearing (e.g., < 20 Hz; Todd et al., 2008).

Dibble (1995) originally proposed that there is a necessary intensity differential of 10 to 30 dB between low and mid-band frequencies for some music to be enjoyable, the so-called "rock-and-roll threshold." Todd and Cody (2000) had originally proposed that the vestibular organs may be responsible for the existence of this threshold. Their study found that a 90 dBA dance music signal could be used to induce cVEMP's (Todd & Cody, 2000). Further research has provided evidence of vestibular low frequency sensitivity and seems to support their claim (Todd et al., 2007, 2008, 2014). Analysis of data regarding how listeners choose volumes and report enjoyment should take potential vestibular effects into account.

Loudness Perception

Although two sounds may be presented at an equal SPL, they may sound perceptually different depending on their spectral content. Sivian and White (1933) were among the first to demonstrate this effect in their experiments, testing the minimum sound pressure required for each frequency to be audible. They found that the minimum audible pressure (MAP) for low frequencies required much more intensity than higher frequencies, which sloped down sharply to peak sensitivity at around 4,000 Hz (Sivian & White, 1933). Higher frequencies were also later shown to decrease in sensitivity and curve upward (Northern et al., 1972).

Fletcher and Munson (1933) expanded on this research by plotting how frequency and loudness were related at different stimulus intensity levels. They asked participants to make loudness judgements comparing the rest of the frequency range to a 1,000 Hz reference tone. The researchers reported their results as equal loudness contours that showed how much intensity is needed at all other frequencies to sound equally as loud as the reference tone. At lower reference intensity levels (i.e., 40 dB), the curves approximate the sloping MAP curves reported by Sivian and White (1933). However, as intensity increases, the contours flatten and indicate that perceptual differences disappear at higher intensities. The phon unit was proposed to compare different frequencies in terms of their loudness. For example, a 40 phon 1,000 Hz tone and a 40 phon 200 Hz tone are equal in loudness even though the necessary intensities for them to match are different (Fletcher & Munson, 1933). The equal loudness contours have also been used as the basis for the A, B, and C-weighting scales used in sound level measurement. The A-weighting scale (dBA) uses the 40 phon loudness contour and weights the spectral information in a signal according to the audibility of each frequency at its respective SPL. Alternatively, the B and C-weighting scales use the 70 and 100 phon contours, respectively, and apply more weight to the lower frequencies since they are more audible at higher intensities (Gelfand, 2016).

While the equal loudness contours provide a way to explain the relationship between loudness and frequency, they do not provide a way to compare overall loudness and intensity. Stevens (1936) proposed the sone unit as a ratio-based scale for discussing loudness in terms of intensity. One sone is equivalent to a 40 dB SPL 1,000 Hz reference tone and a doubling of loudness, or 2 sones, is equivalent to an increase of 10 dB or phons. The sone scale shows that loudness grows at a slower rate than intensity (Stevens, 1936). Also known as Stevens power law, this growth rate holds true for intensities at or above 40 dB SPL or phons at 1,000 Hz (Stevens, 1957). However, Hellman and Zwislocki (1961) pointed out that the growth rate for loudness is much faster below the reference intensity.

The duration of the stimulus may also influence the perception of loudness. Hood (1950) showed that the perceived loudness of a signal decreases if that sound is presented over a period of up to 5 minutes. In other words, the auditory system is adapting to the stimulus over time (Hood, 1950). This effect has generally been attributed to the physical characteristics of the AN. In a post-stimulus time, histogram showing the firing activity of the fibers of the AN, firing height decreases in the presence of a constant stimulus (A. R. Møller, 1983). However, Scharf (1983) later clarified that the amount of auditory adaptation differs from person to person and even between ears. For example, musicians particularly seem to have less adaptation than non-musicians (Micheyl et al., 1995). Also, adaptation occurs more for higher frequency tones than lower frequency tones or narrow-band noise (Miśkiewicz et al., 1993).

Loudness measurement also must consider whether the stimulus is being heard monaurally or binaurally. Causse and Chavasse (1942) conducted an experiment that measured differences in perceived loudness between tones presented in one or both ears. They reported that there was a binaural loudness benefit of 3 dB near threshold and the effect gradually increased to 6 dB at around 35 dB SL (Causse & Chavasse, 1942). This effect was termed the binaural summation of loudness (Hirsh, 1948). Additionally, Marks (1978) was able to demonstrate perfect binaural summation across several frequencies, indicating that sound heard binaurally is perceived as twice as loud as sound heard monaurally.

Another factor in making loudness judgements is the degree of sensitivity of the auditory system to changes in intensity. Riesz (1928) originally reported that the just-noticeable-difference levels or difference limen (DL) were dependent on intensity level and frequency. Subsequent experiments have supported that the DL for intensity decreases as the intensity of the signal increases (Florentine et al., 1987; Jesteadt et al., 1977). Some researchers have disagreed with Riesz (1928) about the relationship between the DL for intensity and the frequency of the signal that is presented. Later studies showed that the DL for intensity is consistent for frequencies up to 4,000 Hz, but that it will increase with frequencies above 4,000 Hz depending on the listener (Florentine et al., 1987; Jesteadt et al., 1977). Houtsma et al. (1980) found that the DL for white noise remained consistent around 0.6 to 0.8 dB SPL for all intensities above 10 dB SPL in normal hearing listeners. Turner et al. (1989) demonstrated that for the 20 dB SL to 80 dB SL intensity range at 500 and 6,000 Hz, DL may range from around 1.5 dB SPL to 0.5 dB SPL and 2 dB SPL to 0.5 dB SPL, respectively, using a gated signal.

Certainly, the ability of the normal hearing auditory system to detect changes in intensity is sensitive to within several tenths of a decibel. This is an important consideration for establishing the step size of volume controls in an experiment, particularly where a high intensity signal is involved that could result in lower DL.

Pitch Perception

In the same way that intensity correlates to loudness, frequency is perceptually correlated to pitch. Stevens and Volkmann (1940) asked participants to make pitch judgements again using the 40 phon 1,000 Hz tone as a reference. The unit for measuring pitch is the mel scale, where 1,000 mels corresponds with the 1,000 Hz reference frequency. They found that frequency and mels were scaled similarly up to the 1,000 Hz reference, but pitch grew much more slowly with frequency above that point, such that 16,000 Hz was perceived at around 3300 mels (Stevens & Volkmann, 1940). Zwicker and Fastl (2007) found an even slower growth rate for mels using different measurement techniques. Furthermore, Stevens (1935) showed that loudness may influence pitch perception. In his experiments, increasing the intensity had the effect of increasing the pitch perception for frequencies 3,000 Hz and above, decreasing the pitch perception for frequencies below 1,000 Hz, and not affecting the frequency range between 1,000 and 3,000 Hz (Stevens, 1935). Experiments that followed revealed that the24ffectt is at most a 3% shift from the initial frequency with an increase of 40 dB SPL (Terhardt, 1979; Zwicker & Fastl, 2007).

Frequency Selectivity and Auditory Filters

Sensitivity to changes in frequency also varies depending on the frequency and intensity of the signal being presented. Wier et al. (1977) measured the DL for frequency using frequencies ranging from 200 to 8,000 Hz and intensity levels from 5 to 40 dB SL. The results of their experiment showed that DL for frequency can range from 1 Hz with a 200 Hz signal at 40 dB SL to around 100 Hz for an 8,000 Hz signal at 10 dB SL. In general, the DL for frequency increases with increasing frequency and decreasing intensity (Wier et al., 1977).

The variable sensitivity of the auditory system to changes in frequency is better understood via the concept of auditory filters. Fletcher (1940) first hinted at the existence of auditory filters in masking experiments that determined how much of a white noise spectrum was needed to mask a pure tone. He found that the threshold for a pure tone would increase as the spectrum of white noise increased from a narrower to a wider bandwidth. Beyond a certain bandwidth of noise, the pure tone signal threshold no longer increased. This bandwidth limit was termed the critical bandwidth for masking a pure tone and demonstrates the shape of the auditory filter centered at the pure tone frequency (Fletcher, 1940). In experiments that measured the critical bandwidths for normal hearing listeners, it was found that bandwidths can range from 100 Hz for a 500 Hz center frequency to 2,000 Hz for a 10,000 Hz center frequency (Hawkins & Stevens, 1950). However, there were some discrepancies about bandwidths for frequencies below 500 Hz. Hawkins and Stevens (1950) reported that bandwidths increased to 200 Hz again below the 200 Hz center frequency. More recent experiments reported that bandwidths continue to decrease below 500 Hz in a linear fashion to approximately 50 Hz for a 100 Hz center frequency (Fidell et al., 1983; Rosen & Stock, 1992; Shailer & Moore, 1983). Patterson and Moore (1986) explained this discrepancy as a difference in the auditory processing efficiency at low frequencies. Two listeners with the same auditory filter shapes and masking levels may have different thresholds based on the auditory system’s ability to follow the signal and detect changes. The original calculations for critical bandwidth assumed that efficiency remained constant for low frequencies, but the more recent experiments showed that efficiency, in fact, increases with lower frequencies and results in decreased critical bandwidth (Patterson & Moore, 1986).

Pitch and loudness are important factors to consider when asking participants to make loudness judgements, especially at higher intensities. If music is turned up to a high enough intensity, then loudness growth will not be as dramatic from 70 dB to 95 dB SPL as it is for 10 to 35 dB, for example. It is important to use a weighting scale that properly weights low frequencies according to their audibility at higher intensities. Binaural hearing effects should also be considered when interpreting results as participants will receive an extra 6 dB of loudness from listening with both ears. Lastly, the size and critical bandwidths of the auditory filters at low frequencies will be crucial to consider when designing experimental conditions. If some experimental signal conditions have more low frequency energy than others, the cutoff frequencies for filtering the signal will need to take critical bandwidth into account for the changes to be theoretically detectable by the auditory system.

Personal Listening Devices and Preferred Listening Levels

With the rise in popular use of PLDs, the hearing health community has been concerned with how the public interacts with these devices and whether their PLLs and length of listening time could put them at risk of music-induced hearing loss (MIHL). An extensive body of research exists for understanding the demographics and behavior of users, as well as the output and effects of the various devices associated with music-listening through headphones (Fligor, 2009; Punch et al., 2011).

Trends in Personal Listening Device Use and Habits

Early research (e.g., Catalano & Levin, 1985) raised concern that PLD use may commonly exceed the Occupational Safety and Health Administration recommended noise dosages based on listening time and intensity and lead to MIHL, particularly among high-school and college-aged people who were thought to be the more common users of the new technology. Music-induced hearing loss has been distinguished from noise-induced hearing loss in order to specifically discuss how high-intensity music, for example from concerts, nightclubs, PLDs, and professional music playing, can cause hearing loss (American Academy of Audiology, 2020; Portnuff et al., 2011). In subsequent studies of leisure activities and noise (e.g., Meyer-Bisch, 1996), researchers revealed that frequent PLD use may correlate with an increase in audiometric thresholds among young people, which prompted even further research into the listening habits of young people. Unfortunately, while age became a principal factor for concern and research in PLD usage early on, no studies were done to prove that young people were the predominant users of PLDs and, therefore, those most at risk (Torre, 2008). In the first expansive study of PLD usage trends, Zogby (2006) conducted a national phone survey of 1,000 adults and 300 teenagers. The results of this survey demonstrated that the teenage group was twice as likely to use an iPod or MP3 player as adults and teenagers also reported louder listening volumes. However, the notable issue in this study was that listening volumes were subjectively categorized from “low” to “very loud” with many responding in the “loud” and “somewhat loud” categories whose definitions likely varied with the participant. Also, the “adult” age group included all participants 18 to 70 years old, providing little data to discern how specific age ranges correlated to PLD usage beyond age 18 (Zogby, 2006). Following this study, much research specifically tried to quantify the levels of noise exposure from PLD usage, particularly with younger users. Many researchers (e.g., Hoover & Krishnamurti, 2010; Portnuff et al., 2011; Vogel et al., 2008; Williams, 2005, 2009) demonstrated evidence that at least some percentage of PLD users are at risk for MIHL based on self-reported listening volumes and length of listening session, up to 51% among college populations (Levey et al., 2011). Others have reported no dangerous sound exposure from PLD usage (Epstein et al., 2010).

Effects of Age, Sex, and Socioeconomic Background on Preferred Listening Level

Following the Zogby (2006) survey, more recent research has been conducted to look closer at the age-related demographics of PLD use. Fligor et al. (2014) surveyed 160 adults and confirmed that age is a significant factor for listening habits, with participants aged 24 years and younger reporting increased PLD use and louder PLLs. Moreover, in a survey of 4,185 Australian PLD users, Gilliver et al. (2017) reported that users aged 18 to 35 were at a higher risk of hearing loss from higher PLLs and longer average listening times. Most recently, Feder et al. (2019) surveyed over 10,000 Canadians ranging from ages 6 to 79 and asked participants for their weekly PLD use and whether they believed that their PLD use could be considered a “loud” activity. Their results also suggested that younger age correlates to frequent loud PLD usage and leisure noise exposure, although the researchers again asked subjects to subjectively determine if they listened to “loud” volumes (Feder et al., 2019). Parents were also surveyed on their children’s PLD use and results confirmed PLD popularity among younger age groups that had been proposed in prior research (Båsjö et al., 2016; le Clercq et al., 2018).

Apart from age, research on PLD usage and habits has also proposed sex as a factor for risky listening behavior. However, the results from studies conducted to observe the effects of sex on PLD usage have been inconsistent. There have been many studies where results showed that men were at a higher risk for MIHL due to higher PLLs (e.g., Keith et al., 2011; Torre, 2008; Williams, 2005, 2009) and potentially longer listening times (Kahari et al., 2011). Other researchers have shown no differences between male and female listeners (Fligor et al., 2014;

Gilliver et al., 2017; Vogel et al., 2014) or louder PLLs for males only while listening in quiet (Levey et al., 2011).

Additionally, factors such as education level, socioeconomic background, and ethnicity have been studied as factors in PLD listening habits. In the Zogby (2006) survey, participants were categorized as Hispanic or non-Hispanic for discussing results. The survey showed that Hispanic users overall reported higher PLD listening volumes, particularly Hispanic teenage respondents (Zogby, 2006). In their study of race and ethnicity on listening behavior, Fligor et al. (2014) determined that both factors were correlated with higher noise exposure, with African American and Hispanic participants reporting the highest levels. Moreover, several researchers (Dreher et al., 2018; Vogel et al., 2008, 2014) found that lower socioeconomic status was associated with higher PLLs in studies of teenage PLD users. Twardella et al. (2017) also stated that being in a single-parent household and lower parental education correlated with higher PLLs and listening duration among adolescents. However, Feder et al. (2019) and Fligor et al. (2014) did not support either education or socioeconomic background as factors relating to PLD usage in their respective surveys of users in urban environments and the broader Canadian population. Therefore, results have been mixed regarding a correlation between socioeconomic status and PLD habits.

Effects of Background Noise and Headphone Type on Preferred Listening Level

Researchers realized that there are many factors other than personal demographics that may also influence users’ PLL. Hodgetts et al. (2007) conducted a study specifically measuring the influence of background noise on listener’s PLL. Their experiment included three different noise scenarios including quiet, street noise, and multi-talker babble. They reported that the street noise and multi-talker babble resulted in much higher PLLs of 85.4 and 83.7 dBA, respectively, when compared to the quiet condition at 76.0 dBA (Hodgetts et al., 2007). In a study released soon after, Torre (2008) reported that one of the most common listening situations for a population of college students was while exercising. Hodgetts et al. (2009) then followed up with an experiment specifically evaluating listening behavior while exercising. The exercise-in-noise condition resulted in PLL's 2.5 dBA higher than the resting-in-quiet condition (Hodgetts et al., 2009). Portnuff et al. (2011) further supported the conclusion that PLL's increase in background noise in an experiment for each of the 7 noise conditions used, including various levels of pink noise up to 80 dBA, bus noise, and airplane cabin noise. Preferred listening level increases up to 12 dBA for earbud-style headphones were shown for both the 70 dBA pink noise and 70 dBA bus noise, with lower PLLs reported for the supra-aural headphones and the lowest levels reported with an in-ear isolating headphone at similar background noise levels (Portnuff et al., 2011).

In addition to background noise, the type of headphone has been investigated as a factor for choosing PLL. Fligor and Cox (2004) first investigated the effects of headphone style on the output volume from PLDs and found that insert-style in-ear headphones for one manufacturer resulted in output levels up to 9 dBA higher, although they concluded that the effect was inconsistent across all manufacturers. In a later related study, Fligor and Ives (2006) chose to investigate how earphone type realistically affects listener behavior and measured users' PLL for music with over-the-ear, two IE, and earbud-style headphones. They found that the earbud-style headphones resulted in the highest average PLL. The researchers attributed the higher PLL's to the lack of sound isolation in the earbuds (Fligor & Ives, 2006). Portnuff et al. (2011) and Olive et al. (2016) also supported the conclusion that earbuds lead to higher average PLL's in comparison to in-ear, supra-aural, and over-the-ear style headphones. Noise cancelling headphones can also affect a listener's PLL. Liang et al. (2012) demonstrated that PLL's for music were reduced when noise cancellation was turned on in quiet and noisy listening conditions compared to PLL's for standard earbud headphones and with noise cancellation turned off.

Effects of Music Preference and Enjoyment on Preferred Listening Level

While the risk of hearing loss from PLD use was clearly a concern for many researchers, others have studied the underlying psychological reasons for the enjoyment of loud music. Juslin and Vastfjall (2008) identified six underlying mechanisms for the emotional response to music (brainstem reflex, evaluative conditioning, emotional contagion, visual imagery, episodic memory, and musical expectancy). Brainstem reflex and evaluative conditioning described the emotional reflex from hearing a loud dissonant sound or sound that associated with another stimulus. Emotional contagion, visual imagery, and episodic memory related to the quality of the music and its ability to associate with sad or happy emotions or conjure related images or memories in the listener's mind. Musical expectancy described the emotion related to the confirmation or violation of the expected sequence in music. For example, a listener may become surprised if a chord progression of E through F does not end in the chord G (Juslin & Vastfjall, 2008). Axelsson et al. (2010) observed the effects of different aspects of sound on the pleasantness, eventfulness (i.e., liveliness), and familiarity of soundscapes. His analysis included the effects of loudness and low frequency sound. Overall, loudness was positively correlated with pleasantness and eventfulness while low frequency sound was only negatively correlated with eventfulness (Axelsson et al., 2010). Welch and

Fremaux (2019) went further and discussed the social factors for loud music enjoyment. They pointed out that loud music forms a sense of celebration, group cohesion, masks environmental noise, masks inner thoughts, and creates an environment that fosters intimacy (Welch & Fremaux, 2019). The effect of music intensity level has also been studied in restaurants where it has been demonstrated that SPLs for music correlated to customer satisfaction and the amount of time customers will stay at a table. Sound pressure levels for music were considered optimal for customer satisfaction at a “comfortable” listening level (64.4 dBA); however, “comfortable but loud” listening levels (70.2 dBA) led to slightly reduced customer satisfaction and reduced time spent at the table (Novak et al., 2010). Furthermore, other researchers have reported that loud music levels lead to faster drink consumption at bars and nightclubs (Guéguen et al., 2008).

The preferred genre of music is another factor that has been considered for choosing a certain listening level. Research observing the differences in overall output SPLs between genres has been mixed, with some reporting higher output SPLs for pop and rock (Kim & Han, 2018) and others reporting consistent SPLs across all genres except for classical (Hammershoi et al., 2016). Cullari and Semanchick (1989) demonstrated early on that loudness and genre preference were correlated by asking listeners to rate 10 selections of music in terms of their preference for the music from 1 to 7 and then listen again to set the music to their preferred level. Their results found a significant correlation between the listeners’ preference for the music and louder listening levels (Cullari & Semanchick, 1989). Fucci et al. (1993) also demonstrated that participants’ preference for the rock genre resulted in reduced loudness judgements for those who preferred rock music more so than for those who did not prefer it. Their results showed that participants who preferred rock music consistently rated the music lower on a numerical magnitude estimation scale across intensity levels ranging from 10 to 90 dB SL (Fucci et al., 1993). In PLL measurement research, the effect of genre has been discussed but rarely tested (i.e., Levey et al., 2011; Portnuff & Fligor, 2006; Portnuff et al., 2011). Fligor et al. (2014) surveyed PLD users and asked for their preferred genre, but their analysis did not show any significant correlation between the genre and higher PLLs. However, their experiment only took samples from the participants' PLDs in the moment and did not ask them to listen to other music genres for comparison (Fligor et al., 2014). Almeida et al. (2020) provided participants with the option to choose one preferred song and measured differences between their genre choice and other genres. However, they found no difference between the PLL's of the preferred and non-preferred genres (Almeida et al., 2020). Hoshina et al. (2022) compared PLLs for the classical and pop-rock genres with and without active noise cancellation, but they did not note any significant differences between the listening levels for those genres.

Overall, there are many potential elements that shape what PLL listeners choose. While age seems to be the most frequently considered factor, other factors such as sex, race, ethnicity, and socioeconomic background are also worth observing, as their effect on listeners' PLL remains uncertain. While preference for genre has been considered as a factor that may affect PLL in some experiments (Almeida et al., 2020; Fligor et al., 2014), it is unclear whether listeners may be more sensitive to changes in sound quality for music they prefer. Further research could reveal whether changes in sound quality (e.g., from using better or poorer quality headphones) changes the volume levels that listeners choose for music they prefer.

Preferred Listening Level Laboratory Measurement

Sound level measurement of PLLs and headphones can be difficult depending on the goals of the experiment and access to equipment. In fact, many researchers have searched for methods to measure PLLs outside of the laboratory to get a more accurate idea of real-world PLD usage. Also, rather than taking SPL measurements, some researchers conducting large surveys have relied on self-reported values for listening volume and length of a typical listening session (i.e., Danhauer et al., 2009; Feder et al., 2019; Gilliver et al., 2017; Zogby, 2006). As previously discussed, self-reported listening volumes are dependent on the user's subjective definition of loud sound, and it is difficult to know the accuracy of those values. To address this issue, Portnuff et al. (2013) conducted a study to compare self-reported volumes and listening times with values measured over a long period of time using a dosimeter. The design of this study allowed for a very accurate portrayal of listener behavior; however, the researchers pointed out that dosimetry is time consuming and may not be appropriate for all types of research. Fortunately, their results showed that survey questions asking PLD users to rank their "usual" volume control level from 1 to 10 could be used in conjunction with self-reported listening times to closely predict their total noise exposure (Portnuff et al., 2013).

Another method to measure user PLLs in the field was implemented by Epstein et al. (2010). The researchers approached users at various locations and made digital recordings of the PLD stimulus at the user's listening level in that moment. The recordings were later used in conjunction with ear canal to estimate the actual levels reaching the tympanic membrane (TM; Epstein et al., 2010). Portnuff et al. (2013) questioned the validity of these measurements and pointed out that recordings in the moment did not account for volume changes as the user changed environments.

Most studies objectively measuring user PLLs have tended to rely on two methods for sound level measurement. One method is accomplished using microphone-in-real-ear (MIRE) measurements and the second uses a manikin technique. The MIRE technique requires that the participants be seated in front of the measurement equipment. A probe microphone is inserted into the participant's ear canal to within 5mm of the TM. A reference microphone at the opening of the ear canal compares the input signal with the probe microphone measurement to factor out the probe tube resonances (Hammershoi & Møller, 1996). Therefore, the probe microphone system can make dB SPL measurements to see exactly how much intensity and spectral content is reaching the participant's TM (Mueller et al., 2017). However, noise exposure standards are reported in dBA free-field values and do not factor for effects from the transfer function of the outer ear (TFOE) unique to an individual based on one's anatomy (National Institute for Occupational Safety and Health, 1998). Consequently, the dB values obtained at the TM must have the TFOE subtracted out to be comparable to standardized free-field noise values (International Organization for Standardization [ISO], 2002).

The manikin technique uses an artificial ear in a dummy head to simulate the effects of the HRTF without having to measure each participant's individual ear canal with probe mic measures. The standardized version of this method is known as the Knowles Electronic Manikin for Acoustic Research (KEMAR; International Organization for Standardization [ISO], 2004). Non-standard methods, such as the Jolene educational tool (Martin & Martin, 2007) have also been used in experimental research (i.e., Almeida et al., 2020; Fligor et al., 2014; Park et al., 2017). Although the manikin ear is artificial, it still must factor for the false ear's canal resonance to calculate free-field equivalent dBA values (ISO, 2004). Moreover, Berger et al. (2009) demonstrated that the Jolene manikin was accurate for measuring the output from circum-aural, supra-aural, and earbud-style headphones, but did not accurately measure in-the-ear headphones. Christensen et al. (2013) compared the MIRE and manikin techniques by measuring the frequency responses of several headphones to see how much the manikin response differed from the real ear. The results showed that the manikin may overestimate the intensity at the TM from 5 to 8000 Hz by 5 dB; however, it should be noted that the artificial ear used in this experiment was neither KEMAR nor created from the Jolene cookbook (Christensen et al., 2013). Recently, Almeida et al. (2020) conducted an experiment comparing SPL measurements taken with the MIRE technique and a Jolene manikin. Their results showed a significant difference only in the 4,000 Hz band between methods (Almeida et al., 2020).

CHAPTER III

METHODOLOGY

Participants

Participants for this study were recruited from a young adult population in the Northern Colorado region. Participants were recruited via a flyer, email, and word-of-mouth by a graduate clinician or supervising faculty member. All participants gave written consent to participate in the study and were assigned a numerical identifier to protect their identity (see Appendix A). Recruitment, consent, and data collection for all participants was conducted with approval from the Institutional Review Board (IRB) at the University of Northern Colorado (see Appendix B).

Male and female participants were recruited for this study. Participants were excluded from the study if they were younger than 18 or older than 35 years of age. The older age cutoff for inclusion was intended to limit the effects of age on frequency selectivity. Each participant was screened with an otoscopic examination and air-conducted pure-tones. Inclusion in the study required that the participant responded consistently in both ears to pure tones presented at 20 dB hearing level (HL) from 125 to 8,000 Hz in an audiometric booth that met the American National Standards Institute (ANSI, 1999) standard values for permissible ambient noise levels. A GSI Audiostar Pro audiometer and Sennheiser HDA200 headphones calibrated within 1 year were used for the hearing screening. Any participant who did not meet the passing criteria for the hearing screening was provided a referral form if any follow-up treatment was recommended (see Appendix C).

Materials and Instrumentation

Survey Instruments

The experiment included a pre-test and post-test listener survey. The surveys were designed in Qualtrics and presented on an iPad tablet. Participants were asked to complete a pre-test survey to collect information about demographics, previous musical or audio engineering training, musical genre preference, and the make and model of the headphones the participant used most frequently for music listening. The participants' top three preferences for music genre were ranked with a provided list that included hip-hop/rap, blues, classical, country, Latin, electronic, folk, hip-hop, jazz, reggae, rock, and heavy rock (i.e., punk, metal) with an option to type in any unnamed genre. If the make and model of each participant's most frequently used headphone were not available, the type of headphone was elicited by the graduate clinician researcher with care to distinguish between an in-the-ear headphone and non-sealing earbud (see Appendix D).

After completing the experimental listening tasks, participants were also asked to complete a post-test survey. For this survey, participants rated their familiarity with each of the songs chosen by the researcher for the listening tasks (see Appendix E).

Computer Equipment, Headphones, and Volume Control

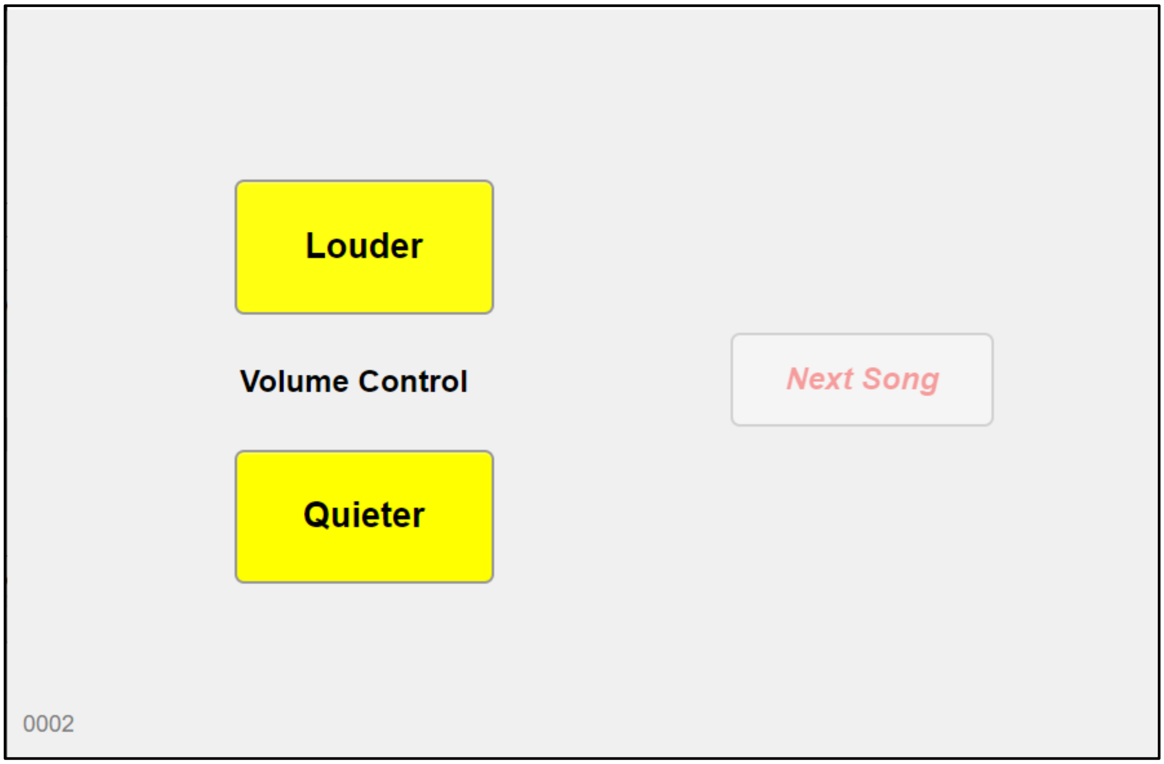
The headphones used in this study were Bose QuietComfort 35 II noise cancelling headphones connected via a cable to a computer running Matlab version R2019a software. The noise cancellation feature of the headphones was left turned on for the entirety of the data collection process. While ambient noise was not a concern during the experiment, active noise cancellation had the added benefit of reducing distortion in the music signal and extending the range of the headphone’s frequency response (D. Gauger, personal communication, October 18, 2020).

In order to verify that the headphones would not risk damage to the participants hearing at higher volume settings, a simulated real ear on a KEMAR manikin was used to collect the dB SPL output of the headphones with a white noise signal. The output of the headphones using a white noise signal at the maximum volume setting (100%) was 98 dBA SPL. Each participant’s maximum listening time for this experiment was 8 minutes (16 stimuli lasting 30 seconds each). According to NIOSH (1998) noise exposure standards, the maximum listening time at 98 dBA is 23 minutes before reaching 100% recommended noise dosage. Therefore, participants could not reach a full noise dosage even if listening at the maximum volume setting for the entire duration of the data collection process.

A custom application and graphical user interface were designed to collect the participants’ volume setting data using Matlab. Upon starting the application for each participant, the program accessed a folder with the experimental songs and created a randomized playlist using all 16 experimental stimuli. The researcher was able to access and run the application from the computer’s main screen while the participant had access to the application’s user interface on a separate monitor screen. The user interface was controlled with a USB mouse and allowed the participant to start the data collection process when ready and then make volume setting adjustments up or down as needed (see Figure 1). The participant was required to listen to all 30 seconds of each musical stimulus before continuing to the next item in the playlist. A separate window was generated that showed the user a progress bar indicating how much time remained to finish their volume setting selection before the song ended. Upon finishing the playlist, the user’s final settings for each stimulus were saved in a Microsoft Excel file version 16.54.

Figure 1

Matlab Graphical User Interface



Listening Conditions and Tasks

For the experimental testing conditions, 30-second segments of three songs were used from the rock, pop, and classical genres based on consistent spectral density characteristics similar to Olive and Welti (2015; see Table 1). Although classical music is traditionally referred to as a "piece," the term "song" will be used in place of "piece" for simplicity. Upon agreement to participate in the study, each participant was additionally asked to provide the song title and artist for one personally preferred song. The experimenter then purchased and downloaded the song for use in the experimental session.

Table 1

Artists and Songs Chosen for the Experiment

Artist	Song Title	Description
Lady Gaga feat. Arianna Grande	"Rain On Me"	Pop
Thin Lizzy	"The Boys Are Back in Town"	Rock
Mozart	"Divertimento in D Major, K. 136 #1 Allegro, performed by the Berliner Philharmoniker Orchestra"	Classical
Any	Any	Listener Preferred Song

All song stimuli used for the listening task underwent loudness normalization according to the International Telecommunications Union (2015) broadcast recommendation of -23 LUFS. The stereo channels for each stimulus were normalized independently to preserve the original mixing quality of each song and ensure proper loudness levels for each stimulus. All song files were converted to .wav files for use with Audacity version 3.0.2 audio editing and recording software. Each of the 4 song options (rock, pop, classical, and preferred) were then paired with 4 filter settings in the Audacity software for a total of 16 randomly presented testing conditions. One setting consisted of a baseline setting with no filtering applied to the source signal and the other three settings consisted of a series of high-pass filters with corner frequencies (CF) at 100-, 173.2-, and 300 Hz. All filters were fourth order high-pass filters with a roll-off of 24 dB per octave. Participants listened to all song stimuli binaurally throughout the data collection process. Figure 2 demonstrates the long-term average spectrum from 0 to 20,000 Hz for the baseline "no filter" rock, pop, and classical song segments with 300 Hz marked as a reference for the corner frequency of one high-pass filter setting. Figure 3 displays the long-term average spectrum from 0 to 2,000 Hz with labels for the 100, 173, and 300 Hz high-pass filter corner frequencies. Table 2 describes the experimental matrix.

Figure 2

Long-Term Average Spectrum from 0 to 20,000 Hz for the Baseline "No Filter" Rock, Pop, and Classical Song Segments

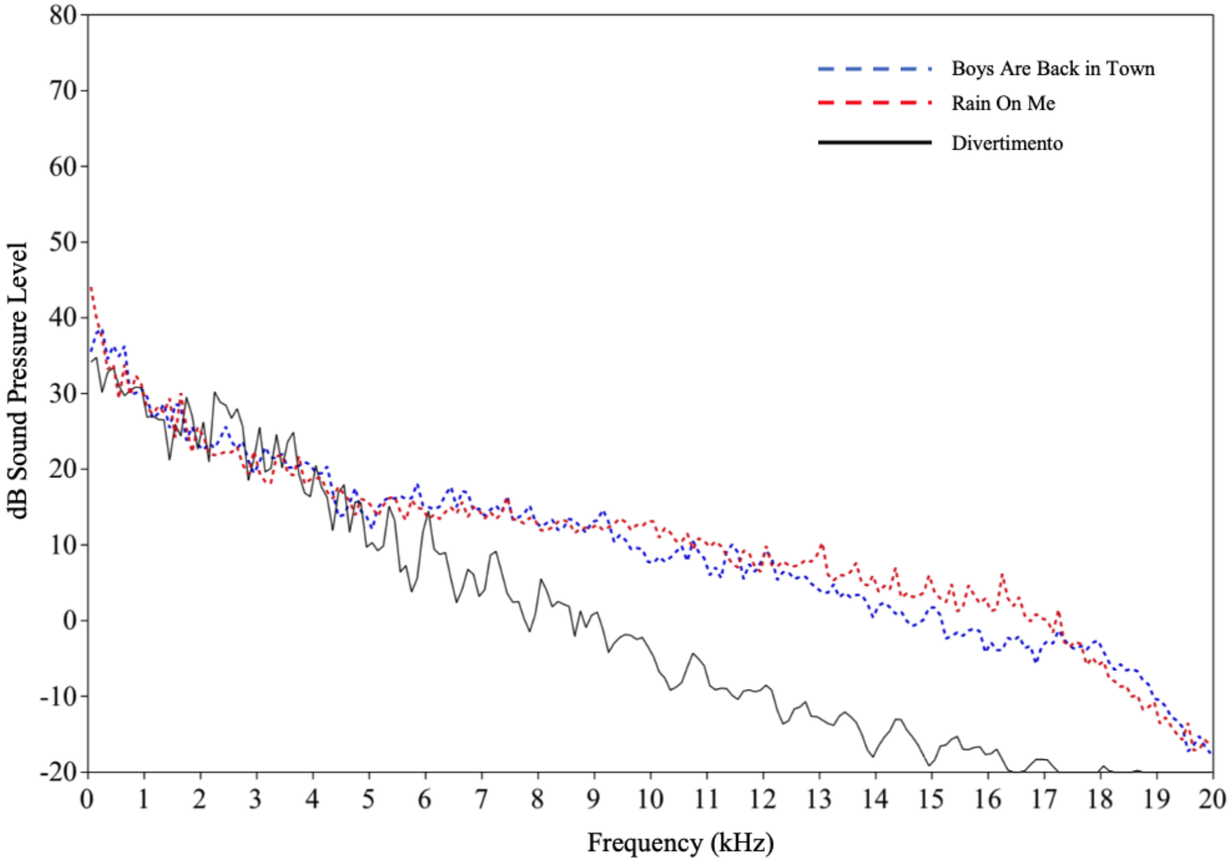


Figure 3

Long-Term Average Spectrum from 0 to 2,000 Hz for the Unfiltered Experimental Stimuli with High-Pass Filter Corner Frequencies for 100, 173, and 300 Hz

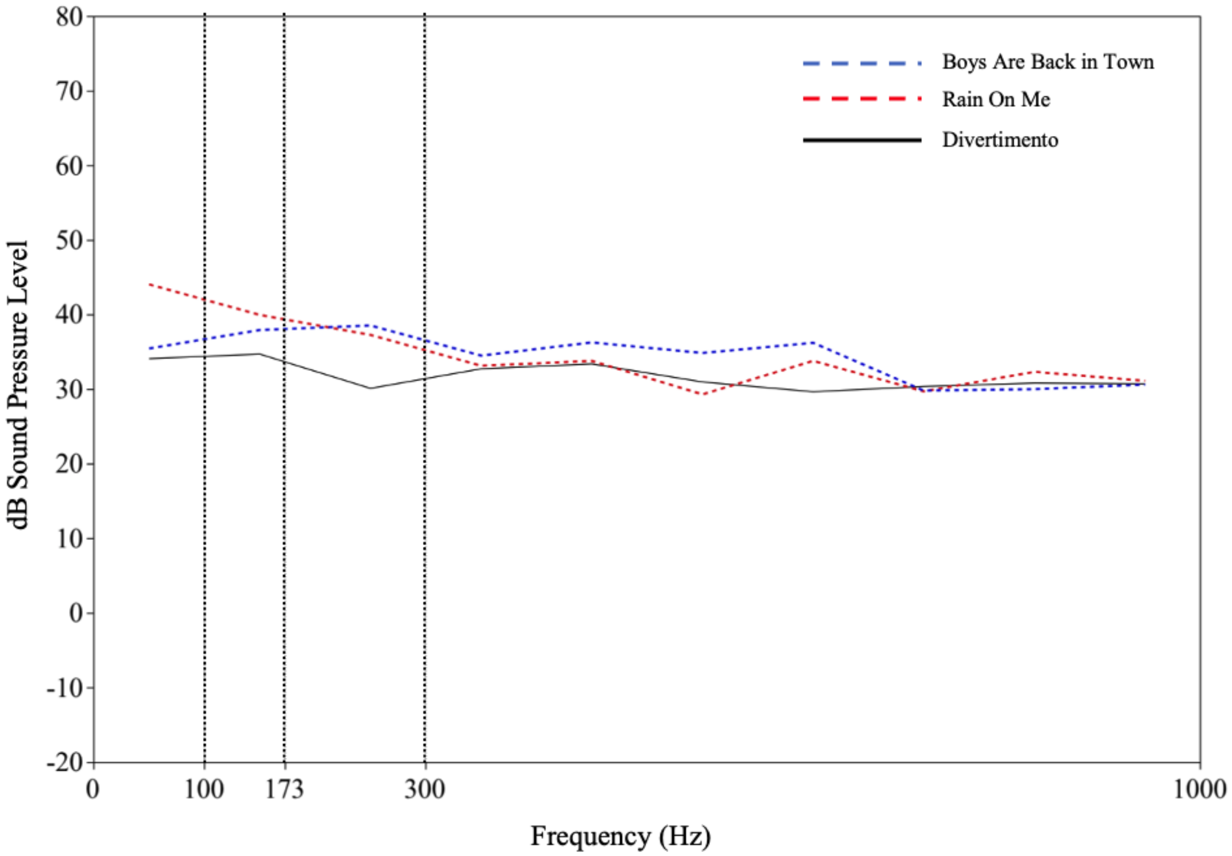


Table 2

Experimental Matrix

Stimuli (presented in random order)	Song	Filter Condition
1	Rain On Me	Baseline--no change
2	Rain On Me	High Pass Filter: 100 Hz CF
3	Rain On Me	High Pass Filter: 173 Hz CF
4	Rain On Me	High Pass Filter: 300 Hz CF
5	The Boys Are Back in Town	Baseline--no change
6	The Boys Are Back in Town	High Pass Filter: 100 Hz CF
7	The Boys Are Back in Town	High Pass Filter: 173 Hz CF
8	The Boys Are Back in Town	High Pass Filter: 300 Hz CF
9	Divertimento	Baseline--no change
10	Divertimento	High Pass Filter: 100 Hz CF
11	Divertimento	High Pass Filter: 173 Hz CF
12	Divertimento	High Pass Filter: 300 Hz CF
13	Preferred	Baseline--no change
14	Preferred	High Pass Filter: 100 Hz CF
15	Preferred	High Pass Filter: 173 Hz CF
16	Preferred	High Pass Filter: 300 Hz CF

The outcome for the volume setting for each condition was measured as a percentage of the total volume control range from 0 to 100%. The initial volume setting was 2.3% of the volume range with increments increasing or decreasing on a logarithmic scale so that the volume changes sounded natural to the listener in terms of loudness growth (Hellman & Zwislocki, 1961; Stevens, 1957). There were 36 potential volume settings in total. All potential volume settings are listed in Table 3.

Data Collection

Prior to beginning the data collection procedure, each participant was verbally given the following instructions:

> You are going to listen to a total of 16 song segments under headphones. These song segments come from 4 different songs. Three of the songs have been chosen by the researcher and one will be your preferred choice of song. You will hear each song segment a total of four times for 30 seconds per song. The order of the song segments has been randomized so you may hear a different song or the same song as you complete the task. Please choose the volume setting that you prefer for each song once the song starts playing. If you are done with your volume selection before the song ends, you may finish listening to the song without making more adjustments. To start the playlist, you will select the “play song” button. Once the segment has finished, you may select the “next song” button to continue on to the next song. You have control over the volume so if the headphones become too loud or uncomfortable, you may turn down the volume or remove the headphones if needed. I will give you a signal to remove the headphones if further instruction is needed.

Table 3

Range of Volume Settings Used for the Data Collection Process in Matlab

Volume Step No.	Volume setting in Matlab as a Function of % of the Full Volume Range
1	0.5
2	0.6
3	0.7
4	0.8
5	1.0
6	1.1
7	1.2
8	1.5
9	1.6
10	1.9
11 (initial setting)	2.3 (initial setting)
12	2.6
13	3.0
14	3.6
15	4.2
16	4.8
17	5.6
18	6.5
19	7.7

Table 3 (continued)

Volume Step No.	Volume setting in Matlab as a Function of % of the Full Volume Range
20	8.9
21	10.3
22	12.0
23	14.0
24	16.2
25	18.9
26	22.0
27	25.6
28	29.8
29	34.6
30	40.3
31	46.9
32	54.6
33	63.5
34	73.9
35	86.0
36	100.0

The participant was then shown how to manipulate the user interface with the mouse and asked to put the headphones on themselves to minimize effects from error in researcher placement (Masiero & Fels, 2011). The participant then began the 16 experimental listening tasks. Upon completion of the tasks, the research facilitator ensured that all responses for the listening tasks were saved in Qualtrics. The participant was then asked to complete the post-test listener survey.

Data Analysis

The data collected from the listening tasks and survey responses were analyzed in percent full scale (PFS), a percentage of the full volume control range, using SPSS Statistics version 27.0 software. A two-way repeated measures analysis of variance (ANOVA) was used to determine if the experimental filtered conditions were statistically significant at the .05 alpha level for effects on the participants' preferred volume in PFS (Girden, 1992). Mauchly's test of sphericity was performed to determine if the data met the assumption that variances were similar between the filter setting and song groups. A post-hoc analysis with a Bonferroni correction was also used to compare the mean volume setting in PFS between the filter setting groups and songs used for this experiment. This analysis also allowed for a comparison of mean volume setting in PFS for each song to determine if the preferred song elicited higher volume settings than the songs chosen by the researcher. Finally, a linear regression model and Pearson Correlation analysis were performed to determine if there was a correlation between the participant's chosen volume settings in PFS for each song and their rating of familiarity for that song (Freedman, 2009).

CHAPTER IV

RESULTS

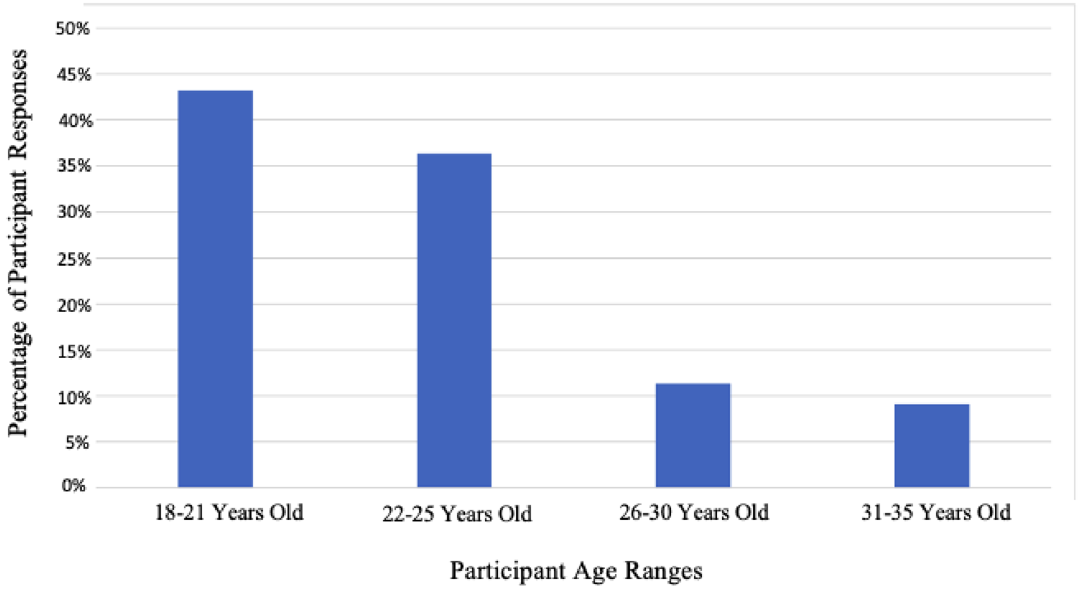
Participants

Participant Demographics

In total, 44 participants were recruited for this study via word-of-mouth and a printed flyer approved by the IRB of the University of Northern Colorado. The participants were 63.6% (*n* = 28) female, 34.1% (*n* = 15) male, and 2.3% (*n* = 1) non-binary. Of the 44 participants who completed the survey, 43.1% (*n* = 19) were aged 18-21 years, 36.3% (*n* = 16) were aged 22-25 years, 15.9% (*n* = 7) were aged 26-30 years, and 9.0% (*n* = 4) were aged 31-35 years (see Figure 4). All participants were screened for hearing thresholds at 20 dBHL or below and passed prior to completing the listening tasks.

Figure 4

Percentage of Participant Survey Responses for Age Range



Participant Survey Responses

Responses to the survey indicated that 68.1% (*n* = 30) of participants preferred listening to music on headphones, 20.5% (*n* = 9) preferred listening with a Bluetooth speaker, 9.0% (*n* = 4) preferred listening through a built-in cell phone or laptop speaker, and 2.2% (*n* = 1) preferred listening through a car stereo (see Figure 5). In choosing their top 3 preferred genres, the majority of participants (90.9%, *n* = 40) ranked the pop, rock, and hip-hop/rap genres as at least one of their most preferred, with 68.1% (*n* = 30) of participants ranking pop, 59.0% (*n* = 26) ranking rock, and 47.7% (*n* = 21) ranking hip-hop/rap (see Figure 6).

Figure 5

Percentage of Participant Survey Responses for Preferred Music Listening Transducer

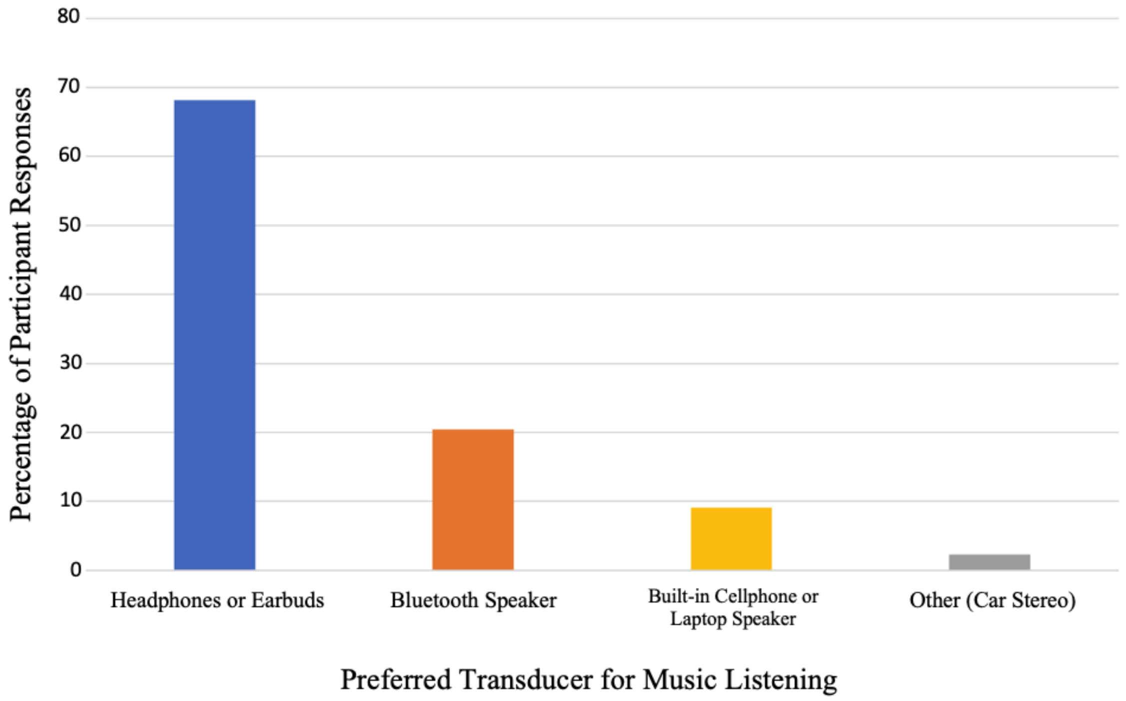
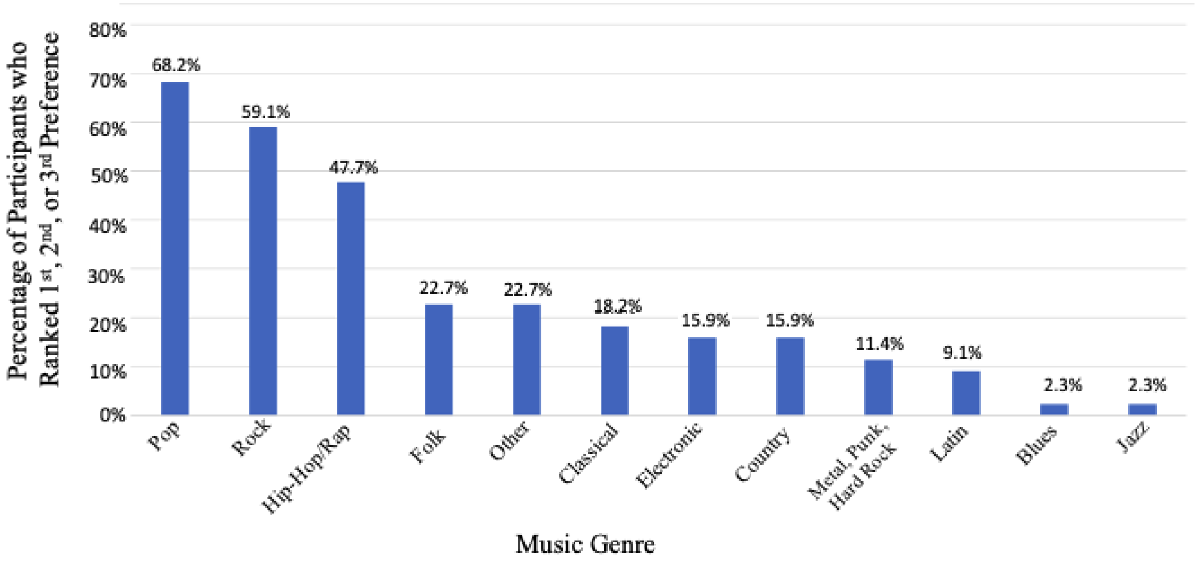


Figure 6

Percentage of Participant Survey Responses for Top Three Genre Ranking



Preferred Listening Levels

Descriptive Statistics

Observed means and standard deviations for each experimental stimulus are reported in PFS in Table 4. An alternate perspective for the analysis would be to convert the data from percentage of the volume range to decibel full scale (dBFS), a measurement of the decibel level for each volume setting relative to the maximum volume setting. In order to observe differences in the data using both methods, figures in the following sections reflect the data in percentage of total volume range and dBFS. It was shown that the observed means for the pop and preferred songs gradually increased from the baseline to the 300 Hz filter setting. Observed means for the rock song varied, with the 100, 173, and 300 Hz filter settings all having lower means than the baseline setting. Observed means for the classical song also varied, with the 100 and 300 Hz filter settings demonstrating higher means and 173 Hz demonstrating a lower mean when compared to baseline. Observed means for the classical song indicated that volume settings for this song were generally lower than the other songs. The greatest difference in observed means occurred when changing from the baseline (no filter) to the 300 Hz filter setting while listening to the preferred song (1.79%), with smaller differences noted for the pop (1.18%), classical (0.56%), and rock songs (0.63%) as compared to baseline. Standard deviations for the rock, pop, and preferred songs were larger than the means for 10 of the 12 filter settings, indicating that there was a lot of variability in the data and volume settings for some participants skewed much higher than the mean.

Table 4

Observed Means and Standard Deviations for the Experimental Stimuli as a Function of Filter Setting

		Volume Setting Chosen (%)		% of Full Volume Range	
Song (Genre)	Filter Setting	Minimum	Maximum	Observed Mean	*SD*
The Boys Are Back in Town (Rock)	No Filter	1.5	29.8	6.66	7.21
	100 Hz	1.2	29.8	6.20	6.33
	173 Hz	1.0	29.8	6.45	6.86
	300 Hz	1.1	22.0	6.03	5.37
Rain On Me (Pop)	No Filter	1.5	40.3	5.60	7.37
	100 Hz	1.6	34.6	5.53	6.18
	173 Hz	1.5	34.6	6.11	6.66
	300 Hz	0.5	29.8	6.78	6.12
Divertimento (Classical)	No Filter	0.8	14.0	3.67	2.58
	100 Hz	0.6	16.2	3.84	3.04
	173 Hz	0.5	10.3	3.63	2.06
	300 Hz	0.5	14.0	4.23	2.89
Preferred Song (Any)	No Filter	1.5	54.6	6.96	9.11
	100 Hz	1.6	63.5	7.47	10.56
	173 Hz	1.6	63.5	7.92	10.30
	300 Hz	1.5	54.6	8.75	10.39

Figure 7 plots estimated marginal means, weighted means based on covariates, in PFS for each filter setting as a function of each experimental stimulus. Figure 8 plots the estimated marginal means of volume settings in dBFS. The estimated marginal means followed the same trend as the observed means.

Figure 7

Estimated Marginal Means of Volume Settings in Percent Full Scale for Each Filter Setting as a Function of Song Stimulus

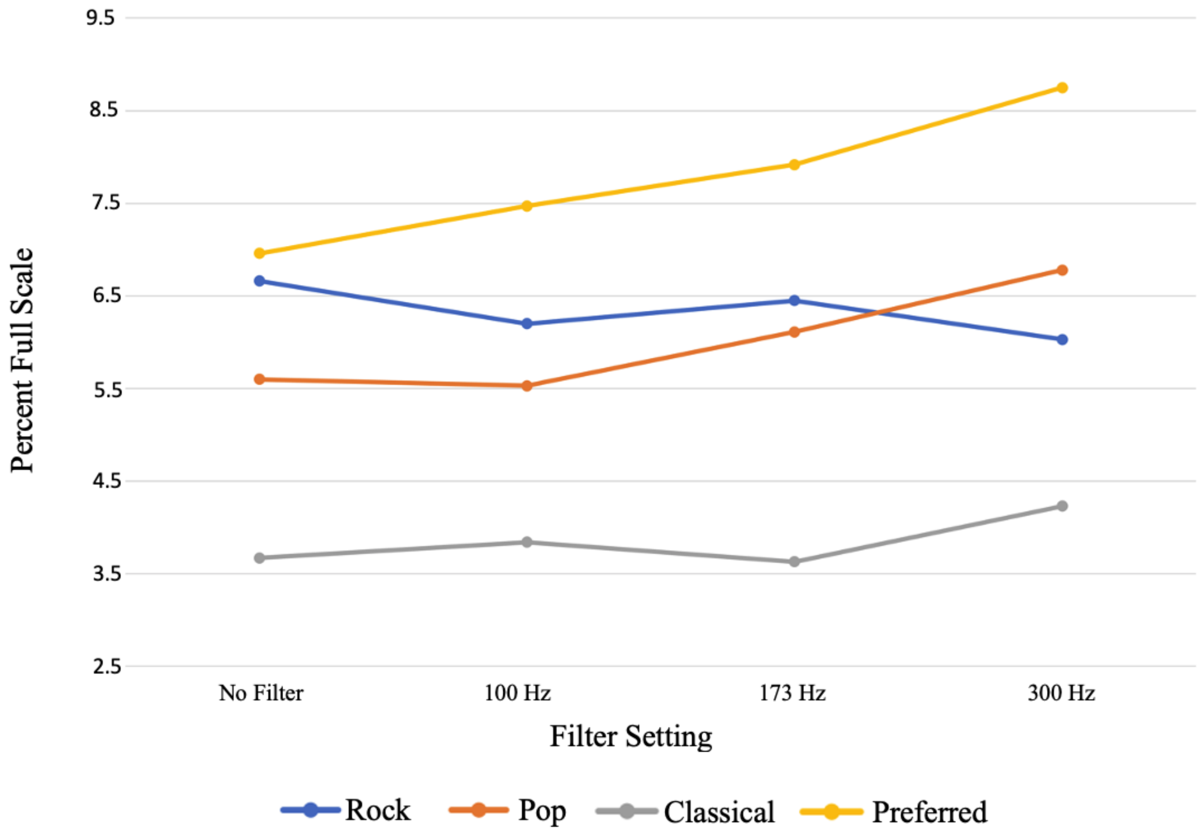
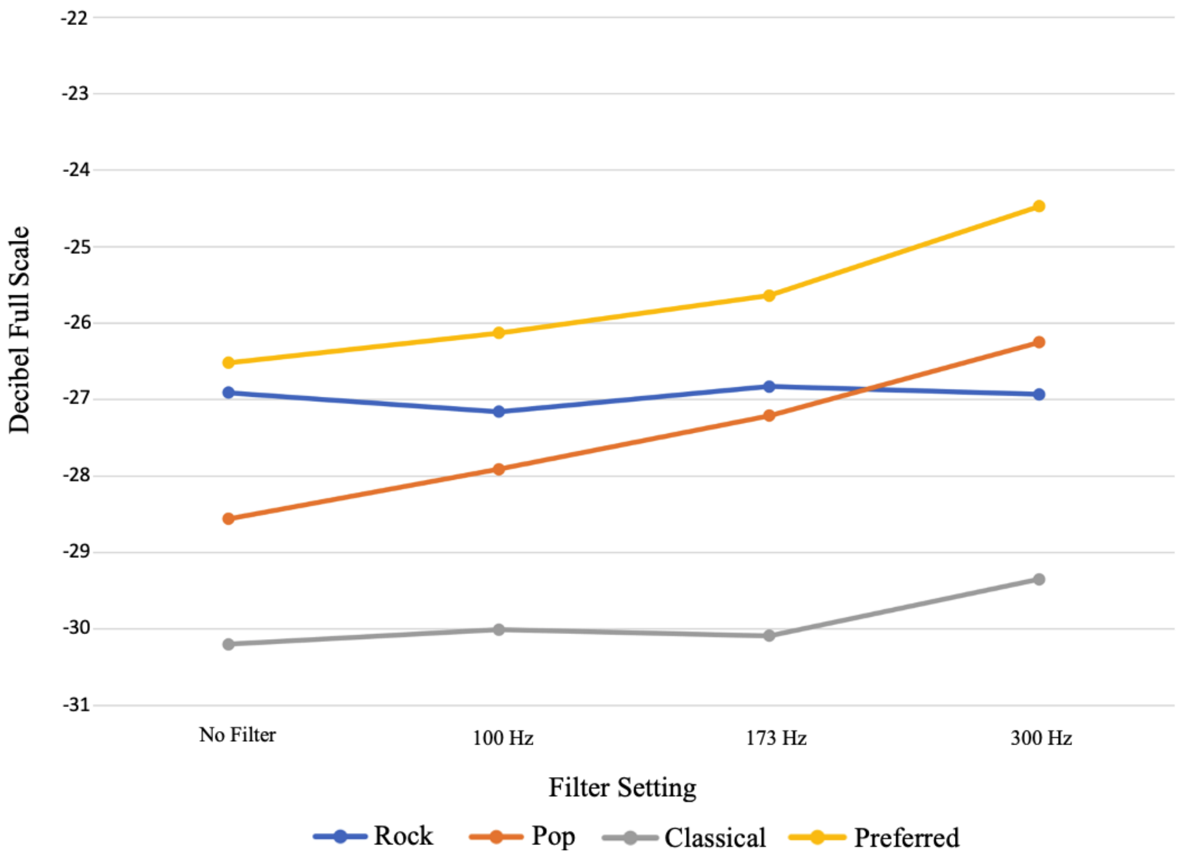


Figure 8

Estimated Marginal Means of Volume Settings in Decibel Full Scale for Each Filter Setting as a Function of Song Stimulus



Figures 9 and 10 plot the overall estimated marginal means in PFS and dBFS, respectively, for volume setting for each filter setting across all four songs. In general, this figure demonstrates that the volume setting increases as more low frequency sound is removed. The increase in volume setting across the filter settings was somewhat curvilinear, with smaller increases from the baseline to 100 Hz filter setting and larger increases from the 173 Hz to the 300 Hz filter setting.

Figure 9

Estimated Marginal Means of Volume Setting in Percent Full Scale for Each Filter Setting Averaged Across All Four Song Stimuli

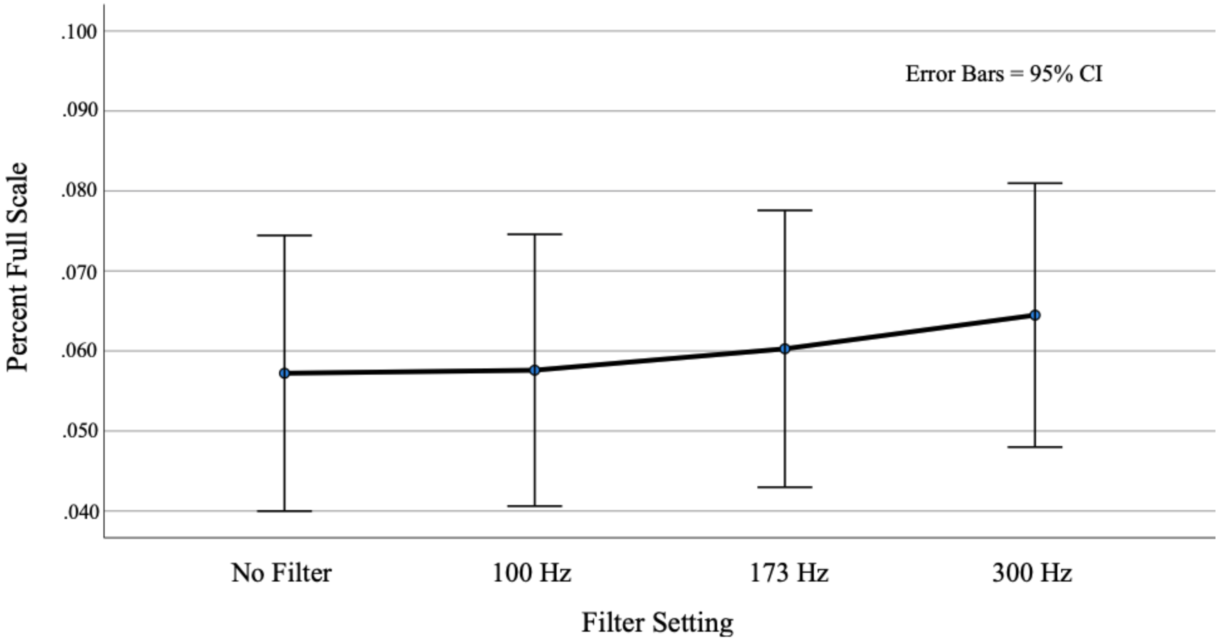
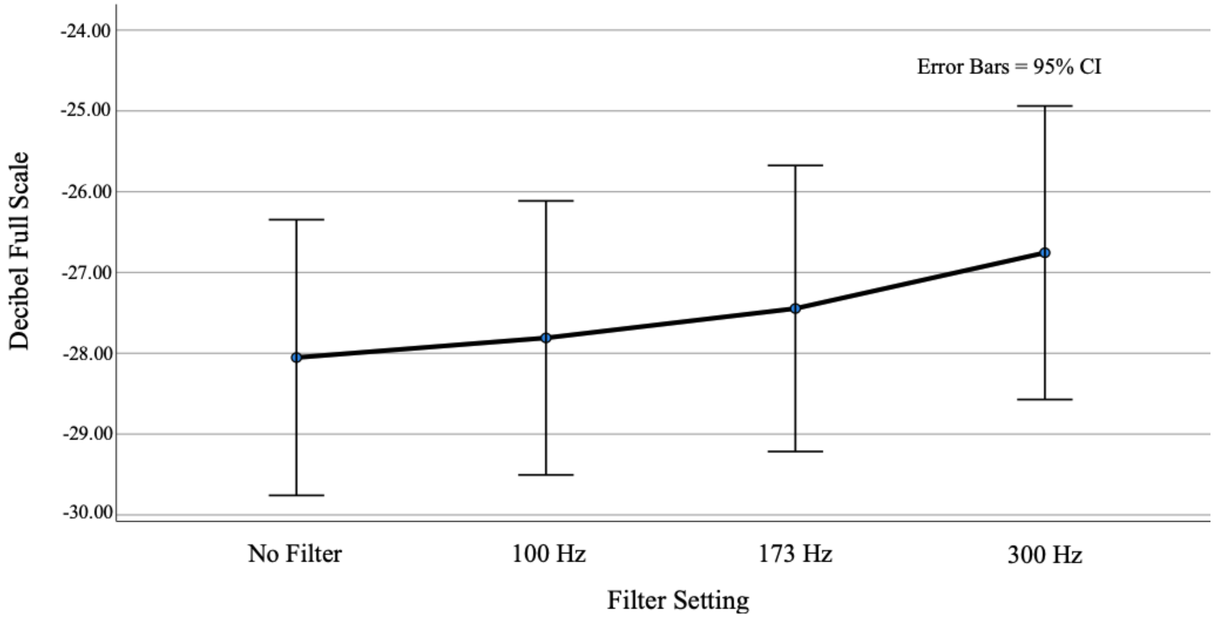


Figure 10

Estimated Marginal Means of Volume Setting in Decibel Full Scale for Each Filter Setting Averaged Across All Four Song Stimuli



Relationship Between Volume and Filter Settings

The 44 participants' chosen volume settings in PFS for all 16 stimuli were compiled for a within-subjects two-way repeated measures ANOVA. In order to interpret the significance of the two-way repeated measure ANOVA, Mauchly's Test of Sphericity must be performed in order to test whether variances of the differences between the song and filter setting groups were the same (see Table 5). The significance for this test was not greater than $p = .05$; therefore, the sphericity assumption was not met for the songs, filter settings, or the interaction between these three groups. Therefore, a Greenhouse-Geisser correction factor for the degrees of freedom (df) was used to determine the significance for differences between the songs, filter settings, and the interaction effects to determine significant changes over time.

Table 5

Mauchly's Test of Sphericity and Within-Subjects Effects for Songs, Filter Settings, and Interactions

Groups	Mauchly's Test of Sphericity	*df* (Greenhouse-Geisser)	*F*-Statistic	*p*-value
Songs	< 0.000	1.678	5.501	.009 *
Filter Settings	0.014	2.473	4.449	.009 *
Interaction Effects	< 0.000	3.916	3.101	.018 *

* Statistically significant for the $p \leq 0.05$ level.

There were significant differences between the four songs ($p = .009$) and the four filter settings ($p = .009$) after applying the Greenhouse-Geisser correction factor. Additionally, the results were significant for interactions between these two groups, indicating that there were significant changes for volume across all songs and filter settings ($p = .018$). Table 6 shows the results for Mauchly's test of sphericity and the significance for within-subjects effects for the songs, filter settings, and interaction effects.

Post-hoc analysis with a Bonferroni adjustment revealed that the classical song was statistically different from the rock song ($p = .013$) and the preferred song ($p = .044$), but no other significant differences were found between the rock, pop, classical, and preferred songs (see Table 6). Furthermore, there was a significant difference between the baseline "no filter" setting and the 300 Hz filter setting ($p = .012$). There were no other significant differences between the filter settings (see Table 7).

Table 6

Post-Hoc Pairwise Comparisons of Mean Difference of Average Volume Setting in Percent Full Scale for Rock, Pop, Classical, and Preferred Songs

Song Comparison (1, 2)	Mean Difference (1-2)	Standard Error	*p*-value
Rock, Pop	0.003	0.005	1.000
Rock, Classical	0.025	0.008	.013 *
Rock, Preferred	-0.014	0.009	.721
Pop, Classical	0.022	0.008	.058
Pop, Preferred	-0.018	0.012	.922
Classical, Preferred	-0.039	0.014	.044 *

* Statistically significant for the $p \leq 0.05$ level.

Table 7

Post-Hoc Pairwise Comparisons of Mean Difference of Average Volume Setting in Percent Full Scale for the Baseline, 100 Hz, 173 Hz, and 300 Hz Filter Settings

Filter Setting Comparison (1, 2)	Mean Difference (1-2)	Standard Error	*p*-value
Baseline, 100 Hz	0.000	0.002	1.000
Baseline, 173 Hz	-0.003	0.002	1.000
Baseline, 300 Hz	-0.007	0.002	.012 *
100 Hz, 173 Hz	-0.003	0.002	.992
100 Hz, 300 Hz	-0.007	0.003	.078
173 Hz, 300 Hz	-0.004	0.003	.701

* Statistically significant for the $p \leq 0.05$ level.

Influence of Song Familiarity

A Pearson Correlation analysis was used to determine to what degree the Likert ratings of song familiarity correlated to the volume settings for the baseline filter setting for each song. A linear regression analysis was also used to determine if the Likert ranking of familiarity could be used to predict volume setting for each song. Only the baseline filter setting values were used in order to eliminate effects from individual variability in terms of how each participant responded to the filtered music.

No significant correlation was found between Likert ranking of familiarity and the baseline volume settings for the rock (p = .473), pop (p = .341), and classical (p = .106) songs. A positive or negative correlation would indicate that volume setting increased or decreased directly with ratings of familiarity. Pearson correlations indicated that there was a very weak negative correlation between rankings of familiarity for “The Boys Are Back in Town” and baseline volume setting for that song (r = -.011), a very weak positive correlation between rankings of familiarity for “Rain On Me” and baseline volume setting for that song (r = .064), and a weak positive correlation between “Divertimento” and baseline volume settings for that song (r = .194). Furthermore, no significant *R*-squared value was found for the linear regression analysis of the rock (p = .946), pop (p = .683), and classical (p = .213) songs. Table 8 reports the values of the Pearson Correlation, the *R*-squared values, and their respective significance values.

Table 8

Pearson Correlation and R-Squared Values for Song Volume Setting in Percent Full Scale and Likert Ranking of Familiarity Using Baseline "No Filter" as the Reference Value

Song	Pearson Correlation I	*p*-value	*R*-Squared	*p*-value
The Boys are Back in Town (Rock)	-.011	.473	.000	.946
Rain On Me (Pop)	.064	.341	.004	.683
Divertimento (Classical)	.194	.106	.038	.213

Summary

As outlined in Chapter 1, the following were the research questions proposed in this study:

Q1 Is there a significant relationship between listeners' volume setting for music and the low frequency response of the signal?

Q2 Does a listener's preferred song result in higher volume settings compared to the experimental songs?

Q3 Is a listener's rating of familiarity of a song associated with listener preferred volume setting for that song?

The first part of this analysis was performed to determine the relationship between the listener preferred volume setting and the amount of low frequency sound present in the experimental songs. Additionally, observed means were used to determine if there were significant differences between the average volume setting for the songs chosen by the researcher and the preferred song chosen by each participant. A two-way repeated measures ANOVA analysis was used to demonstrate that there were significant differences between the songs (p = 0.009) and the filter settings that removed low frequency sound (p = 0.009), as well as interaction effects between these groups (p = 0.018). A post-hoc analysis revealed that there were significant differences between the classical song and the rock songs (*p* = 0.013), and between the classical song and the preferred song (*p* = 0.044). The observed means for the classical song indicated that volume settings were lower for that song than for the rock and preferred songs (see Table 4, Figure 7). There were also significant differences between the baseline “no filter” filter setting and 300 Hz filter settings (*p* = .012).

The second part of the analysis was intended to determine if there was any relationship between the listener selected volume setting for each pre-selected song and the Likert ranking of familiarity in the post-test survey. A positive or negative correlation would indicate that ranking of familiarity with a song directly correlated with volume settings for that song. A regression analysis revealed that there were no significant correlations between the volume setting and Likert ranking of familiarity from the survey (see Table 8). The Pearson correlation indicated very weak correlation values between the volume settings and rankings of familiarity for “The Boys Are Back in Town” (*r* = -.011) and “Rain On Me” (*r* = .064), and a weak positive correlation was found between volume settings and ranking of familiarity for “Divertimento” (*r* = .194).

CHAPTER V

DISCUSSION

Preferred Listening Levels

Low Frequency Sound and Preferred Listening Level

Previously, researchers have investigated how listeners choose their PLL by looking at factors such as external noise, music listening devices, and demographic information (i.e., Fligor et al., 2014; Hodgetts et al., 2007; Portnuff et al., 2011). Alternatively, this study was primarily focused on how the quality of the music signal in terms of low frequency response could have an effect on PLL. Thus far, only one other researcher has cursorily investigated the relationship between low frequency energy and PLL. Olive et al. (2016) showed how a poor fit with insert earphones led to leakage of low frequency energy out of the ear canal and increased PLLs for study participants. However, there was no precise control for how much low frequency energy was lost and a detailed relationship between the presence of low frequency energy and PLL could not be determined. This study implemented a non-filtered baseline setting and three high-pass filter settings with CFs at 100, 173, and 300 Hz to determine if a gradually increasing loss of low frequency energy in a music stimulus would cause the participant to choose higher PLLs. The data demonstrated that there was a gradual increase in PLL as a function of a percentage of the volume range from the baseline to the 300 Hz filter setting on average across all 43 participants. Although, the only statistically significant increase in PLL from baseline was for the 300 Hz filter setting (p = 0.012).

The finding from the data analysis suggested that absence of low frequency energy in music did indeed cause listeners to increase the volume setting on average. The real-world implications of this finding are that listeners who use devices that have a poor low frequency response or allow low frequencies to leak out of the ear (i.e., poorly fit insert earphones) could be increasing volume to compensate for the loss of low-frequency energy. Additionally, the use of noise cancellation in headphones may change the low frequency response of the music and affect how a listener chooses their PLL (Liang et al., 2012; D. Gauger, personal communication, October 18, 2020). The gradual increase in PLL as low frequency energy was removed likely correlated to the stimulation of the auditory filters along the basilar membrane. As fewer auditory filters were stimulated, it became more likely that the listener would notice the change and adjust their PLL. Moreover, the nonlinear growth in PLL may correlate to the nonlinear growth in critical bandwidth and lack of efficiency for auditory processing at low frequencies (Patterson & Moore, 1986).

It should be noted that the gradual increase in PLL across the filter settings was not found for all participants. In fact, observations from the data showed that some participants decreased volume as more low frequency energy was removed. A small number of participants made no changes to their PLL regardless of filter setting. Furthermore, some participants could be categorized as “quiet” or “loud” listeners in that they tended to listen at lower or higher than average volumes for all filter settings.

Song Preference and Preferred Listening Level

In the past, few researchers have considered the effect of song or genre preference when measuring PLLs. Hodgetts et al. (2007) and Fligor et al. (2014) took field recordings of participants PLDs in the moment to measure real-world PLLs with music that the listener supposedly preferred. However, neither experiment allowed the participant to listen to other genres for comparison. Almeida et al. (2020) did allow participants to choose one preferred song for the experiment and found no significant differences in PLL for the preferred and non-preferred songs.

The current study was unique in that it included frequency response changes to the same music segments over time; therefore, a preferred song was incorporated into the experiment to determine whether participants were more sensitive to these changes in their preferred song compared to the songs chosen by the researcher. Observed means from the data showed that the preferred song correlated to higher PLLs than the other three songs used in the experiment and that the preferred song had the greatest increase between the baseline non-filtered setting and the 300 Hz high-pass filter setting. Nevertheless, the only statistically significant difference reported in the data analysis was for the classical song, which was significantly lower in PLL than the rock ($p = 0.013$) and preferred ($p = 0.044$) songs. This finding contrasted with Fligor et al. (2014) where there were no differences noted for PLL between genres. It is important to note that the low-frequency sound removed from the classical song was less than that from the rock or pop song, particularly from 173 to 300 Hz (see Figure 3).

Overall, the data from this experiment suggested that genre preference may not have any influence in how a listener chooses their PLL for music. This was similar to the results found by Almeida et al. (2020). One issue in the current study was that there was a lot of potential variability for genre within the participants' preferred song selections. Genres selected by participants included pop, rock, classic rock, folk, country, and instrumental music. The preferred songs likely had differing characteristics based on low frequency content in the music and how the song was mixed. Therefore, changes in the low frequency energy in the music may have only been noticeable to the participant given enough low frequency energy present in the original mix of the song and the participant's preference for hearing bass in their music. Some genres such as folk or non-classical instrumental music may also be generally preferred to be heard at lower-than-average volumes in a similar manner as the classical song in this study.

Song Familiarity and Preferred Listening Level

In prior laboratory studies on PLL or noise dosage measurement, researchers have carefully chosen songs for their experiments based on several factors including popularity to limit effects on PLL choice from song preference (i.e., Hammershoi et al., 2016; Hodgetts et al., 2007). This study also used songs for the listening tasks in part based on the likelihood that the participant would be familiar with the song. A question asked in the current study was whether familiarity with a song would correlate with PLL to help determine the value of considering popularity when choosing an experimental song stimulus.

A Pearson correlation analysis of the participants' PLL and Likert ranking of familiarity revealed no significant relationship for the rock, pop, or classical songs. These results suggested that familiarity may not be an important factor when considering song stimuli for PLL measurement in the laboratory. Songs in the current study and past similar studies were selected based on additional factors such as spectral density and amplitude characteristics (i.e., Hammershoi et al., 2016; Hodgetts et al., 2007; Olive & Welti, 2015). One issue with choosing "familiarity" as the ranked characteristic was that it did not necessarily imply preference for a song, only that the participant knew of the song or had heard the song previously. However, given that preference for a song was considered in the listening tasks for this study, including ranking of the participants' familiarity with the songs chosen could help tease out this nuance. Overall, the analysis of the results for both the preferred song and familiarity with the songs chosen for the experiment suggested that personal preference or familiarity for an experimental music stimulus likely had little influence on PLL.

Study Limitations

This study was intended to be a pilot study to investigate the possible effects of low frequency sound on PLL and inform future research directions in the area of PLL measurement. Therefore, one limitation of the current study was the small sample size (*n* = 44), which did not meet the required number to apply the results to the larger population.

Because the preferred song had to be clipped and filtered by the researcher just prior to the data collection process, the first 30 seconds of active playback was universally chosen for all preferred songs regardless of spectral and amplitude characteristics. This led to an unknown amount of variability between the preferred songs and possible researcher error given that the stimuli had to be filtered in the moment. A checklist was used during the creation of the preferred song stimuli in attempts to limit errors.

The concept of genre can be limiting in research as the genre label for a piece of music may change depending on who is assigning the label. Some genres, such as “rock” or “pop,” span such a broad range of musical sounds, subgenres, and cultures that it can be extremely difficult to identify a song that fits any prototypical mold for “rock” or “pop.” Therefore, one major limitation of this study was that each genre category selected for the experiment included only one song from that genre. The logistical decision to limit the number of songs per genre to one was intended to simplify the data collection and analysis process for this study. However, it was likely that the songs chosen did not meet every participant’s subjective definition of a “rock” or “pop” song, in turn affecting how they chose their PLL.

Lastly, while the headphones and equipment used in the data collection process remained consistent across all participants, the headphones were not calibrated for output between data collection sessions and days. While it was possible that the headphone performance could have varied from one participant to another, it should not have changed the outcomes as the data were analyzed within-subjects rather than between subjects.

Study Strengths

Prior researchers in the area of PLL measurement have been concerned primarily with other factors such as external noise, headphone type, headphone fit, and demographic factors. One strength of this study was that it was the first known study to investigate how changes to the quality of the music signal itself could affect a listener's PLL. The study controlled for age-related variability in listening behavior by limiting the age range of participants to a younger population of university students. Additionally, this study benefitted from the use of noise cancellation technology to extend the low frequency response of the headphones.

Future Directions

The data analysis in this study was primarily concerned with evaluating whether changes in low frequency energy in a music signal would lead to higher PLLs for participants. While it was found that participants did tend to increase their PLL on average, observations from the data revealed that some participants responded in the opposite direction or not at all. In order to clarify how listeners may respond to the removal of low frequency sound from music, future investigations might consider an analysis that investigates changes either up or down in volume setting from the baseline condition, rather than just an analysis of the mean volume setting for each filter category. Moreover, they could investigate what participant characteristics could explain why they turned the volume setting down rather than up or made no changes at all. For example, people who are trained musicians or who typically listen to music with higher quality equipment might more easily recognize when a music signal has been degraded and turn the volume setting down in response to a filter/bass change they find unpleasant. Conversely, a listener who is only accustomed to listening to music through transducers with poor frequency response may not notice any change or may be less inclined to change their PLL as low frequency sound is removed. Given that there was already a documented effect on PLL from factors such as headphone style, headphone fit, and external noise, future researchers could investigate whether combining these conditions with changes in the low frequency content of music might lead to even greater changes in PLL.

The significance of using a preferred song when measuring PLLs remained somewhat unclear from the results found in this study. While there were no statistically significant differences between the preferred song and the songs chosen by the researcher, observational means of the preferred listening levels for the preferred song were higher than the other songs. A larger sample size may be needed to fully clarify if any differences might exist. Nevertheless, future researchers may consider incorporating a participant chosen song in their research should time and resources allow it as there could still be the possibility that the preferred song could more accurately elicit real-world responses. If a preferred song was used, the researchers may also consider limiting the genres that the participant could select in hopes that they might avoid music choices such as classical music that elicit overall quieter PLLs or that lack emphasis in low frequency sound. For example, they might prompt the participant to choose their favorite upbeat song or a song they prefer for dancing or exercise.

Summary

The purpose of this study was to investigate the relationship between a listener’s PLL and the amount of low frequency sound in music. The study also investigated the relationship between a listener’s PLL, their music preference, and familiarity with the songs used in the experiment.

The results from this study demonstrated that low frequency sound has the potential to influence listening behavior. On average, the participants in this study increased their PLL as low frequency sound was removed, although a significant difference was only noted for the 300 Hz filter setting. This may have real-world implications, including higher listening levels for those who listen with transducers that have a poor low frequency response due to poor sound quality or fit in the ear. However, it is possible that this average increase in volume setting did not describe all the effects taking place as more filtering was applied. To identify all the other potential effects of removing low frequency sound goes beyond the scope of this pilot study. Future research may attempt to identify all varieties of listener reactions to this experiment and what characteristics might help explain their behavior.

This study did not demonstrate that using a preferred or familiar song could cause listeners to choose a significantly higher PLL. It was not clear whether the genre and low frequency content of the songs selected by the participants affected the overall results in the current study. It could be possible that a different experimental approach or limitations on the type of song that could be selected would lead to different results when allowing for a preferred song. Further research and a larger sample size could aid in confirming whether a preferred song could have any significant effect on PLL.

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APPENDIX A

PARTICIPANT CONSENT FORM

CONSENT FORM FOR HUMAN PARTICIPANTS IN RESEARCH
UNIVERSITY OF NORTHERN COLORADO

Project Title: The Effect of Low Frequency Sound on Listening Level
Researcher: Sam Pennington, Au.D. Graduate Student
Phone: (xxx) xxx-xxxx
E-mail:

The primary purpose of this study is to determine the degree to which the absence or presence of low frequency sound in music affects the listener's volume setting for different music genres.

After signing this consent form, you will be asked to provide a preferred song to be used during the experiment that the researcher will purchase and download. You will then undergo a hearing screening where the researcher or an audiology graduate clinician will perform otoscopy and test your hearing with pure tones to determine that your auditory sensitivity falls within normal limits for hearing. After the hearing screening, you will fill out a brief on-line survey (Qualtrics) to provide some information regarding basic demographics (age and sex), preferred music genres, typical devices used for music listening, and musical or audio engineering training.

After filling out the first survey, I will instruct you on how to manipulate the volume control and place the headphones on your own ears in order to complete the listening task. For the listening task, you will first hear a practice song in order to practice adjusting the volume. You will then hear 16 different song segments and will be asked to adjust the volume setting for each song segment to your preferred setting. Once you have completed setting the volume for all 16 song segments, I will signal you to remove the headphones. If you experience discomfort at any time during the listening task, you may remove the headphones. After removing the headphones, you will be asked to complete a second survey to report your familiarity with the songs chosen by the researcher.

We will not be collecting any personally identifiable information and all information will be stored under a unique subject identification number. Outcomes of the survey will be shared with our research partners at Bose Corporation. Consent forms are stored separately in a locked file cabinet in the primary researcher's laboratory. There will be no connection between the consent form name and the data collected via Qualtrics.

Potential risks in this project are minimal. There are no greater risks than those during routine listening with consumer headphones. The initial volume setting for the headphones will be at a soft, comfortable level. You will not be able to adjust the volume for the headphones to levels loud enough to potentially damage your hearing. You are welcome to stop listening at any point in time should you desire. There are minor benefits to you for participating in this study, you will have a chance to experience listening to music, including your preferred song, with noise-cancelling headphones and receive a $5 gift card to Starbucks.

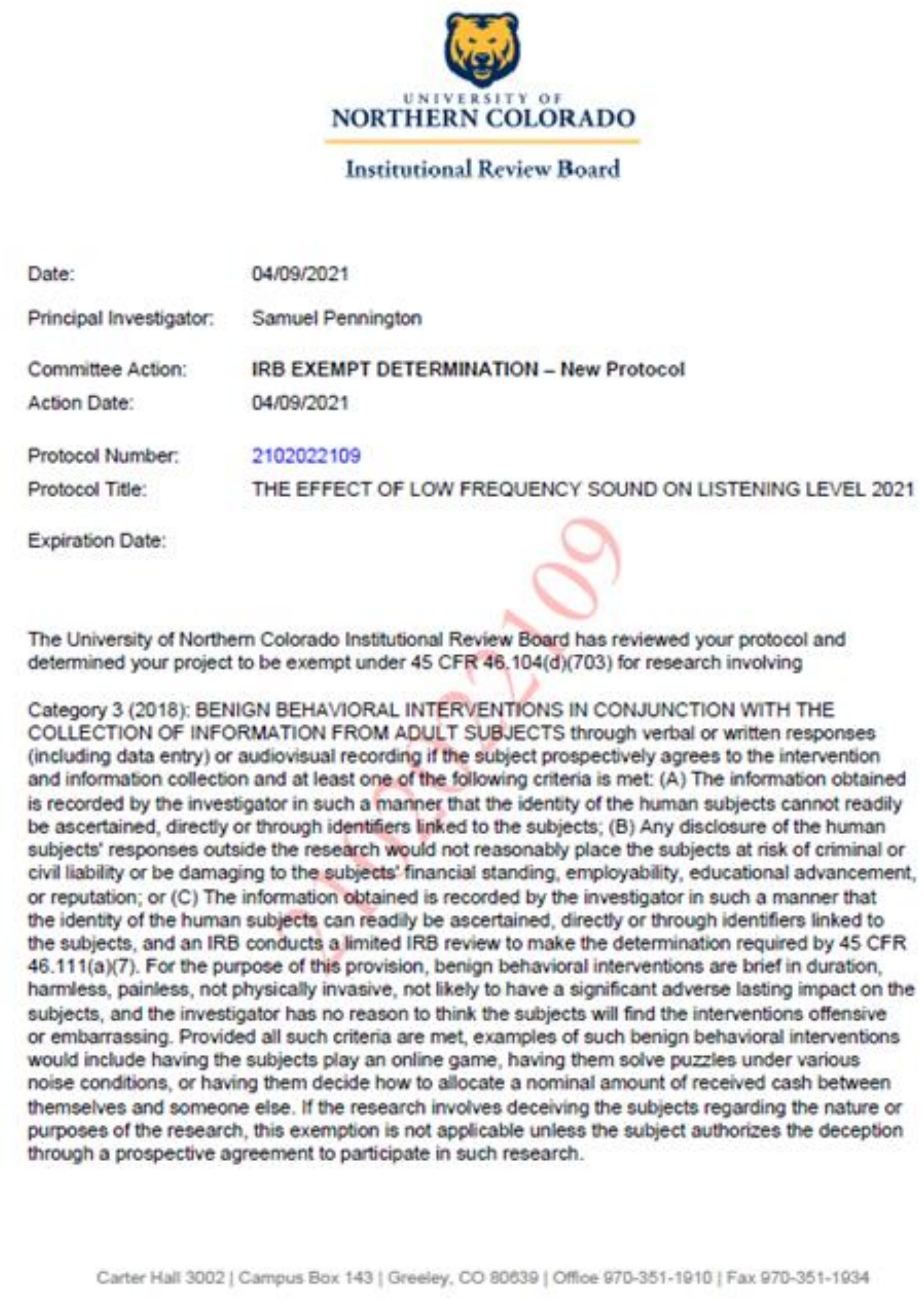
Participation is voluntary. You may decide not to participate in this study and if you begin participation, you may still decide to stop and withdraw at any time. Your decision will be respected and will not result in loss of benefits to which you are otherwise entitled. Having read the above and having had an opportunity to ask any questions, please sign below if you would like to participate in this research. A copy of this form will be given to you to retain for future reference. If you have any concerns about your selection or treatment as a research participant, please contact Nicole Morse, Office of Research, Kepner Hall, University of Northern Colorado Greeley, CO 80639; 970-351-1910.

______________________________________ ____________
Subject’s Signature Date

______________________________________ ____________
Researcher’s Signature Date

APPENDIX B

INSTITUTIONAL REVIEW BOARD APPROVAL



UNIVERSITY OF
NORTHERN COLORADO

Institutional Review Board

Date: 04/09/2021

Principal Investigator: Samuel Pennington

Committee Action: **IRB EXEMPT DETERMINATION – New Protocol**

Action Date: 04/09/2021

Protocol Number: 2102022109

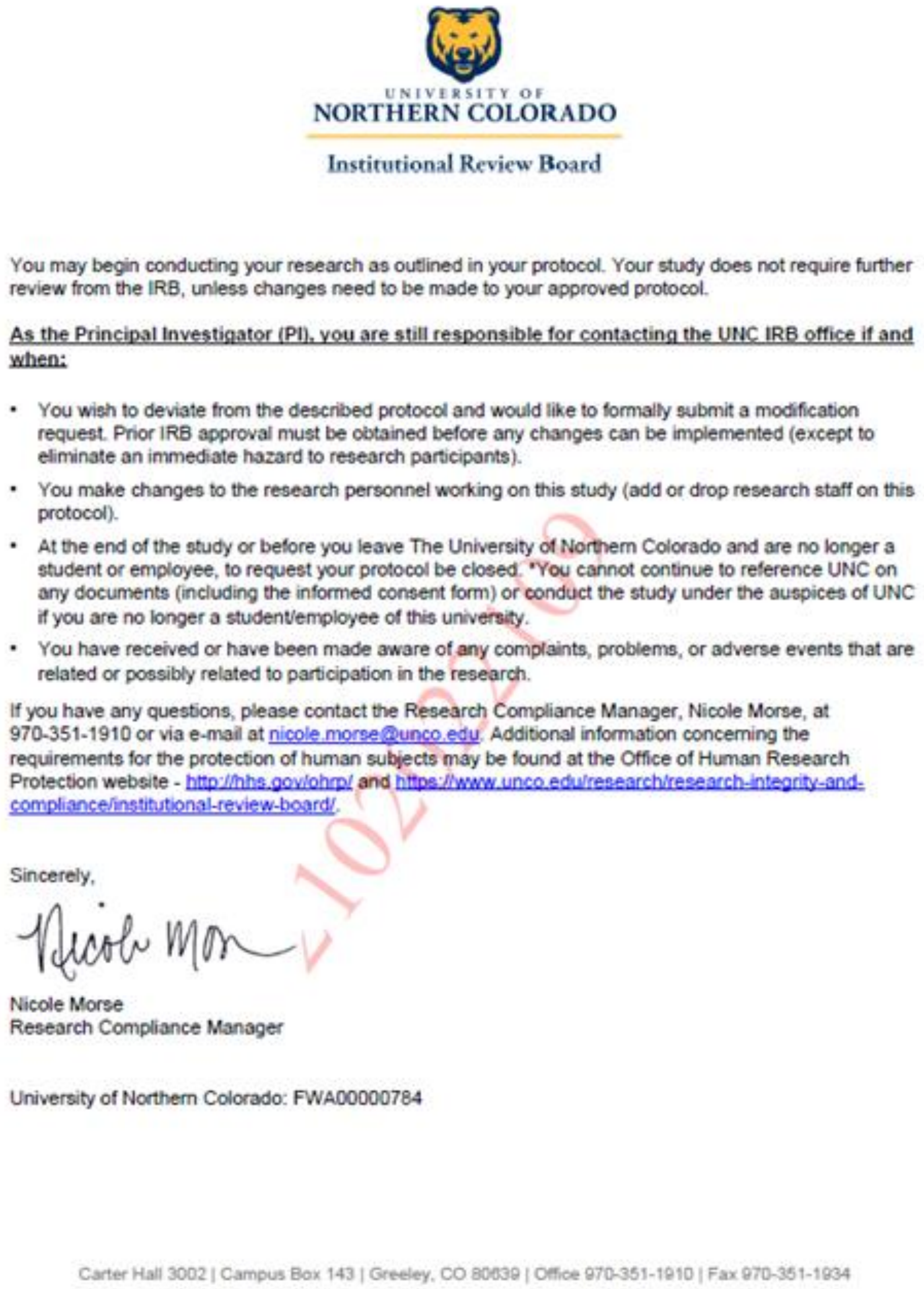
Protocol Title: THE EFFECT OF LOW FREQUENCY SOUND ON LISTENING LEVEL 2021

Expiration Date:

The University of Northern Colorado Institutional Review Board has reviewed your protocol and determined your project to be exempt under 45 CFR 46.104(d)(703) for research involving

Category 3 (2018): BENIGN BEHAVIORAL INTERVENTIONS IN CONJUNCTION WITH THE COLLECTION OF INFORMATION FROM ADULT SUBJECTS through verbal or written responses (including data entry) or audiovisual recording if the subject prospectively agrees to the intervention and information collection and at least one of the following criteria is met: (A) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects; (B) Any disclosure of the human subjects' responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation; or (C) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects can readily be ascertained, directly or through identifiers linked to the subjects, and an IRB conducts a limited IRB review to make the determination required by 45 CFR 46.111(a)(7). For the purpose of this provision, benign behavioral interventions are brief in duration, harmless, painless, not physically invasive, not likely to have a significant adverse lasting impact on the subjects, and the investigator has no reason to think the subjects will find the interventions offensive or embarrassing. Provided all such criteria are met, examples of such benign behavioral interventions would include having the subjects play an online game, having them solve puzzles under various noise conditions, or having them decide how to allocate a nominal amount of received cash between themselves and someone else. If the research involves deceiving the subjects regarding the nature or purposes of the research, this exemption is not applicable unless the subject authorizes the deception through a prospective agreement to participate in such research.

Carter Hall 3002 | Campus Box 143 | Greeley, CO 80639 | Office 970-351-1910 | Fax 970-351-1934



UNIVERSITY OF
NORTHERN COLORADO

Institutional Review Board

You may begin conducting your research as outlined in your protocol. Your study does not require further review from the IRB, unless changes need to be made to your approved protocol.

As the Principal Investigator (PI), you are still responsible for contacting the UNC IRB office if and when:

- You wish to deviate from the described protocol and would like to formally submit a modification request. Prior IRB approval must be obtained before any changes can be implemented (except to eliminate an immediate hazard to research participants).
- You make changes to the research personnel working on this study (add or drop research staff on this protocol).
- At the end of the study or before you leave The University of Northern Colorado and are no longer a student or employee, to request your protocol be closed. *You cannot continue to reference UNC on any documents (including the informed consent form) or conduct the study under the auspices of UNC if you are no longer a student/employee of this university.
- You have received or have been made aware of any complaints, problems, or adverse events that are related or possibly related to participation in the research.

If you have any questions, please contact the Research Compliance Manager, Nicole Morse, at 970-351-1910 or via e-mail at nicole.morse@unco.edu. Additional information concerning the requirements for the protection of human subjects may be found at the Office of Human Research Protection website - http://hhs.gov/ohrp/ and https://www.unco.edu/research/research-integrity-and-compliance/institutional-review-board/.

Sincerely,

Nicole Mor

Nicole Morse
Research Compliance Manager

University of Northern Colorado: FWA00000784

Carter Hall 3002 | Campus Box 143 | Greeley, CO 80639 | Office 970-351-1910 | Fax 970-351-1934

APPENDIX C

HEARING SCREENING REFERRAL FORM

HEARING SCREENING REFERRAL FORM

OTOSCOPY

Right Ear:

Clear_______ Partial Blockage_______ Total Blockage_______

Left Ear:

Clear_______ Partial Blockage_______ Total Blockage_______

HEARING SENSITIVITY (P = PASS, R = REFER)
Tones were presented at 20 dBHL

Right Ear:

125HZ____ 250Hz____ 500Hz____ 1000Hz____ 2000Hz____ 4000Hz____ 8000Hz____

Left Ear:

125HZ____ 250Hz____ 500Hz____ 1000Hz____ 2000Hz____ 4000Hz____ 8000Hz____

Given these results, it is advised that you follow-up with one or more of the following healthcare providers:

Primary Care Physician ______

Ear-Nose-Throat Specialist ______

Audiologist ______

If you have any questions regarding the tests we conducted today or the status of your hearing, please do not hesitate to contact the researcher or the UNC Speech and Audiology clinic.

CONTACT INFO

Researcher:

Sam Pennington
(xxx) xxx-xxx

UNC Speech and Audiology clinic:

Located in the basement of Gunter Hall
1828 10th Ave., Greeley, CO 80639
(970) 351-201

APPENDIX D

PRE-TEST SURVEY

PRE-TEST SURVEY

The following survey questions are intended to collect some non-identifying demographic information and any prior experiences with music listening. Please answer the questions to the best of your ability. If you are unsure how to answer a question, please ask the research facilitator for assistance.

1. What is your sex?

   ○ Male
   ○ Female
   ○ Intersex

2. What is your age?

   ○ 18 – 21 years old
   ○ 22 – 25 years old
   ○ 26 – 30 years old
   ○ 31 – 35 years old

3. Please rate your three favorite music genres in order of preference, with a 1 indicating the most preferred genre:

   _____ Hip-Hop/Rap
   _____ Pop
   _____ Rock
   _____ Metal, Punk, Hard Rock
   _____ Blues
   _____ Country
   _____ Latin
   _____ Electronic
   _____ Jazz
   _____ Classical
   _____ Folk
   _____ Other (Please specify ___________)

4. What type of device do you use most often to listen to music?

   - ○ Headphones or earbuds
   - ○ Built-in cell phone or laptop speaker
   - ○ Bluetooth Speaker
   - ○ Home stereo
   - ○ Other (please specify) ___________________

5. What is the make and model of headphones that you use most often? If you do not know the make or model, please as the research facilitator for assistance.

   Make ____________________

   Model ____________________

   Other (specify type) ____________________

6. Are you a trained musician or training to be a musician?

   YES NO

7. Are you an audio engineer or training to be an audio engineer?

   YES NO

APPENDIX E

POST-TEST SURVEY

POST-TEST SURVEY

Please rate your familiarity with the song on a scale of 1 to 5, where 1 indicates you are not at all familiar with the song and 5 indicates you are extremely familiar with the song.

Rock Song – “The Boys Are Back in Town” by Thin Lizzy

Please rate your familiarity with this song

Not Familiar at All				Extremely Familiar
1	2	3	4	5

Pop Song – “Rain On Me” by Lady Gaga feat. Ariana Grande

Please rate your familiarity with this song (circle one)

Not Familiar at All				Extremely Familiar
1	2	3	4	5

Classical Song – “Divertimento in D Major, K. 136 #1 Allegro” performed by the Berliner Philharmoniker Orchestra

Please rate your familiarity with this song (circle one)

Not Familiar at All				Extremely Familiar
1	2	3	4	5

APPENDIX F

RAW DATA

Table 9

Participant Chosen Volume Settings for the Rock and Pop Songs

Participant No.	Rock				Pop			
	No Filter	100 Hz	173.2 Hz	300 Hz	No Filter	100 Hz	173.2 Hz	300 Hz
001	0.036	0.042	0.036	0.036	0.036	0.036	0.026	0.056
002	0.048	0.048	0.056	0.048	0.077	0.048	0.056	0.056
003	0.023	0.023	0.03	0.03	0.023	0.026	0.03	0.036
004	0.023	0.023	0.03	0.026	0.016	0.023	0.023	0.036
005	0.036	0.036	0.048	0.056	0.03	0.042	0.048	0.048
006	0.023	0.023	0.023	0.023	0.023	0.023	0.026	0.023
007	0.036	0.03	0.03	0.056	0.03	0.042	0.03	0.042
008	0.089	0.089	0.103	0.077	0.042	0.089	0.048	0.103
009	0.12	0.14	0.12	0.12	0.14	0.103	0.12	0.14
010	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.005
011	0.026	0.019	0.023	0.026	0.026	0.023	0.026	0.026
012	0.026	0.026	0.026	0.03	0.016	0.026	0.019	0.026
013	0.023	0.03	0.042	0.036	0.03	0.089	0.048	0.103
014	0.023	0.026	0.026	0.023	0.016	0.016	0.023	0.016
015	0.12	0.03	0.03	0.036	0.016	0.023	0.065	0.03
016	0.103	0.089	0.077	0.077	0.12	0.12	0.12	0.12
017	0.023	0.03	0.023	0.023	0.023	0.023	0.023	0.023
018	0.056	0.056	0.056	0.077	0.026	0.026	0.042	0.077
019	0.023	0.03	0.03	0.026	0.019	0.03	0.016	0.019
020	0.03	0.03	0.036	0.036	0.023	0.023	0.023	0.023
021	0.023	0.023	0.03	0.03	0.019	0.023	0.026	0.03
022	0.048	0.042	0.048	0.056	0.042	0.048	0.056	0.077

Table 9 (continued)

Participant No.	Rock				Pop			
	No Filter	100 Hz	173.2 Hz	300 Hz	No Filter	100 Hz	173.2 Hz	300 Hz
023	0.256	0.22	0.298	0.103	0.056	0.065	0.103	0.048
024	0.03	0.042	0.036	0.03	0.023	0.023	0.03	0.065
025	0.089	0.103	0.065	0.077	0.065	0.077	0.089	0.089
026	0.089	0.089	0.065	0.12	0.077	0.077	0.12	0.089
027	0.256	0.298	0.256	0.189	0.403	0.346	0.346	0.256
028	0.03	0.03	0.03	0.023	0.023	0.03	0.023	0.03
029	0.016	0.026	0.03	0.019	0.023	0.023	0.026	0.026
030	0.019	0.016	0.015	0.012	0.015	0.023	0.016	0.016
031	0.03	0.03	0.023	0.026	0.023	0.023	0.023	0.023
032	0.077	0.103	0.077	0.065	0.065	0.077	0.065	0.089
033	0.077	0.077	0.077	0.103	0.048	0.056	0.089	0.12
034	0.042	0.042	0.042	0.048	0.036	0.036	0.042	0.048
035	0.162	0.162	0.22	0.22	0.077	0.065	0.089	0.12
036	0.026	0.026	0.036	0.026	0.042	0.03	0.03	0.056
037	0.256	0.162	0.162	0.189	0.162	0.12	0.14	0.189
038	0.056	0.048	0.056	0.048	0.023	0.016	0.036	0.036
039	0.026	0.03	0.026	0.036	0.023	0.026	0.026	0.03
040	0.036	0.023	0.03	0.03	0.042	0.03	0.036	0.048
041	0.298	0.22	0.256	0.22	0.298	0.256	0.298	0.298
042	0.015	0.012	0.01	0.011	0.015	0.016	0.015	0.012
043	0.023	0.023	0.03	0.048	0.036	0.042	0.077	0.103
044	0.042	0.042	0.056	0.042	0.077	0.056	0.056	0.077

Table 10

Participant Chosen Volume Settings for the Classical and Preferred Songs

Participant No.	Classical				Preferred			
	No Filter	100 Hz	173.2 Hz	300 Hz	No Filter	100 Hz	173.2 Hz	300 Hz
001	0.023	0.026	0.023	0.016	0.042	0.056	0.042	0.056
002	0.048	0.048	0.065	0.056	0.056	0.065	0.056	0.048
003	0.023	0.023	0.023	0.03	0.023	0.023	0.03	0.056
004	0.036	0.023	0.036	0.042	0.023	0.023	0.023	0.048
005	0.026	0.026	0.03	0.042	0.03	0.036	0.042	0.065
006	0.023	0.023	0.023	0.016	0.023	0.023	0.023	0.026
007	0.016	0.016	0.019	0.023	0.03	0.036	0.03	0.03
008	0.077	0.077	0.048	0.089	0.023	0.042	0.065	0.023
009	0.103	0.14	0.077	0.089	0.077	0.065	0.089	0.12
010	0.019	0.019	0.019	0.005	0.019	0.019	0.019	0.016
011	0.019	0.019	0.019	0.026	0.026	0.026	0.019	0.026
012	0.016	0.026	0.026	0.026	0.03	0.03	0.026	0.042
013	0.089	0.103	0.103	0.103	0.036	0.056	0.089	0.056
014	0.03	0.023	0.023	0.023	0.03	0.023	0.023	0.026
015	0.036	0.03	0.023	0.036	0.065	0.048	0.036	0.048
016	0.056	0.042	0.042	0.056	0.14	0.162	0.189	0.162
017	0.023	0.023	0.023	0.023	0.036	0.023	0.023	0.048
018	0.03	0.042	0.036	0.056	0.03	0.036	0.036	0.048
019	0.03	0.036	0.036	0.036	0.026	0.03	0.023	0.042
020	0.03	0.023	0.023	0.023	0.036	0.042	0.042	0.048
021	0.023	0.023	0.023	0.023	0.023	0.023	0.03	0.042
022	0.056	0.048	0.042	0.077	0.036	0.042	0.042	0.056

Table 10 (continued)

Participant No.	Classical				Preferred			
	No Filter	100 Hz	173.2 Hz	300 Hz	No Filter	100 Hz	173.2 Hz	300 Hz
023	0.036	0.036	0.077	0.048	0.546	0.635	0.635	0.546
024	0.026	0.023	0.019	0.023	0.03	0.042	0.03	0.042
025	0.026	0.036	0.036	0.026	0.103	0.14	0.189	0.14
026	0.042	0.048	0.042	0.065	0.077	0.077	0.103	0.103
027	0.023	0.036	0.042	0.048	0.256	0.346	0.189	0.403
028	0.015	0.016	0.015	0.019	0.023	0.023	0.026	0.023
029	0.016	0.019	0.019	0.019	0.026	0.026	0.03	0.03
030	0.023	0.019	0.015	0.019	0.015	0.016	0.016	0.015
031	0.008	0.006	0.005	0.005	0.036	0.036	0.036	0.048
032	0.056	0.048	0.056	0.048	0.103	0.065	0.077	0.077
033	0.042	0.042	0.056	0.042	0.056	0.065	0.089	0.103
034	0.023	0.026	0.023	0.023	0.042	0.048	0.048	0.056
035	0.042	0.065	0.048	0.077	0.103	0.103	0.162	0.14
036	0.026	0.03	0.036	0.036	0.056	0.042	0.056	0.077
037	0.077	0.048	0.065	0.103	0.14	0.14	0.22	0.256
038	0.03	0.036	0.048	0.036	0.103	0.103	0.089	0.089
039	0.026	0.023	0.026	0.026	0.026	0.03	0.03	0.036
040	0.03	0.042	0.036	0.065	0.048	0.056	0.065	0.077
041	0.14	0.162	0.077	0.14	0.256	0.22	0.22	0.298
042	0.036	0.023	0.023	0.026	0.026	0.023	0.023	0.026
043	0.023	0.03	0.036	0.023	0.077	0.065	0.077	0.056
044	0.016	0.016	0.016	0.03	0.056	0.056	0.077	0.077