Music Intensity in the Ear Canal in Quiet and in Subway Noise Using Four Different Headphones

Meghan A. Joyce

The Graduate Center, City University of New York

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MUSIC INTENSITY IN THE EAR CANAL IN QUIET AND IN SUBWAY NOISE USING FOUR DIFFERENT HEADPHONES

by

MEGHAN A. JOYCE

A capstone research project submitted to the Graduate Faculty in Audiology in partial fulfillment of the requirements for the degree of Doctor of Audiology, The City University of New York

2018
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by

Meghan A. Joyce

This manuscript has been read and accepted for the Graduate Faculty in Audiology in satisfaction of the dissertation requirement for the degree of Doctor of Audiology, Au.D.

Date

[Brett A. Martin, Ph.D., CCC-A]
Chair of Examining Committee

Date

[John A. Preece, Ph.D.]
Executive Officer

THE CITY UNIVERSITY OF NEW YORK
ABSTRACT

Music Intensity in the Ear Canal in Quiet and in Subway Noise Using Four Different Headphones

by

Meghan Joyce

Advisor: Brett Martin, Ph.D., CCC-A

Background: Noise-induced hearing loss, hearing loss caused by exposure to loud sounds, affects individuals of all ages. One cause of noise-induced hearing loss is listening to music at high intensities on personal listening devices, such as the iPhone. The aim of this study was to compare the intensity of music in the ear canal when presented in quiet at multiple volume settings through 4 different headphone styles (2 over the ear and 2 earbuds) to the intensity of the music in the ear canal when presented in typical subway noise. The results were used to determine recommended listening durations for the iPhone based on earphone style and music intensity in quiet listening environments and on the subway.

Method: This study used an iPhone 6s to present a 30 second clip of the 2015 #1 song “Uptown Funk” by Mark Ronson, featuring Bruno Mars (Billboard, 2015). The output of the iPhone was fed to a Zwislocki coupler inserted into the left ear of Knowles Electronic Manikin for Acoustic Research (KEMAR) and RMS sound intensity was measured using a sound level meter. A total of 4 different headphones were used to present the music clip in two conditions (in quiet and in 80dBA of subway noise). The music was played at 4 different iPhone volume settings: 25%, 50%, 75% and 100% of the maximum volume. Measured intensities were then compared to the
WHO and EPA allowable listening levels of a 24-hour period in order to determine safe listening
duration as a function of music intensity and background noise.

**Results:** In terms of volume setting across all 6 headphone conditions, 25% of maximum volume
had recorded peak amplitudes ranging from 52.8 dB SPL (Sony ZX series) to 82.6 dB SPL
(PowerBeats Plugged) in quiet and 76.4 dB SPL (Beats Studio) to 85.8 dB SPL (Apple EarPods
Plugged and Sony ZX Series) in noise. 100% of maximum volume had recorded peak amplitudes
ranging from 93.3 dB SPL (PowerBeats Unplugged) to 119.4 dB SPL (Beats Studio) in quiet and
94.3 dB SPL (PowerBeats Unplugged) to 119.4 dB SPL (Beats Studio) in noise. In terms of the
difference in dB SPL between quiet and noise conditions, the in-the-ear earbuds had a range
from 0 dB SPL (Apple EarPods Plugged at 100% volume) to 30.9 dB SPL (Apple EarPods
Unplugged at 25% volume). For the over-the-ear headphones, the differences in dB SPL between
the quiet and noise conditions ranges from 0 dB SPL (Beats Studio at 100%) to 33 dB SPL (Sony
ZX Series at 25%).

Recommended listening durations decreased as volume setting increased, as would be expected.
At a volume setting of 25%, listening durations were longest--at least 8 hours for all headphones
in quiet or in noise. At a volume setting of 100%, however, listening times decreased, ranging
from 1 hour to 14 seconds, depending on headphone.

**Conclusions:** In subway noise, the intensity of the music plus the noise reached potentially
damaging levels. Some earphone styles offered more protection from the subway noise than
others. For the over-the-ear style, the Beats Studio headphones offered the most protection.
Although the SONY headphones provide longer listening durations in the presence of subway
noise, especially at 75% and 100% of maximum volume, less of the signal reaching ear level was
the desired music. For the in-the-ear style, the PowerBeats, when well-sealed in the ear canal,
offered the most protection from the subway noise. The PowerBeats also yield the longer safe listening times. Overall, the over-the-ear style headphones provide more protection and longer listening durations in the presence of subway noise compared to in-the-ear earbuds. This study provides data that could be used to promote awareness regarding the dangers of listening to music at loud intensities for long durations, especially in the presence of background noise.
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Introduction

Noise induced hearing loss (NIHL), hearing loss caused by exposure to loud sounds, is a health condition that can affect individuals of all ages. It is the second most common form of sensorineural hearing loss and the most common occupational and environmental hazard (Rabinowitz, 2000). Although excessive noise exposure leading to noise induced hearing loss is typically associated with occupational environments, such as working in construction or at a factory, excessive noise exposure can occur in other environments as well. For example, newborns who spend extended periods of time in the neonatal intensive care unit (NICU) after birth are at greater risk of noise induced hearing loss from the loud ventilators and machinery used (Mayrand et al., 2005). Noise exposure is also found in the military, in the form of blast explosions and gun fire (Coles et al., 1968; Kim et al., 2016; Yankaskas, 2013). Teens and adolescents who listen to music at high intensities and for long periods of time are also at risk of developing noise induced hearing loss (Vogel et al., 2008). The World Health Organization reported that 1.1 billion teenagers and young adults are at risk of hearing loss from listening to music at high intensities (WHO, 2015). With continuous exposure, noise induced hearing loss can become a permanent condition with no form of recovery possible (Meinke et al., 2012). According to Hoffman et al. 2006, approximately 26 million Americans between the ages of 20 and 69 have hearing loss due to noise exposure. In order to prevent noise induced hearing loss, education regarding hearing health, the potential negative effects of noise exposure, and ways to prevent noise-induced hearing loss is needed.

Hearing loss is linked with several negative health conditions (Agrawal et al., 2009; Daniel, 2007; Strawbridge et al., 2000). Individuals with hearing loss are a greater risk for having communication difficulties, such as difficulty understanding speech in background noise
Communication difficulties can potentially impact a person’s everyday social life. A number of studies have shown that hearing loss results in a poorer quality of life due to reduced social interactions, isolation and a sense of exclusion (e.g., Ciorba et al., 2012; Dalton et al., 2003; Schmuziger et al., 2006). In addition to hearing loss, excessive noise exposure has also been linked to non-auditory conditions, such as hypertension and cardiovascular disease (Daniel, 2007; Gershon et al., 2012). In addition, educational performance is affected in background noise, leading to difficulties with learning and memory (Bronzaft & McCarthy, 1975; Gershon et al., 2012; Ristovska et al., 2004). Although there are multiple negative health conditions associated with noise exposure, it is important to note that noise induced hearing loss is usually preventable. There are many preventative measures and working regulations currently in place around the world to prevent noise induced hearing loss. With proper education and preventative measures, such as wearing hearing protection, noise induced hearing loss should be reduced (Clark & Bohne, 1999; Fausti et al., 2005; Hong et al., 2013).

The Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) provided recommended noise exposure limits for workers exposed to occupational noise, such as machinery. These recommended exposure limits (RELs) are based upon a 5-day work week with 8 hour days, assuming individuals are in quieter conditions the remainder 16 hours each day and on the weekends (Kardous et al., 2016). For example, NIOSH recommended average sound exposure limits for occupational noise exposure are 85 dBA, for an 8-hour work day. In other words, an individual can be exposed to 85 dBA of continuous noise for 8 hours a day before they reach the maximum allowable daily limit (NIOSH, 2016). The World Health Organization (WHO) and the Environmental Protection
Agency (EPA) have also developed allowable listening limits; however, an important addition was the consideration of all potential sound exposure including occupational, environmental, and recreational exposure. Since noise exposure is not only common in the workplace, WHO and EPA include all of these sources of noise exposure for a 24-hour time period, rather than an 8-hour work day. The WHO (Berglund et al., 1999) and EPA (1979), suggest that individuals should not be exposed to average noise levels that exceed 70 dBA for every 24 hours of exposure or 75 dBA for an 8-hour exposure. Allowable noise exposure is a function of two main factors: duration of noise exposure and the frequency-weighted level of the noise (measured in dBA) (Neitzel, 2009; Rabinowitz, 2000). As noise intensity increases, the allowable duration of exposure without damage decreases (Neitzel, 2009). For example, the allowable noise dose without potential damage for a 70 dBA signal is 24 hours. However, for a 75 dBA signal, the allowable duration before damage decreases significantly to 8 hours (EPA, 1979). While in some locations it may be easy to avoid noise exposure that exceeds these limits, it can be difficult in urban areas, which have a number of noise sources, including mass transit, which is commonly used (Gershon, 2006). In urban areas, noise exposure doses approach these limits regularly in many individuals. For example, Neitzel (2012), using the 70 dBA recommended exposure limit, determined that 1 in 10 NYC commuters had noise exposure in excess of this limit from transit noise alone. Therefore, application and knowledge of recommended exposure limits may be beneficial in preventing noise-induced hearing loss, especially in urban areas where noise exposure is common.

The New York City Metropolitan Transportation Authority (MTA) consists of many different forms of public transportation, including busses, subways, and railroads. In 2009, it was documented that of all of New York City’s forms of mass transit, the subway system had the
highest noise levels, often approaching dangerous listening levels of over 90 dBA (Neitzel et al., 2009). The New York City subway system was one of the first mass transit systems ever created. The system was built over 100 years ago, a time when sound-damping materials were not used and acoustic requirements did not exist. As a result, the NYC subway system is one of the loudest mass transit systems around the world (Gershon, 2012). Researchers determined the average intensity within the interior of a NYC subway car is 79 dBA, with the highest intensity reaching 97.8 dBA (Neitzel et al., 2009). In order to determine noise levels, intensity data were sampled from each of the 26 MTA subway lines, with a target measurement duration of 10 minutes while the subway car was in motion, and measured at the ear using a type II noise dosimeter located in the center of the transit vehicle (Neitzel, 2009). With continuous daily exposure, the levels measured are considered hazardous for hearing health and can potentially damage the auditory system, especially for individuals that ride mass transit for extended periods of time each day. Furthermore, the platforms of subway lines also have high intensities, with an average level of 81.1 dBA and the highest intensity recorded at 102.1 dBA (Neitzel et al., 2009). According to the WHO and EPA recommended exposure limits, an individual can only be exposed to a 100 dBA sound for only a minute and a half without damaging hearing health. Therefore, time spent on the platform each day waiting for the subway car to arrive can also be hazardous to one’s hearing health. Despite this, subway ridership in New York City continues to grow each year. In 2015, there were over 1.7 billion subway rides, with an average of 5.6 million riders each weekday (MTA, 2015). While NYC mass transit is commonly used by commuters from the suburbs, approximately 55% of NYC residents also use the subways (Netizel et al., 2012).
According to Gershon et al. (2012), the average commute time for NYC subway riders is approximately 68 minutes a day. In order to pass time on these lengthy commutes, passengers typically read, listen to music, or engage in other leisure activities. Listening to music on personal electronic devices, such as a smartphone, has become increasingly popular with the advancement of technology (Lopatovska et al., 2011). According to Lopatovska et al. (2011), listening to music was the most popular passive activity while commuting on the New York City subway. Of the total number of individuals being observed during this study, approximately 17% of subway passengers used their mobile devices to listen to music. Due to the noisy subway cars and the additional noise caused by curvature of subway tracks and wheel squeal (Shah et al., 2016; Shimokura & Soeta, 2012), individuals have reported a need to raise the volume of their personal devices to overcome such background noises (Airo et al., 1996; Hodgetts et al., 2007; Shimokura & Soeta, 2012). Hodgetts et al. (2007), determined that adults using personal listening devices listened to music in quiet at an average intensity of 76.0 dBA, whereas in the presence of street noise, individuals listened at an average of 85.4 dBA. Maffei et al. (2011) concluded 49% of passengers interviewed for their study preferred to listen to music on their personal devices at 85-100% of the maximum volume; which can reach over 100 dBA at the eardrum. When recreational noise exposure, such as listening to music, is combined with environmental background noise, such as subway noise, the noise dose is raised (Yu et al., 2016). This leads to potentially hazardous listening levels and increases the risk of noise induced hearing loss. According to Levey et al. (2011), a majority (58.2%) of personal listening device users exceeded recommended sound exposure limits, suggestive of a greater risk for noise-induced hearing loss. Han et al. (2015) concluded that it is expected for passengers to have a risk of some degraded speech perception ability when listening to music in the presence of
background noise, like the subway, for long durations. Listening to music via personal listening devices at loud intensities for long duration in the presence of competing background noise can be very dangerous to hearing safety (Maffei et al., 2011). There are currently no studies that analyze listening levels of personal listening devices in the presence of subway noise based on headphone style and volume output.

The type of headphones used while listening to personal devices can directly impact the amount of sound entering the ear. According to Liang et al. (2012), approximately 90% of listeners using personal music players reported using the manufacturer-supplied headphones. For example, many individuals using an Apple iPhone or iPod to listen to music also use the Apple earbuds that come with these devices. The earbud style is designed to channel sound directly into the listener’s ear canal. Over-the-ear style headphones are also popular for listening to music via personal devices. Since the headphone physically covers the ear, some of the high frequency background noise is blocked from entering the ear. This blocking is referred to as passive noise reduction (Liang et al., 2012). Some earbud style earphones may passively reduce noise, but only if they fit tightly (seal) in the ear canal. Other over-the-ear headphones are equipped with noise-reduction technology, and are known as active noise-canceling headphones. These headphones have active circuits designed to reduce low frequency noise (Gan et al., 2005; Kuo et al., 2006; Liang, 2012). These headphones have a noise-canceling circuit that generates an “anti-noise” signal with the exact opposite phase of the incoming waves of noise (Gan et al., 2005; Kuo et al., 2006; Liang, 2012). Headphone style directly impacts the acoustic signal entering the auditory system, including the intended music as well as unwanted background noise. Certain headphones will have better noise-canceling capabilities, and certain headphone styles provide more hearing protection.
The aim of this study was to compare the intensity of music in a standard ear canal when presented in quiet at multiple volume settings through four different headphone styles (two over the ear and two earbuds) to the intensity of the music in the ear canal when presented through these same headphones in background of typical subway noise. The results were used to determine recommended time limits for a personal music player (iPhone) based on earphone style and music intensity in quiet listening environments and on the subway. This study also intended to provide data which could be used to promote awareness and educate New York commuters about hazardous listening levels and potential risk of hearing loss.

**Methods**

No human subjects participated in this study. In order to measure intensity levels in a standard ear canal, KEMAR, (Knowles Electronic Manikin for Acoustic Research) a head and torso simulator designed specifically for acoustic research, was used. A total of four different earphones--two earbuds and two over-the-ear headphones were tested using an iPhone 6s as the music player. The headphones tested included two earbuds (Apple EarPods and Beats by Dr. Dre: PowerBeats) and two over-the-ear headphones (Sony ZX Series and Beats by Dr. Dre: Beats Studio). The two in-the-ear earbuds (Apple EarPods and PowerBeats) were tested how they naturally fit in the ear (unplugged) as well as sealed off with putty (plugged). Since in-the-ear headphones are designed to fit most adult ears, putty was used to create a complete seal in order to simulate a more accurate and custom fit. The plugged and unplugged condition was used as a means of comparison to reveal how the intensity measured in the ear canal can vary depending on how the earbuds fit in the listener’s ear.
The music stimulus was a 30 second clip (1:57 to 2:27) of “Uptown Funk” by Mark Ronson, featuring Bruno Mars. This song was selected because it was listed on Billboard as the most popular song for 2015 (Billboard, 2015). After appropriate calibrations, the output of the iPhone was coupled to a Zwislocki coupler inserted into the left ear of Knowles Electronic Manikin for Acoustic Research (KEMAR) and RMS sound intensity was measured using a Larson Davis Laboratories Precision Integrating Sound Level Meter (Model 800B) sound level meter. A total of four headphones were used to present the music clip in two conditions-- in quiet and in subway noise (80 dB). The music was played at 4 different volume settings: 25%, 50%, 75% and 100% of the maximum volume.

The background subway noise was a pre-recorded clip from onboard the interior of a NYC subway car. The subway noise was recorded using a Sony PCMD50 Professional Portable Stereo Digital Recorder (24 bits, 44.1 kHz). The on-board stereo electret condenser microphones built into the recorder were set to an XY pattern of 90° resulting in a 2-channel, stereo recording. Since most NYC subways run underground throughout the borough Manhattan, where ridership is busiest (MTA, 2015), this recording was made onboard the interior of a NYC subway 6 train between the 33rd St and Grand Central Stops. The individual obtaining the recording was standing up near the train door, holding the microphone at chin level, in an attempt to imitate a binaural recording.

The recording was then edited from a 2:30 to a 0:30 second audio file on a digital audio workstation (DAW) comprised of Pro Tools 12 software on an Apple MacMini with 2.8 GHz dual-core Intel Core i5 running OS X El Capitan. 3-6 dB of overall gain was added to the original recording. The recording was analyzed with the Waves WLM Loudness Meter plugin. This provided a -20Leq(a) level across the 0:30 second signal. The Leq(a) is the A-weighted
sound pressure level (SPL) averaged over a period of time. No additional signal processing was employed. Using Adobe Audition, a spectra was created for the frequency response of the subway noise (Figure 1). According to the frequency analysis of the subway noise, the frequency response was greatest in the low frequencies, specifically around 100 to 400Hz.

Testing took place in a double-walled sound attenuated booth. The background subway noise was played from 2 speakers located at ear level, 1 meter away from KEMAR at a 30° azimuth, using an RMS intensity of 79 dBA, the average interior intensity of NYC subway cars (Neitzel et al., 2009). This subway noise was delivered to the loudspeakers through the audio jack from a 2016 Apple Macbook (See Figure 2 for diagram of setup). This setup was chosen to mimic that of Liang et al. 2012.

Peak amplitude of the 30 second music clip at the ear level of KEMAR was measured using a Larson Davis Laboratories Precision Integrating Sound Level Meter (Model 800B) set to linear and slow (continuous, no filter, no hold). A Zwislocki coupler was fit to the left ear of KEMAR. An Etymotic Research ER 11 ½” microphone system with DFI enabled was connected to the sound level meter and was used to record the intensity of the music (in quiet and in subway noise) at each of the four iPhone volume settings. The difference in sound intensity measured at ear level between the quiet condition and noise condition for each headphone at each volume setting was computed in order to determine how much background noise is entering the ear canal at each of the four volume settings. Then, using the WHO and EPA’s recommended noise exposure levels based off a 24-hour day, recommended listening levels for each headphone were calculated based on peak intensities measured at each volume setting.
Further, peak amplitude of the music in 1/3 octave bands centered from 31.5 Hz-16,000 Hz were also measured for each headphone at each volume setting in quiet and in subway noise using the Larson Davis Laboratories Precision Integrating Sound Level Meter (Model 800B).

In addition to recording the intensity of the music clip in quiet and in subway noise, the frequency response of each headphone was obtained by replacing the music stimulus with broadband noise. The signal from the coupler-microphone combination was recorded onto a Dell Latitude D610 computer using Adobe Audition software. These recordings were then converted into spectra via Adobe Audition and this was performed at all four iPhone volume settings.

**Results**

**Peak Amplitudes As A Function of Earphone, Volume Setting, and Noise Condition**

Peak amplitudes of the music at all four volume settings in quiet and in subway noise are shown in Table 1. In the quiet condition for the in-the-ear style earbuds, the smallest measured peak amplitude was measured at 25% maximum volume of the Apple EarPods Unplugged, at 53.3 dB SPL. The greatest measured peak amplitude was measured at 100% maximum volume of the Apple EarPods Plugged, at 108.4 dB SPL. In the quiet condition for the over-the-ear headphones, the smallest measured peak amplitude was measured at 25% maximum volume of the Sony ZX Series, at 52.8 dB SPL. The greatest measured peak amplitude was measured at 100% maximum volume of the Beats Studio headphones, at 119.4 dB SPL.

In the subway noise condition, the smallest measured peak amplitude for the in-the-ear style headphones was measured at 25% of maximum volume for the PowerBeats Unplugged at 80.9 dB SPL. The greatest measured peak amplitude was measured at 100% maximum volume for the Apple EarPods Plugged at 108.4 dB SPL. In the subway noise condition the smallest
measured peak amplitude for the over-the-ear style headphones was measured at 25% of maximum volume Beats Studio at 76.4 dB SPL. The greatest measured peak amplitude was measured at 100% maximum volume for the Beats Studio at 119.4 dB SPL.

In terms of volume setting across all 6 headphone conditions, 25% of maximum volume had recorded peak amplitudes ranging from 52.8 dB SPL (Sony ZX series) to 82.6 dB SPL (PowerBeats Plugged) in quiet and 76.4 dB SPL (Beats Studio) to 85.8 dB SPL (Apple EarPods Plugged and Sony ZX Series) in noise. 50% of maximum volume had recorded peak amplitudes ranging from 68.9 dB SPL (Apple EarPods Unplugged) to 84.1 dB SPL (PowerBeats Plugged) in quiet and 82.6 dB SPL (Beats Studio) to 88.6 dB SPL (Apple EarPods Plugged) in subway noise. 75% of maximum volume had recorded peak amplitudes ranging from 84.1 dB SPL (Apple EarPods Unplugged) to 97.4 dB SPL (Beats Studio) in quiet and 86.9 dB SPL (Apple EarPods Unplugged) to 97.6 dB SPL (Beats Studio) in noise. 100% of maximum volume had recorded peak amplitudes ranging from 93.3 dB SPL (PowerBeats Unplugged) to 119.4 dB SPL (Beats Studio) in quiet and 94.3 dB SPL (PowerBeats Unplugged) to 119.4 dB SPL (Beats Studio) in noise.

**Difference (in dB SPL) between quiet condition and noise condition**

Difference (in dB SPL) between the quiet condition and noise condition are shown in Table 2. For the in-the-ear earbuds, the difference in dB SPL between the quiet and noise conditions ranges from 0 dB SPL (Apple EarPods Plugged at 100% volume) to 30.9 dB SPL (Apple EarPods Unplugged at 25% volume). For the over-the-ear headphones, the differences in dB SPL between the quiet and noise conditions ranges from 0 dB SPL (Beats Studio at 100%) to 33 dB SPL (Sony ZX Series at 25%).
For the in-the-ear earbuds, at 25% of maximum volume, the difference in dB SPL between the quiet and noise conditions ranges from 2 dB SPL (PowerBeats Plugged) to 30.9 dB SPL (Apple EarPods Unplugged). At 50% of maximum volume, the difference in dB SPL ranges from 1.4 dB SPL (PowerBeats Plugged) to 16.0 dB SPL (Apple EarPods unplugged). At 75% of maximum volume, the difference in dB SPL ranges from 0.5 dB SPL (PowerBeats Plugged) to 2.8 dB SPL (Apple EarPods unplugged). At 100% of maximum volume, the difference in dB SPL ranges from 0 dB SPL (Apple EarPods Plugged) to 1.0 dB SPL (PowerBeats unplugged).

For the over-the-ear headphones, at 25% of maximum volume, the difference in dB SPL between the quiet and noise conditions ranges from 10.8 dB SPL (Beats Studio) to 33 dB SPL (Sony ZX Series). At 50% of maximum volume, the difference in dB SPL ranges from 1.5 dB SPL (Beats Studio) to 15.5 dB SPL (Sony ZX Series). At 75% of maximum volume, the difference in dB SPL ranges from 0.2 dB SPL (Beats Studio) to 3 dB SPL (Sony ZX Series). At 100% of maximum volume, the difference in dB SPL ranges from 0 dB SPL (Beats Studio) to 0.1 dB SPL (Sony ZX Series).

Apple EarPods and PowerBeats had greater differences in intensity in the unplugged condition at all 4 volume settings compared to the plugged condition.

**Peak Amplitudes in 1/3 Octave Bands As A Function of Earphone, Volume Setting, and Noise Condition**

Peak amplitudes of the music in quiet and in subway noise for the 1/3 octave frequency bands are shown in figures 3-8. In the quiet condition for all six headphone conditions, as volume increases, the intensity of each octave band increases. It can be concluded that 25% of
maximum volume yielded lowest intensities at all octave bands and 100% of maximum volume yielded largest measured intensities at all octave bands for all six headphone conditions in quiet.

In the quiet condition for the Apple EarPods Plugged, peak amplitudes across the 1/3 octave bands range from 12.1 dB SPL (at 31.5Hz) to 44.7 dB SPL (at 500Hz) at 25% of maximum volume and from 51.4 dB SPL (at 31.5Hz) to 92.8 dB SPL (at 500Hz) at 100% maximum volume. In the noise condition, peak amplitudes across the 1/3 octave bands range from 17.9 dB SPL (at 1600Hz) to 69.4 dB SPL (at 500Hz) at 25% of maximum volume and 42.2 dB SPL (at 31.5Hz) to 77.8 dB SPL (at 2000Hz) at 100% of maximum volume. In the quiet condition for the Apple EarPods Unplugged, peak amplitudes across the 1/3 octave bands range from 11.1 dB SPL (at 31.5Hz) to 44.1 dB SPL (at 1000Hz) at 25% of maximum volume and from 42.8 dB SPL (at 31.5Hz) to 83.3 dB SPL (at 1000Hz) at 100% maximum volume. In the noise condition, peak amplitudes across the 1/3 octave bands range from 18.2 dB SPL (at 31.5Hz) to 67.5 dB SPL (at 500Hz) at 25% of maximum volume and 39.1 dB SPL (at 31.5Hz) to 78.6 dB SPL (at 2000Hz) at 100% of maximum volume.

In the quiet condition for the PowerBeats Plugged, peak amplitudes across the 1/3 octave bands range from 11.2 dB SPL (at 63Hz) to 32.4 dB SPL (at 2000 and 4000Hz) at 25% of maximum volume and from 38.3 dB SPL (at 31.5Hz) to 79.1 dB SPL (at 4000Hz) at 100% maximum volume. In the noise condition, peak amplitudes across the 1/3 octave bands range from 15.9 dB SPL (at 1600Hz) to 66.7 dB SPL (at 500Hz) at 25% of maximum volume and 48.3 dB SPL (at 1600Hz) to 84.4 dB SPL (at 10000Hz) at 100% of maximum volume. In the quiet condition for the PowerBeats Unplugged, peak amplitudes across the 1/3 octave bands range from 8.8 dB SPL (at 31.5Hz) to 47.7 dB SPL (at 1000Hz) at 25% of maximum volume and from 47.4 dB SPL (at 31.5Hz) to 86.4 dB SPL (at 1000Hz) at 100% maximum volume.
noise condition, peak amplitudes across the 1/3 octave bands range from 22.1 dB SPL (at 16000Hz) to 69.9 dB SPL (at 500Hz) at 25% of maximum volume and 43.1 dB SPL (at 16000Hz) to 83.4 dB SPL (at 1000Hz) at 100% of maximum volume.

In the quiet condition for the Sony ZX Series, peak amplitudes across the 1/3 octave bands range from 10.1 dB SPL (at 31.5Hz) to 30.3 dB SPL (at 2000Hz) at 25% of maximum volume and from 43.2 dB SPL (at 31.5Hz) to 77.2 dB SPL (at 2000Hz) at 100% maximum volume. In the noise condition, peak amplitudes across the 1/3 octave bands range from 22.8 dB SPL (at 16000Hz) to 69.2 dB SPL (at 500Hz) at 25% of maximum volume and 44.4 dB SPL (at 31.5Hz) to 77.5 dB SPL (at 500Hz) dB at 100% of maximum volume.

In the quiet condition for the Beats Studio, peak amplitudes across the 1/3 octave bands range from 2.9 dB SPL (at 31.5Hz) to 40.8 dB SPL (at 1000Hz) at 25% of maximum volume and from 55 dB SPL (at 31.5Hz) to 94.8 dB SPL (at 250Hz) at 100% maximum volume. In the noise condition, peak amplitudes across the 1/3 octave bands range from 2.1 dB SPL (at 31.5Hz) to 66.5 dB SPL (at 500Hz) at 25% of maximum volume and 53.3 dB SPL (at 31.5Hz) to 95.1 dB SPL (at 250Hz) at 100% of maximum volume.

**Frequency Response of Each Earphone**

The frequency response of each earphone is shown in Figures 9-14. It was determined that for each headphone tested, the frequency response remained consistent at all four volume settings and the intensity increases as the volume setting increased. For the Apple EarPods plugged (Figure 9), the frequency response is greatest at approximately 4500Hz and lowest at 20,000Hz. There are also peaks at approximately 2000Hz, 7000Hz, and 1100Hz. For the Apple EarPods unplugged (Figure 10), the frequency response is greatest at approximately 5500Hz and lowest at 20,000Hz. There are also peaks at approximately 2000Hz and 1500Hz. For the
PowerBeats plugged (Figure 11), the frequency response is greatest at approximately 800Hz and lowest at 17000Hz. There are also peaks at approximately 5000Hz, 10000Hz, 13000Hz, 15000Hz, and 19000Hz. For the PowerBeats unplugged (Figure 12), the frequency response is greatest at approximately 100Hz and lowest at 19000Hz. There are also peaks at approximately 5500Hz and 12000Hz. For the SONY ZX Series headphones (Figure 13), the frequency response is greatest at approximately 100-300Hz and lowest at 20000Hz. There are also peaks at approximately 1500Hz, 7500Hz, 11000Hz, and 15000Hz. For the Beats Studio headphones (Figure 14), the frequency response is greatest at approximately 15000Hz and lowest at 20000Hz. There are also peaks at approximately 700Hz, 4500Hz, 6000Hz, 8000Hz, and 18000Hz.

**Recommended Listening Durations as a Function of Earphone, Volume Setting and Noise Condition**

Recommended listening durations for each earphone were determined as a function of volume setting and noise condition. Results are shown in Table 3. Listening duration decreased as volume setting increased, as would be expected. At a volume setting of 25%, listening duration were longest; at least 8 hours for all headphones in quiet or in noise.

At a volume setting of 100%, listening times decreased. For Apple EarPods Plugged, recommended listening durations at 100% volume was approximately 112 seconds, in quiet and in noise. For Apple EarPods Unplugged, recommended listening durations at 100% were approximately 30 min in quiet and in subway noise. For PowerBeats Plugged, recommended listening durations at 100% were approximately 30 min in quiet and in subway noise. For PowerBeats Unplugged, recommended listening durations at 100% were approximately 1 hour in quiet and in subway noise. For Sony ZX Series, recommended listening durations at 100% were
approximately 30 min in quiet and in subway noise. For Beats Studio, recommended listening durations at 100% were approximately 14 seconds in quiet and in subway noise.

For the in-the-ear headphones, the PowerBeats yield the longest listening time compared to the Apple EarPods in both the plugged and unplugged conditions. For example, PowerBeats at 100% of maximum volume in the plugged condition yielded a recommended listening duration of 30 minutes, whereas the Apple EarPods in the plugged condition yielded a recommended listening duration of 112 seconds. For each volume setting, the in-the-ear earbuds in the unplugged conditioned permitted longer listening durations. For example, at 100% of maximum volume PowerBeats plugged yielded a recommended listening duration of 30 minutes, whereas the PowerBeats unplugged yielded recommended listening durations of 1 hour. Although the unplugged condition permits longer listening durations, more of the unwanted subway is entering the ear canal at each volume level.

It was also determined that for the over-the-ear headphones in the noise condition, the SONY headphones permit longer listening durations for 75% (Sony: 4 hours; Beats: 30 min) and 100% (Sony: 30 min; Beats 14 secs) of the volume, whereas the Beats Studio headphones permit longer listening times at 25% (Sony: 8 hours; Beats: >8 hours) and 50% (Sony: 8 hours; Beats: >8 hours) of maximum volume. Although the SONY headphones provide longer listening durations at 75% and 100% of maximum volume, less of the signal reaching ear level is the desired music.

**Significance and Implications**

This study is intended to obtain data which can be used to advise urban dwellers on safe music listening for those that rely on mass transit regularly. Since subway riders are at risk for noise-induced hearing loss depending on their commute times, it is important for riders to protect
their hearing and not cause further damage from listening to music at high intensities. When
determining the most appropriate headphone for commuting in noisy environments, it is
important for listeners to not only consider the recommended listening levels at each volume
setting, but to also consider the amount of background noise being recorded at ear level.

It was determined that across all six headphone conditions and in both the quiet and
subway noise environment, 25% of maximum volume had the lowest intensities measured at the
ear level and 100% of maximum volume had the highest intensities measured at ear level. It was
also concluded that for all 6 headphone conditions, louder intensities were recorded at ear level
in the subway noise condition compared to the quiet condition at all 4 volume settings.

Additionally, when comparing the unplugged condition to the plugged condition for the
Apple EarPods and PowerBeats, it was determined the unplugged condition measured lower
intensities at all volume levels, resulting in longer listening durations. However, when comparing
the difference between quiet and noise between the plugged and unplugged conditions, the
unplugged condition allowed more noise to leak into the ear canal compared to the plugged
condition. Although the unplugged condition has a smaller recorded intensity for each volume
setting, more of the sound reaching ear level is the undesired subway noise, not the music. It can
be concluded that the better the seal a listener has between their ear and the earbuds, the louder
the desired signal will be and less of unwanted background noise will enter the ear canal.

It was also determined out of the two over-the-ear headphones, the one that prevents the most
background noise from entering the ear canal is the Beats by Dr. Dre: Beats Studio. Although
Beats Studio have the shortest recommended listening time at 100% maximum volume, it is less
likely a listener would want to increase the volume that high since there is not as much
background noise interfering. Data also suggests that across all conditions, Sony ZX series
headphones have the greatest difference between quiet and noise at all volume settings, followed by Apple EarPods.

When comparing peak amplitudes in 1/3 octave bands, the subway noise had significant effects at all four volume settings at all octave bands for the Apple EarPods in the plugged and unplugged conditions. The low frequency bands in the lower volume settings (25% and 50% of maximum volume) had the greatest increase in measured intensity. It was also noted that the low frequency bands at high volume settings decreased in intensity compared to quiet. For PowerBeats in the plugged and unplugged conditions, the subway noise had minimal effect on the higher frequencies at all four volume settings. For the low frequency bands, such as 250-500Hz, the lower volume settings were greatly impacted by the subway noise, increasing the measured intensity by approximately 40 dB SPL.

For the SONY headphones, the subway noise had minimal effect on the higher frequencies at all four volume settings as well. For the low volume settings in the low frequencies, the subway noise significantly increased the recorded intensities. For the Beats Studio headphones, the subway noise had minimal effect across all frequency bands. It can be concluded that the Apple EarPods were impacted by the subway noise the most and the Beats Studio were impacted by the subway noise the least.

When commuting in the presence of background noise, it is important that listeners who use in-the-ear headphones have tightly-fit earbuds that do not permit unwanted background noise from entering the ear canal. For listeners that use the over-the-ear headphones, it is important to utilize headphones, such as the Beats Studio devices, that prevent more unwanted background noise from entering the ear canal compared to Sony ZX series. If commuters have
headphones that prevent unwanted background noise from entering the ear canal, they will be less likely to increase the volume to unsafe listening levels.
### Table 1: Sound intensity (dB SPL) at ear level (measure in RMS)

<table>
<thead>
<tr>
<th>Volume Setting (% of maximum volume)</th>
<th>In-the-ear earbuds</th>
<th>Over-the-ear headphones</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quiet</td>
<td>Noise</td>
</tr>
<tr>
<td>Apple EarPods (Plugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apple EarPods (unplugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beats by Dr. Dre: PowerBeats (plugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beats by Dr. Dre: PowerBeats (unplugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>25%</strong></td>
<td>61.6</td>
<td>85.8</td>
</tr>
<tr>
<td><strong>50%</strong></td>
<td>79.6</td>
<td>88.6</td>
</tr>
<tr>
<td><strong>75%</strong></td>
<td>94.3</td>
<td>97.0</td>
</tr>
<tr>
<td><strong>100%</strong></td>
<td>108.4</td>
<td>108.4</td>
</tr>
</tbody>
</table>

### Table 2: Difference (in dB SPL) between quiet condition and noise condition

<table>
<thead>
<tr>
<th>Volume Setting (% of maximum volume)</th>
<th>In-the-ear earbuds</th>
<th>Over-the-ear headphones</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quiet</td>
<td>Noise</td>
</tr>
<tr>
<td>Apple EarPods (Plugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apple EarPods (unplugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beats by Dr. Dre: PowerBeats (plugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beats by Dr. Dre: PowerBeats (unplugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>25%</strong></td>
<td>24.2</td>
<td>30.9</td>
</tr>
<tr>
<td><strong>50%</strong></td>
<td>9.0</td>
<td>16.0</td>
</tr>
<tr>
<td><strong>75%</strong></td>
<td>2.7</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>100%</strong></td>
<td>0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### Table 3: Recommended listening durations based on WHO and EPA’s recommended listening limits

<table>
<thead>
<tr>
<th>Volume Setting (% of maximum volume)</th>
<th>In-the-ear earbuds</th>
<th>Over-the-ear headphones</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quiet</td>
<td>Noise</td>
</tr>
<tr>
<td>Apple EarPods (Plugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apple EarPods (unplugged)</td>
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<td>Beats by Dr. Dre: PowerBeats (plugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beats by Dr. Dre: PowerBeats (unplugged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>25%</strong></td>
<td>&gt; 8 Hrs</td>
<td>8 Hrs</td>
</tr>
<tr>
<td><strong>50%</strong></td>
<td>&gt; 8 Hrs</td>
<td>4 Hrs</td>
</tr>
<tr>
<td><strong>75%</strong></td>
<td>1 Hr</td>
<td>30 min</td>
</tr>
<tr>
<td><strong>100%</strong></td>
<td>112 sec</td>
<td>112 sec</td>
</tr>
</tbody>
</table>
Figure 1: A Spectra of the frequency response the recorded subway noise is shown.

Figure 2: A diagram of experimental setting and equipment used is shown.
Figure 3: A plot of peak amplitudes in 1/3 Octave bands as a function of earphone (Apple EarPods Plugged), volume setting, and noise condition is shown.

Figure 4: A plot of peak amplitudes in 1/3 Octave bands as a function of earphone (Apple EarPods Unplugged), volume setting, and noise condition is shown.

Figure 5: A plot of peak amplitudes in 1/3 Octave bands as a function of earphone (PowerBeats Plugged), volume setting, and noise condition is shown.
Figure 6: A plot of peak amplitudes in 1/3 Octave bands as a function of earphone (PowerBeats Unplugged), volume setting, and noise condition is shown.

Figure 7: A plot of peak amplitudes in 1/3 Octave bands as a function of earphone (SONY ZX Series), volume setting, and noise condition is shown.

Figure 8: A plot of peak amplitudes in 1/3 Octave bands as a function of earphone (Beats Studio), volume setting, and noise condition is shown.
**Figure 9:** A Spectra of the frequency response of broadband noise as a function of earphone (Apple EarPods Plugged) and volume setting is shown.

![Frequency Response of Broadband Noise for Apple EarPods Plugged](image)

**Figure 10:** A Spectra of the frequency response of broadband noise as a function of earphone (Apple EarPods Unplugged) and volume setting is shown.

![Frequency Response of Broadband Noise for Apple EarPods Unplugged](image)
**Figure 11:** A Spectra of the frequency response of broadband noise as a function of earphone (PowerBeats Plugged) and volume setting is shown.

**Figure 12:** A Spectra of the frequency response of broadband noise as a function of earphone (PowerBeats Unplugged) and volume setting is shown.
Figure 13: A Spectra of the frequency response of broadband noise as a function of earphone (SONY ZX Series) and volume setting is shown.

Figure 14: A Spectra of the frequency response of broadband noise as a function of earphone (Beats Studio) and volume setting is shown.
References:


