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Strategies for Reducing Auditory Risk from a Typical Drum Set

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STRATEGIES FOR REDUCING AUDITORY RISK FROM A TYPICAL DRUM SET

A Doctoral Scholarly Project Submitted in Partial Fulfillment
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ABSTRACT

Percussionists are at risk for noise-induced hearing loss. They are especially at risk because of the type of sound produced by their instrument – impact noise. The quick onset and offset times combined with the high peak intensity levels can create permanent damage to the auditory system. Damage to the auditory system because of excessive exposure to music is called a music-induced hearing disorder (MIHD).

A MIHD may manifest as many different permanent disorders including music-induced hearing loss, tinnitus, decreased sound tolerance, diplacusis, or dysacusis. Symptoms of these disorders may affect the musicians in their art and their jobs as many musicians rely on their perception of sound and music to play their instruments. Sound exposure can be damaging depending on two factors – the intensity level that the musician is exposed to and the duration of the exposure. Reducing the intensity level of the sound and the duration of the exposure can help protect the musician from permanent auditory damage. Many products on the market offer a safer listening and playing experience for musicians including percussion-specific equipment.

If auditory damage has already occurred, the musician should visit an audiologist who can provide them with care for their MIHD and education about safe sound exposure limits. Best practice guidelines for the audiologist are outlined in Chapter II of the document and include thorough education and verified care and services. Music-induced hearing disorders are preventable. It is the duty of the audiologist to spread awareness and education to percussionists and all musicians for the prevention of MIHD.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

ABR	Auditory Brainstem Response
AEP	Auditory Evoked Potentials
AER	Auditory Evoked Response
CHL	Conductive Hearing Loss
dB	Decibel
dBA	Decibel A-Weighted Curve
dBC	Decibel C-Weighted Curve
dB HL	Decibel Hearing Level
dB SPL	Decibel Sound Pressure Level
DoD	U.S. Department of Defense
EPA	Environmental Protection Agency
HPDs	Hearing Protective Devices
Hz	Hertz
kHz	Kilohertz
kPa	Kilopascal
L_{Aeq}	Equivalent Continuous Sound Pressure Level
L_{Aeq8}	Eight Hour A-weighted Equivalent Sound Level
L_{Peak}	Peak Level
MIHD	Music Induced Hearing Disorder
msec	Millisecond

µsec	Microsecond
NHCA	National Hearing Conservation Association
NIDCD	National Institute of Deafness and Other Communication Disorders
NIHL	Noise-Induced Hearing Loss
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PTS	Permanent Threshold Shift
SNHL	Sensorineural Hearing Loss
SNR	Signal-to-Noise Ratio
TTS	Temporary Threshold Shift
WHO	World Health Organization

CHAPTER I

REVIEW OF THE LITERATURE

High levels of sound exposure over time can cause irreversible, noise-induced hearing loss (NIHL). Auditory trauma can occur after one, high-intensity sound exposure. An individual's noise exposure includes all activities that they participate in, each day. This can range from someone's job to their hobbies including any music either performed or enjoyed. Beginning with the basics of the properties of sound, the following review of the literature will summarize the current research about sound, music, percussion instruments, and the risk to the auditory system if proper protective measures are not taken.

Sources of Sound and How Sound Travels

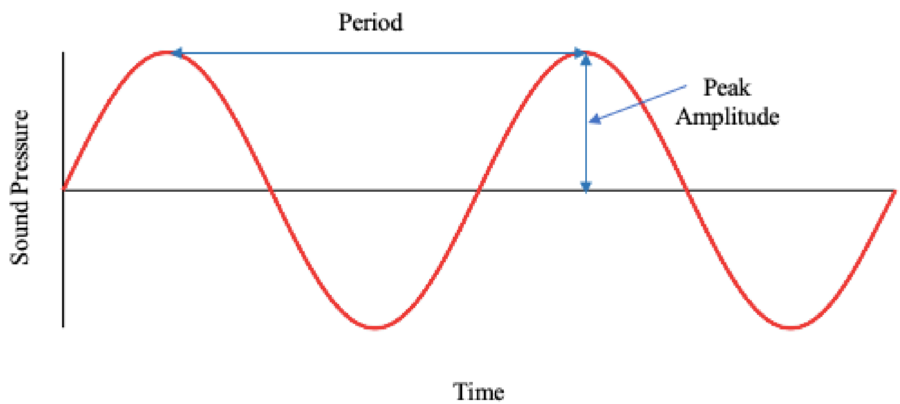
Sound has physical properties that affect how it is perceived and heard in the human auditory system. The following sections will describe these properties of sound as well as how it travels and temporal characteristics.

Physical Properties of Sound

Sound is a result of vibrations traveling through a medium and creating acoustic energy in the form of pressure variations. Sound's physical properties can be categorized by its frequency, speed, wavelength, amplitude, and period. Variations of these properties can change the perceived loudness, pitch, and overall perceived quality of the sound. Figure 1.1 below shows a sine wave with peak amplitude and period detailed.

Figure 1.1

A Sine Wave Moving Through the Air with Labelled Physical Properties of Sound



Note. Image courtesy of Donald Finan, Ph.D.

Frequency

Frequency is measured in Hertz (Hz) and is the number of times a sine wave repeats its pattern per second. Humans can perceive frequencies ranging from approximately 2-20 kHz (Driscoll, 2022; Fletcher & Munson, 1933; Purves et al., 2001). The relationship between frequency and perceived pitch is complex. The perception of the pitch is dependent upon the frequency. Although not a one-to-one relationship, a higher frequency is often associated with a higher perceived pitch. For example, a 0.5 kHz tone is perceived as a lower pitch than an 8 kHz tone.

Speed

The speed of sound is often measured in meters per second (m/s) and is dependent on the medium that the sound is traveling through. For example, sound travels at a rate of 1500 m/s through seawater and 343 m/s through air which is 20° Celsius (Driscoll, 2022). Within the medium, some additional factors and conditions also affect the speed of sound. Using air as the medium for sound to travel through, the air temperature, elevation, humidity, wind speed, or wind direction, will change the speed of sound. For example, sound travels at a rate of 343 m/s through air which is 20° Celsius, however, it slows to a rate of 331.6 m/s through air which is 0° Celsius (Driscoll, 2022).

Wavelength

Wavelength is the distance that one complete cycle occupies in space. It is calculated as the speed of sound divided by the frequency. The higher the frequency is, the shorter the wavelength will be. Higher frequencies are more easily blocked by any barriers in the path of the sound wave because of the shorter wavelengths. Lower frequencies have longer wavelengths and are more likely to travel around physical barriers as opposed to being blocked or absorbed by them (Driscoll, 2022).

Amplitude and Intensity

The amplitude of the sound is the maximum pressure variation that the sound creates above and below the ambient pressure (Driscoll, 2022). The intensity is the power of the sound wave (Jacobsen, 1997). The amplitude of the sound and the intensity of the sound are positively correlated, meaning that the higher the amplitude, the higher the intensity. Intensity is related to the perceived loudness of the sound. The higher the intensity of a given sound, the louder that sound is perceived. Fletcher and Munson (1933) found that the relationship between intensity and perceived loudness is not linear and varies by frequency. The negative effects that sound has on the human auditory system are directly related to the intensity of the sound (Driscoll, 2022). These specific effects will be discussed in the Risk Factors section on page 15.

Period

The period of the waveform created by sound is the amount of time in seconds that it takes one wavelength to pass a specified point. Period and wavelength are positively correlated in the manner that the longer the wavelength of sound, the longer the period of the waveform. As the frequency of the waveform changes, the period of the waveform changes. Period and frequency are inversely related. As the period of the sound wave increases, the frequency decreases (Driscoll, 2022).

Mechanical Vibrations

When an object is excited by an external device, such as a drumstick onto a drumhead, the excited surface, the drumhead in this example, is put into motion called *vibration acceleration*. An object's response from the vibrational stimulation is termed *resonance*. Each object has a resonant frequency, and some have multiple resonant frequencies. When freely vibrating, the surface will vibrate at its *resonant frequency*, also called its "natural" frequency. The resonant frequency or frequencies are dependent on the material that the object is made from (Gelfand, 2017; Newman, 2008).

There are three main physical properties to a vibrating system which include the mass, stiffness, and damping characteristics. Each property affects how the sound is transmitted from the vibration to acoustic soundwaves through the air. The mass of the vibrating system resists the acceleration of the waveform, storing it as kinetic energy. When the system is vibrating, the stiffness of the system temporarily stores the waveform energy as deflection. The damping characteristic dissipates the waveform by taking the kinetic energy and converting it into heat (Watson, 1916).

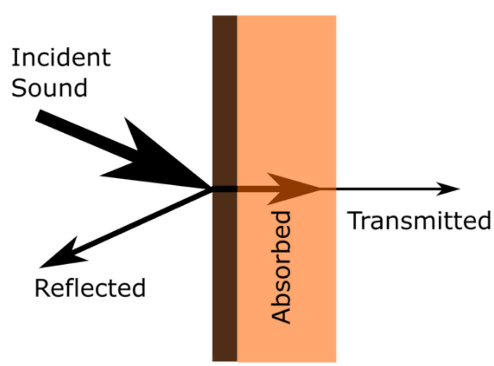
Types of vibration can be classified as *free* or *forced*. *Free vibration* occurs after an object experiences displacement or impact such as a drumstick hitting a drumhead. *Forced vibration* occurs when repeated force is exhibited periodically onto an object to cause it to vibrate such as the rotating equipment in a motor. Vibration can also be classified by the type of waveform that it produces. *Periodic vibration* is the production wave with a repeating pattern. One example of a periodic wave is a sine wave, such as with a pure tone. *Aperiodic vibration* is due to random excitation of an object with irregular contacts, such as a musician striking the snare drum (Driscoll, 2022).

Factors Influencing How Sound Travels

As sound energy travels through the medium of air as a waveform, it will make contact with other materials and mediums. Once the contact is made, the sound is absorbed into, reflected from, and/or transmitted through that material. Figure 1.2 below illustrates these potential reactions.

Figure 1.2

Examples of Absorption, Reflection, and Transmission of Sound



Note. Image courtesy of Donald Finan, Ph.D.

The reaction of the sound wave is dependent on the density and elasticity of the material with which the sound wave makes contact. Generally, as the material increases in density, the amount of sound absorbed and reflected increases while the amount of transmitted sound decreases. As density decreases and the material becomes more porous, more sound is transmitted. This is especially true for high-frequency sounds due to the shorter waveforms moving more easily through the porous material. As the elasticity of the material increases, more sound is transmitted, and less sound is absorbed and reflected. This occurs because the more elastic the material, the more it will begin to vibrate, oscillating with the sound's waveform which more efficiently transmits the sound waves (Watson, 1916).

Temporal Characteristics of Sound

Time-Varying Noise

Most studies about hazardous noise exposure have been about continuous noise. *Continuous noise* stays relatively stable over time with a constant sound pressure level (SPL) without interruption, while *intermittent noise* is comprised of a mix of relatively quiet periods and noisy periods. Some examples of continuous noise are a blower fan or a generator (Driscoll, 2022). Some examples of intermittent noise are found in machinery that cycles through different sound levels such as packaging equipment, saws cutting timber, or forklifts stopping and starting in a warehouse.

Intermittent noise is a term generally used to define many different acoustic environments with variations in the stimulus or noise (Driscoll, 2022). Intermittent noise may be less damaging to the auditory system than continuous and impulse or impact noise but can still be damaging in dangerous doses (Kryter et al., 1966; Patuzzi, 1998; Sataloff et al., 1969, 1983; Schmidek & Carpenter, 1974; Suter, 2017).

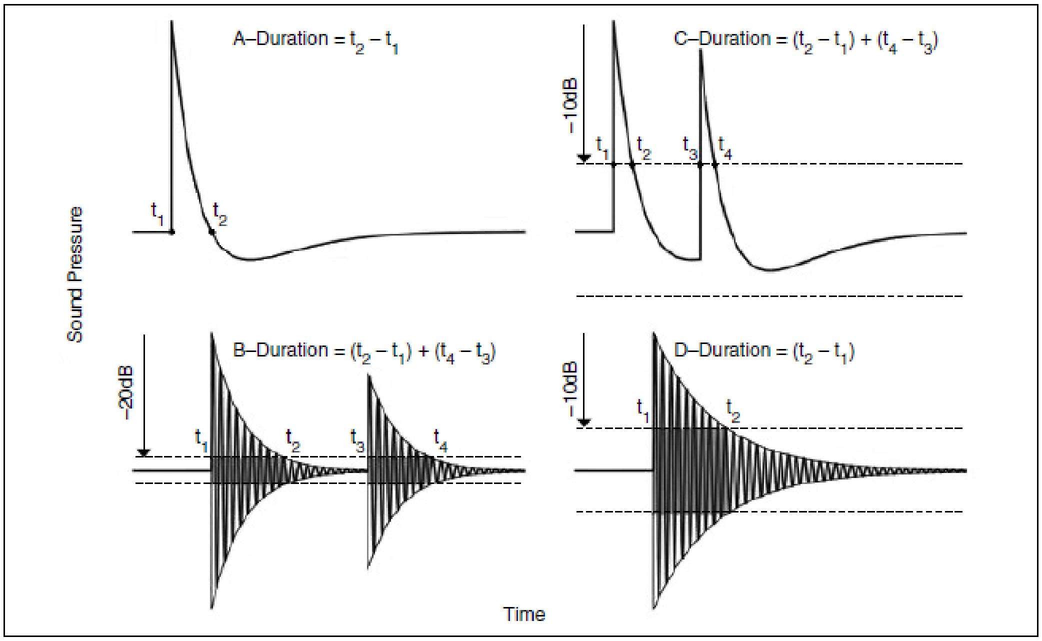
Impulse/Impact Noise

The terms "impact" and "impulse" noise are commonly used interchangeably. Although similar, there are key differences between the two. Most generally, *impulse noise* occurs with a sudden release of energy. Gunfire is an example of impulse noise as is the popping of a balloon. *Impact noise* occurs when two objects strike each other such as two metal plates or a drumstick onto a drumhead (Hamernik & Hsueh, 1991). Acoustically, both impact and impulse noise have very quick onset and offset times (less than one second) with peak intensity levels reaching greater than 100 dB SPL up to 185 dB SPL (Coles et al., 1968; Henderson & Hamernik, 1986; W. J. Murphy et al., 2022). Impact noise tends to carry more low-frequency energy than impulse noise because of the mass and stiffness properties of the materials involved in sound production. The frequency components, however, depend on the resonance of the materials (Hamernik & Hsueh, 1991).

One way to quantify the characteristics of impact and impulse noise is to measure the energy duration. Duration can quantify the structure of impact/impulse noise. A-, B-, C-, and D-duration parameters are used to describe characteristics of the sound energy dissipation over time. A-duration is the time it takes for SPLs to leave and return to ambient pressure (W. J. Murphy et al., 2022). B-duration is frequently used by the DoD in MIL-STD-1474E, and it measures the duration of the impulse energy that follows within 20 dB of the peak amplitude. C-duration is commonly used in a damage-risk criterion from Pfander et al., (1980) and is the duration that the waveform follows within 10 dB of the peak level. Finally, D-duration is used in Smoorenburg's (1982) damage-risk criterion and is the duration of the pressure envelope, rather than the waveform, that follows within 10 dB of the peak level. The figure below illustrates the duration parameters discussed above.

Figure 1.3

Duration Parameters

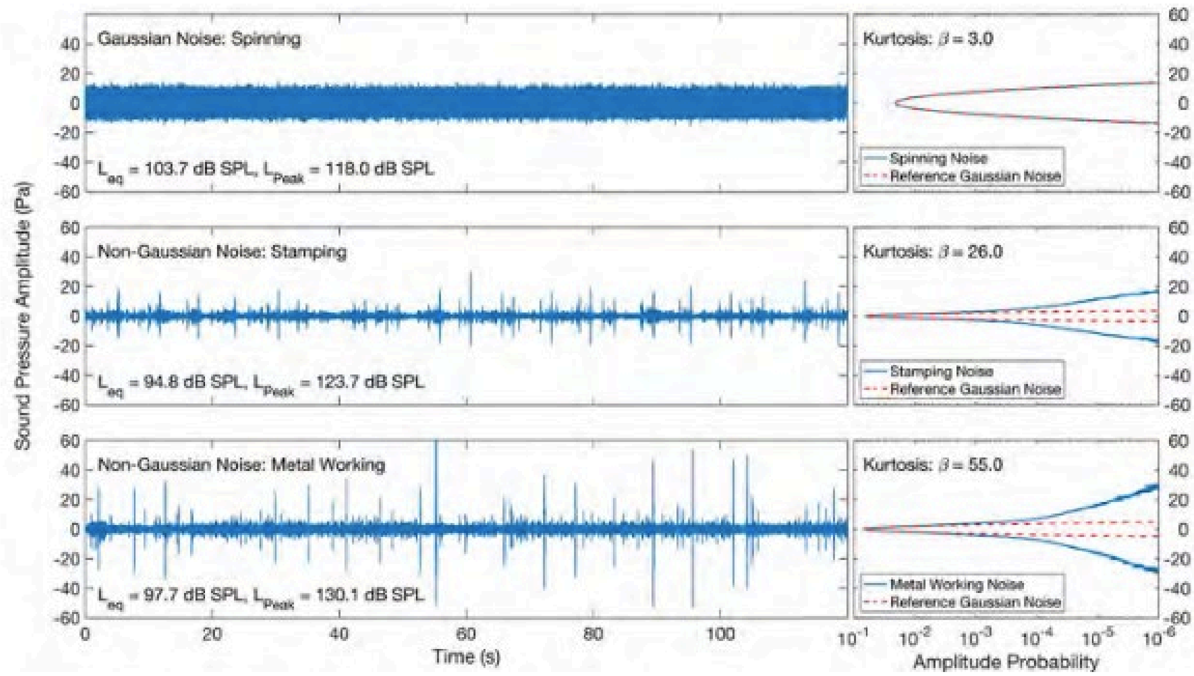


Note. Reproduced from: Figure 6.7 – Definition of duration parameters. By Flamme GA, Murphy WJ. (2022). Chapter 6: Brief high-level sounds. In: The Noise Manual, 6th edition, edited by Meinke DK, Berger EH, Driscoll DP, Neitzel RL, Bright. Reprinted with permission from AIHA.

Other parameters used to describe impact/impulse noise include peak level, rise- and fall times, energy, interval, continuous background noise levels, and kurtosis (Smoorenburg, 2003). The peak level is the greatest SPL from ambient pressure in either a positive or negative direction. The rise and fall times of an impact/impulse noise are very brief. The rise time of an impulse noise produced by a firearm has been measured to be 4 microseconds (µsec) (Nato Research and Technology Organization Neuilly-Sur-Seine, 2000). The energy of an impulse/impact noise is directly related to the damage to the cochlea that the exposure may cause. It is measured by acoustic energy per unit area (Nato Research and Technology Organization Neuilly-Sur-Seine, 2000). The interval of the impulse, or the pressure envelope duration, is less than 1 second (Davis & Clavier, 2017). Kurtosis is a statistical measurement as well as a histogram function of the height of the frequency of occurrence. The kurtosis metric is sensitive to peak, interval, and duration. A kurtosis value of zero is representative of the skewness for a normal distribution. A positive kurtosis value indicates a distribution that is more peaked than normal, whereas a negative kurtosis value corresponds with a distribution shape flatter than normal (Heckert et al., 2002). A graphic illustrating the relation between a waveform produced by multiple sound sources and the amplitude with a kurtosis value is seen below in Figure 1.4. The metal working waveform within Figure 1.4 is an example of impact noise. Impulse or impact noise will have higher kurtosis values than the kurtosis values of continuous or intermittent noise (Zhao et al., 2010). Studies have shown that there is an increased risk of auditory damage from sound with a higher kurtosis value (Qui et al., 2020; Zhao et al., 2010).

Figure 1.4

Wave Forms and Amplitude Probabilities with Kurtosis Values of Three Different Industrial Noises: Spinning, Stamping, and Metal Working



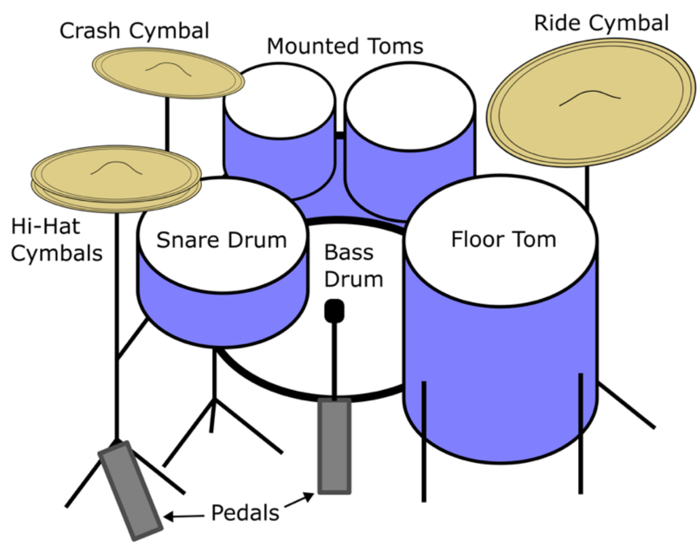
Note. Reproduced from Qiu, W., Murphy, W. J., and Suter, A. (2020). Kurtosis: A new tool for noise analysis. Acoustics Today, 16(4), 39. https://doi.org/10.1121/at.2020.16.4.39 with the permission of the Acoustical Society of America.

Drums as a Source of Sound

In the world of percussion, there are many different types of instruments and drums that all create a different sound and timbre. Most drums, with the exclusion of the tympani or kettle drum, do not produce a definite pitch (Backus, 1977). In a typical drum set, the basic drums used are the snare drum, the tom-tom drums including the floor tom, and the bass drum. The drums are accompanied by cymbals and other auxiliary percussion instruments. When struck, each instrument has its own vibrational properties that create a specific sound unique from the rest. The layout of the typical drum set along with examples of all the instruments described below can be seen in Figure 1.5.

Figure 1.5

Layout of a Typical Drum Set



Note. Courtesy of Donald Finan, Ph.D.

Standard Components a Drum Set and Their Acoustic Characteristics

Snare Drum

The snare drum is a double-headed drum with metal wires, or snares, underneath the bottom drumhead, called the snare drumhead. There is no standard practice for how the drumheads are tuned, however, it is common for the snare drumhead to be tuned with a slightly lower tension than the top drumhead, called the batter head (Rossing et al., 1992). The batter head is struck by the drumsticks, vibrating the snare drumhead which vibrates the snares underneath to create the typical snare drum sound. The snares may be turned off or be moved away from the snare drumhead via a lever, creating a different sound when the batter head is struck. Turning the snares on or off greatly changes the frequencies of the snare drum. In Rossing et al.'s study in 1992, the vibrational or modal patterns of a drum were analyzed following the drum being struck in different places. Depending on the vibrational pattern of the drumhead, frequencies elicited may range from 1.83 to 5.95 kHz. Another factor influencing the sound is the tightness of the snares to the snare drumhead. The tighter the snares rest on the bottom drumhead, the more velocity is needed to rattle the snares (Rossing, 2001). The sound intensity from a snare drum can elicit high peak values. Jaroszewski et al. (2000) collected sound level measurements for many percussion instruments including the snare drum with the snares turned on and off. With the snares turned off, peak level (L_{Peak}) values reached 130.8 dB SPL, and with the snares turned on, L_{Peak} values reached 127.5 dB SPL. These measurements were collected in an isolated practice room with a ¼ inch condenser microphone placed on a tripod and positioned at the ear level of the percussionist. Measurements of a total drum set were also collected and will be summarized in the tom-tom section on page 13.

Bass Drum

The bass drum has two heads that are separated from each other at a greater distance than the two drumheads of the snare drum. They are usually 50-100 cm in diameter. In general, as the diameter of the bass drum increases, the indefinite pitch of the drum will decrease. There are some bass drums with only one drumhead, but two drumheads are typically preferred by percussionists (Rossing et al., 2001). Tuning the bass drum requires altering the tension of the drumheads. The batter drumhead, or the drumhead being struck, is usually tuned to a greater tension than the carry drumhead, or the second vibrating drumhead. In the analysis of the sound spectra of an 82 cm diameter base drum, there are near harmonics seen from 1-2 kHz, however, above 2 kHz the peaks become more inharmonic. The human ear is more sensitive to the range of sound with inharmonic peaks, which is why the bass drum is not perceived to have a definite pitch like the tympani drum (Backus, 1977; Rossing et al., 2001). Fletcher and Bassett (1978) measured SPLsof a bass drum 90 cm in diameter in an anechoic chamber with a General Radio 1933 sound level meter. They measured levels up to 121 dB SPL.

Tom-Tom Drum

The typical drum set has a pair of suspended tom-tom drums called the mounted toms along with a floor tom, located underneath the mounted toms. Each tom-drum has a different diameter and creates a different sound. They may have either one or two drumheads, however, two drumheads are typically used and create a more indefinite pitch. Like the bass drum, as the diameter of the tom-tom drumhead increases, the indefinite pitch of the drum will decrease (Backus, 1977). There is a lack of research about the sound intensity of tom drums, however, Jaroszewski et al. (2000) measured the intensity levels of a full drum set being played in an isolated practice room and found that L_{Peak} values reached 132.8 dB SPL.

Cymbals

The cymbals are a vibrating plate that produces the higher-pitched “shimmer” sound of the drum set. Traditional cymbals used in a drum set are saucer-shaped with a small raised dome in the center. There are many categories of cymbals. Perceptually, cymbals are often described by terms such as bright, sharp, or shimmery. There are six common types of cymbals including crash, ride, clash, China, hi-hat, or effects cymbals. The crash cymbal creates a sharp sound when struck and is used for occasional accents. The ride cymbal has a long sustain that resonates longer than the other cymbals when it is struck. The China cymbal takes on a different shape with its edges turned up instead of turned down as the traditional saucer shape of the other cymbals. The sound of the China cymbal is very cutting and bright. The high-hat cymbals are two small cymbals mounted onto a stand. The high-hat cymbals can be played with the foot pedal or with a drumstick. The distance between the two cymbals is controlled by the foot pedal. The sound created when hit by a drumstick is dependent on the distance between the two cymbals. Effects cymbals are used to produce accented, special sounds. One of the many types of effect cymbals is the splash cymbal which produces a bright sound (MasterClass, 2021).

The diameter of cymbals is highly variable and can range from 20-75 cm. Cymbals may also have many different thicknesses. Depending on the tool used to strike the cymbal and the location of the contact, they can sound very different. Examples of different tools may be a traditional drumstick, a brush, or a chain. Cymbals may be struck on the rim, body, or dome. The fullest sound is produced when the cymbal is struck about one-third of the way in from the rim (Backus, 1977). When the cymbal is struck, three different features have been observed. The first is the strike sound produced by rapid wave propagation. This only lasts for the first millisecond (msec). The second is the stroke peak around 7-10 kHz. This lasts through the next 10-20 msec. The third feature is the aftersound of the cymbal in the range of 3-5 kHz which lasts a second after the first two features. This final feature is what gives the cymbal its signature shimmer sound (Rossing, 2001). There are low-frequency sounds present after striking a cymbal, however, because of the low level, they are not as noticeable as the higher-frequency sounds produced (Backus, 1977). L_{Peak} levels of a pair of crash cymbals measured at the ear level of the musician reached 136.7 dB SPL (Jaroszewski et al., 2000). Each piece of the drum kit elicits a different sound with different frequencies. With this range of frequencies at high intensities, NIHL is a concern for the drumming community. While this manuscript will use the more common term “noise” when referring to hazardous sound that can damage the auditory system, it is acknowledged that music and drumming are not necessarily perceived as “noise” in the common use of the term.

Damage Risk Criteria

Noise Exposure Limits

Several government agencies and other organizations have published standards and guidelines regarding occupational noise exposure limits. These include, but are not limited to, the Occupational Health and Safety Administration (OSHA), the Department of Defense (DoD), the National Institute for Occupational Safety and Health (NIOSH), the Environmental Protection Agency (EPA), and the World Health Organization (WHO) (Berglund et al., 1999; NIOSH, 1998; Office of Noise Abatement and Control, 1974; OSHA, 1983a; U.S. Department of Defense, 2010). These regulatory standards, mandated by law in the U.S., and recommended guidelines, or best practices, set expectations for the allowable exposure to sound levels over a specified period and stipulate requirements for enrollment in hearing conservation programs. These limits are expressed differently and measured in various ways by each agency/organization. The following section will provide an overview of these specifications for noise exposure by regulatory agencies or organizations with a summarizing table at the end of the section.

Occupational Safety and Health Administration 29 CFR 1910;95 Overview

The regulations of OSHA are mandated by law in most general industries. To first define commonly used terms, the time-weighted average (TWA) is the sound exposure averaged over an eight-hour working day. Commonly used measurements are the decibel A-weighted filter (dBA) and the decibel C-weighted filter (dBC). The action level is the TWA which requires hearing tests, optional hearing protection, and hearing conservation program inclusion. The permissible exposure limit (PEL) is the TWA where engineering or administrative controls and/or hearing protection requirements must be put in place to reduce exposure. Under the OSHA 29 CFR 1910.95 (OSHA, 1983a) regulation, the action level is 85 dBA TWA and the PEL is 90 dBA TWA. Sounds from 90-140 dBA are integrated to measure the TWA. A TWA of 90 dBA is considered 100% dose. If the average is over 90 dBA, there is an exchange rate of 5 dB in effect meaning for each additional 5 dB of average exposure, the allowable time is reduced by 50%. For example, if the exposure is 95 dBA, the worker meets a 100% dose after working four hours instead of eight. There is a ceiling limit of 115 dBA, meaning workers should not be exposed to any continuous noise above that set level. Peak impulse noise exposure may not exceed 140 dB SPL (OSHA, 1983a). As expressed earlier, the OSHA regulations are the law, but some industries were exempted such as oil and gas, agriculture, and government. Musicians who are employed by a business with more than 10 employees must abide by these regulations as well.

Department of Defense Instruction 6055.12 Overview

The Department of Defense releases instructions to each of the military branches that outline employee safety, including noise safety. Each branch may make its adjustments to the instructions if they are at least as conservative as the DoD instructions. Both the 8-hour TWA PEL and the action level are 85 dBA using a 3 dB exchange rate which is 2 dB more conservative than the OSHA 29CFR-1910.95 regulation’s 5 dB exchange rate. With every increase of 3 dB from the 85 dBA PEL, there is a 50% reduction of allowable exposure time. Impulse noise levels should not be above 140 dB peak pressure (dBP). If impulse noise levels are above the given limit, engineering and administrative controls should be put into place. Those who are occupationally exposed to impulses ≥140 dBP must be enrolled in a hearing conservation program. When entering an area where impulses over 140 dBP may be present, specific signs must be posted with warnings requiring hearing protection or double hearing protection. The number of allowable impulse exposures in a day is 500 auditory risk units (ARU). An ARU is a metric used for hazard rating; different impulse events have different ARU ratings. MIL-STD-1474E is approved for all departments and agencies within the DoD, including military musicians. Within the different branches of the military, there are additional guidelines that include regulated exposure to ototoxins, double hearing protection, and protection from intense low-frequency noise (U.S. Department of Defense, 2010).

National Institute of Occupational Safety and Health Publication Number 98-126

In 1998, NIOSH published its "Criteria for a Recommended Standard: Occupational Noise Exposure, Revised Criteria 1998" (NIOSH, 1998). This is considered a best practice guideline for occupational noise exposure, meaning that it is encouraged but is not enforced by law. Some of the terminologies differ in the NIOSH 1998 standard from the OSHA 29CFR-1910.95 regulation. Instead of PEL, the recommended exposure limit (REL) is used. The REL is more conservative than OSHA's PEL and references a criterion of 85 dBA TWA integrating all sounds from 80-140 dBA. NIOSH does not specify an action level. The exchange rate is 3 dB, 2 dB less than OSHA's 5 dB exchange rate. The ceiling level does not permit any exposure of any type of noise (continuous, intermittent, impulse) above 140 dBA. Impulse noise should be integrated with the measurement of all other noise (NIOSH, 1998).

Environmental Protection Agency/Office of Noise Abatement and Control 550/9-74-004 Overview

The EPA has a published set of suggestions for appropriate sound exposure limits in the context of public health and safety, and not specific to the workplace. The recommendations from the EPA are based on the 96th percentile of the population, which they recognize as the near entirety of the population. In their publication (Office of Noise Abatement and Control, 1974), it is noted that these suggestions are not guidelines or regulations, but an effort to maximize public safety and comfort. The EPA exposure limits are set to which the public should not be at risk of a PTS of greater than 5 dB over the course of a lifetime. The suggested average exposure over 24 hours, or the Leq_{24}, is below 70 dB. A 3 dB exchange rate is used for integrating sound levels greater than 70 dB. This is equivalent to a 75 dBA 8-hour TWA, commonly used as the average workday. Impulse events should not exceed 145 dB SPL, assuming that they are isolated events or no more than one impulse per day. If the event is ≤25 msec, the peak level should not exceed 167 dB SPL. The EPA's noise level document is a politically neutral document that serves the sole purpose of protecting the hearing of the general population (Office of Noise Abatement and Control, 1974).

World Health Organization Overview

Like the EPA (Office of Noise Abatement and Control, 1974), the WHO (Berglund et al., 1999) has a "conditional" recommendation of a 70 dBA permitted average sound level over 24 hours for leisurely activities throughout a lifetime. A "conditional" recommendation requires much more debate because there is not substantial evidence on the specific topic the WHO (Berglund et al., 1999) is evaluating. There are some WHO (Berglund et al., 1999) recommendations that are strong recommendations, which require much less debate due to the quantity and quality of evidence supporting the net benefit for the public. In an occupational setting, the WHO (Berglund et al., 1999) established an action level of 80 dBA averaged over an eight-hour workday and integrated using a 3 dB exchange rate. The WHO (Berglund et al., 1999) recognizes a lack of research covering possible interventions leading to safe levels of impulse and impact noise exposure from sources such as firearms and has not published damage risk criteria specific to impulse/impact noise while recognizing that that there is a need for one. The most recent guidelines from the WHO (2018) have been published for the office of Europe but have pulled evidence from other countries including the United States. In summary, Table 1.1 below outlines the specific exposure limits for each regulatory agency and organization.

Table 1.1

Noise Exposure Regulations and Guidelines

Organization	**Occupational Safety and Health Administration (OSHA, 1983a)**	**National Institute for Occupational Safety and Health (NIOSH, 1998)**	**Department of Defense (U.S. Department of Defense, 2010)**	**Environmental Protection Agency (Office of Noise Abatement and Control, 1974)**	**World Health Organization (Berglund et al., 1999)**
PEL	90 dBA TWA	-	85 dBA	-	-
REL	-	85 dBA	-	-	-
Leq_{24}	-	-	-	70 dBA	70 dBA
Action Level	85 TWA	-	85 dB TWA	-	80 dBA
Exchange Rate	5 dB	3 dB	3 dB	3 dB	3 dB
Impact & Impulse	140 dB, integrated with other noise exposure	140 dB, integrated with other noise exposure	140 dBP	145 dB SPL or 167 dB SPL if ≤25 msec; one impulse event per day	-
Ceiling	115 dB	140 dB	140 dBC	-	-
Monitoring Noise Exposure	Once for baseline, then as conditions change	Every 2 years if exposure > 85 dB	Annual monitoring for significant threshold shift	-	-

Risk Factors

Continuous versus Intermittent Sound Exposure

Continuous noise is thought to be more dangerous and damaging than intermittent noise, although both may damage the auditory system if safe limits are exceeded. (Patuzzi, 1998; Pourbakht & Yamasoba, 2003; Sataloff et al., 1969; Schmidek & Carpenter, 1974; Suter, 2017). Pourbakht and Yamasoba published a study in 2003 that analyzed the auditory brainstem response (ABR) thresholds and hair cell status of 20 male guinea pigs after being exposed to a one-octave band of noise at 4 kHz for 5 hours. The purpose was to evaluate differences in continuous versus intermittent noise exposures. The guinea pigs were separated into four groups. Group 1 was exposed to 115 decibels SPL (dB SPL) of continuous noise, group 2 was exposed to 115 dB SPL of intermittent noise, group 3 was exposed to 125 dB SPL of continuous noise, and group 4 was exposed to 125 dB SPL of intermittent noise. They found that after the sound exposure, the animals in group 1 had ABR threshold elevations of 32 dB SPL at 2 and 4 kHz and 28 dB SPL at 6 and 8 kHz. When the stimulus was increased to 125 dB SPL (group 3) there was an even greater threshold elevation of up to 57 dB SPL at 4 kHz. The guinea pigs that were exposed to intermittent noise still had a threshold shift but to a lesser degree. Group 4 had a threshold elevation of 10 dB SPL at 2, 4, 6, and 8 kHz. Following the noise exposure, group 2 showed threshold elevations of 25-, 22-, and 16 dB SPL at 2, 4, and 8 kHz, respectively. When comparing the four groups, Group 1 (continuous noise at 115 dB SPL) had significantly higher threshold shifts than the thresholds of Group 2 (intermittent noise at 115 dB SPL) ($p < 0.05$). The animals in Group 4 (intermittent noise at 125 dB SPL) had significantly lower threshold increases than those of Group 3 (continuous noise at 125 dB SPL) ($p < 0.05$). Group 3 experienced the greatest amount of ABR threshold shift for all test frequencies. Cochlear hair cell damage was also evaluated by sacrificing the guinea pigs 15 days after noise exposure, and the number of missing hair cells was counted in surface preparations of the organs of Corti stained with rhodamine-phalloidin. The extent of hair cell damage was comparable to the physiological ABR findings. Although all four groups had damage to the cochlea, the groups exposed to continuous noise had more cochlear damage and greater threshold shift than those animals exposed to intermittent noise. However, the authors noted that the cochlear damage was not proportional to the total noise energy at these intensities.

In 2012, Chung et al. compared the audiometric test results of a group of factory workers who produced farm machinery to a group of firefighters. The factory workers were exposed to more continuous noise overall while the firefighters were exposed to intermittent, variable noise throughout their workdays. The exposure of the factory workers ranged from 66-97 dBA with an average exposure of 82 dBA. Exposure levels were not measured for the firefighters, but past studies suggest an average between 76-79 dBA (Lee et al., 2011). The participants were tested four times over four years: baseline audiometric evaluations first followed by three annual evaluations. Hearing loss over the four years was minor, however, the factory workers had significantly more hearing loss at 2, 3, and 4 kHz on their baseline evaluation when compared to the firefighters ($p<0.0001$). Amongst the factory workers with 10 or more years of employment, average hearing losses at 2, 3, and 4 kHz fell into the hearing-impaired range (audiometric thresholds >25 dB HL). The firefighters that had extended employment also showed elevated thresholds, but far less than those of the factory workers. Hearing losses in the lower frequencies, ≤1 kHz, were minor. Although the risk of hearing loss is less with intermittent noise compared to continuous noise, hazardous levels of either can create hearing loss (Chung et al., 2012; Hamernik et al., 2007; Kryter et al., 1966).

Impulse/Impact Exposure

Impulse and impact noise exposure can be dangerous to the auditory system after just one exposure, called acoustic trauma. Spongr et al., (1998) studied the effects of impact noise on the cochlear microphonic in chinchillas. They exposed 15 chinchillas to impact noise replicating the sound of a hammer hitting a steal plate with peak levels ranging from 107-131 dB SPL. Exposure times were adjusted so each animal would experience the same total amount of acoustic energy. The group receiving the 125 dB SPL impacts was exposed for 7.5 hours while the group receiving 131 dB SPL impacts was exposed for 1.125 hours. There was a control group that remained unexposed. PTSs were present but small in the chinchillas exposed to 107-119 dB SPL but steeply increased in those exposed to 125-131 dB SPL. The most damage following the exposures was 13-17 mm from the apex of the cochlea. This region corresponds to frequencies between 3-8 kHz. The damage to the cochlea following the high-impact noise exposure was permanent and worsened in the days following exposure.

Physical Proximity

When sound travels, it is attenuated by 6 dB every time it doubles in distance. This is known as the *inverse square law* (Driscoll, 2022). Therefore, the closer one is to a sound source, the higher the intensity levels of the sound they are exposed to. Wiggins and Liston (2021) conducted a study in the UK where they measured the sound exposure of a clothed mannequin placed varying distances from a loudspeaker expelling a 90 dB of equivalent continuous SPL (L_{Aeq}) tone with a frequency spectrum ranging from 8-16 kHz to mimic concert exposure to popular music. Measurements were taken at 30 cm, 1m, 2m, and 3m from the loudspeaker at 60 degrees azimuth. Results confirmed that from the 90 dB L_{Aeq} stimulus, there was approximately a 6 dB decrease in sound level measurements for each doubling in distance from the sound source. Although moving further from the sound source reduces the sound exposure, this is not always possible. Other methods are required to protect the hearing system when exposed to high levels of sound.

Hearing Conservation Programs

If occupational noise exposure exceeds the action levels previously discussed, a hearing conservation program (HCP) must be in place (Berglund et al., 1999; NIOSH, 1998; OSHA, 1983a; U.S. Department of Defense, 2010). OSHA 29CFR 1910.95 requires seven components to be included as a part of a HCP. These include noise level/exposure monitoring, engineering and administrative noise controls, provision and use of hearing protection if noise control is insufficient, audiometric monitoring, education of employees, effectiveness of HCP review, and recordkeeping requirements. Noise level monitoring includes tracking potentially harmful auditory environments. The noise levels should be monitored by intensity and duration (OSHA, 1983a). The use of personal hearing protective devices may include earmuffs or ear plugs to reduce the sound energy entering the ear (Hong et al., 2013). The provision of hearing protection devices, audiometric testing, and worker training should be provided at no charge to all noise-exposed workers. A baseline audiometric evaluation should be conducted as well as annual evaluations to monitor hearing sensitivity in noise exposed employees. Education of employees should ideally be completed prior to working in the hazardous noise environment and is required to be repeated annually during each year of employment. Noise exposure measurements should be recorded and kept for two years, and employee audiogram records should be completed and kept for the duration of the employee's employment (OSHA, 1983a).

Noise-Induced Hearing Loss

The National Institute of Deafness and Other Communication Disorders (NIDCD) describes noise-induced hearing loss (NIHL) as temporary or permanent hearing loss that is caused by hazardous noise exposure, either continuous over time or intense, impulse noise (National Institutes of Health, 2014). Forty million, or 24.4% of adults aged from 20-69 years have NIHL either unilaterally or bilaterally in the United States (Carroll et al., 2017). Noise-induced hearing loss can occur in the middle ear, categorized as conductive hearing loss (CHL), or in the inner ear, categorized as sensorineural hearing loss (SNHL). The change in hearing may be manifested by temporary or permanent damage to the auditory system. When exposed to hazardous noise levels, the sound may damage the ear drum, the middle ear ossicles, or the cochlea in the inner portion of the ear. Inside the cochlea, the damage is done to the organ of Corti, and specifically the hair cells on the organ of Corti that are part of the auditory pathway, necessary for sound energy from the outside world to be transmitted into neural signals to the brain to be processed and interpreted. The mechanical damage to the auditory system following hazardous levels of noise is expanded in the mechanical damage section below beginning on page 26.

Etiology of Noise-Induced Hearing Loss

Sound waves enter the auditory system through the outer ear. Sound travels as acoustic energy down the ear canal to the tympanic membrane where it is transduced into mechanical energy as it enters the middle ear space. Here it travels as mechanical energy, transmitted by the three ossicles: the malleus, incus, and stapes. The mechanical energy moves through the stapes and onto the oval window where fluid called perilymph inside the inner ear (cochlea) is displaced, further carrying the sound energy through the inner ear as hydromechanical energy.

Once the sound reaches the inner ear, it travels through many complex coding mechanisms in the organ of Corti, towards the brainstem, where it is transduced into electrochemical nerve signals that travel to the brain to be processed. (Brownell, 1997). Instantaneous high-intensity impulse/impact sound exposure may cause mechanical damage to the hearing system, known as acoustic trauma. Continuous noise exposure to sound levels > 85 dBA over extended periods of time will cause metabolic damage to the hearing system known as gradual onset NIHL.

Mechanical Damage

The high intensity and rapid onset and offset of impact and impulse noise can cause trauma to the middle ear, resulting in CHL, or destruction of the delicate structures within the cochlea, resulting in SNHL (Heupa et al., 2011; Mayorga, 1997; Patterson & Hamernik, 1997; Roberto et al., 1989). A rupture or perforation to the tympanic membrane is the most common ear injury following a rapid, high-intensity sound such as an impulse event (Gan et al., 2016). The average intensity for an immediate tympanic membrane perforation is 185 dB SPL (Garner & Brett, 2007). Through work with cadavers in 1906, Zalewski found that the minimal pressure to create a tympanic membrane perforation was 37 kPa (equal to 125.3 dB SPL). Even if there is no perforation, the tympanic membrane may be weakened after exposure to multiple high-level impulses or impacts (Liang et al., 2017). Hazardous impulse noise exposure can also lead to ossicular chain disruption. This can cause a 30 to 40 dB decrease in hearing threshold (Gulick et al., 1989).

Within the inner ear, intense noise exposure may lead to mechanical damage to the cochlea. Damage can be done to the tectorial membrane, OHCs, stereocilia on the OHCs, or the basilar membrane. Unlike the tympanic membrane and ossicles, many of these structures cannot be repaired after being damaged. Loss of these structures can create a hearing loss of over 40 dB HL (Ryan et al., 2016).

Metabolic Damage

Numerous studies have been conducted to assess the metabolic damage to the inner ear from impact and impulse noise (Dunn et al., 1991; Hamernik & Hsueh, 1991; Henderson et al., 1991; Lataye & Campo, 1996). In Hamernik and Hsueh's study in 1991, 47 randomly selected chinchillas were exposed to variable counts of 150-, 155-, and 160 dB SPL impulse noises inside a reverberant, hard-walled chamber. Permanent threshold shift was quantified by auditory evoked potentials (AEPs) while cochlear hair cell emissions were quantified by distortion product otoacoustic emissions (DPOAEs). Auditory evoked potentials and DPOAEs were measured pre-and post-exposure to evaluate threshold shift and cochlear cell death. Results varied from subject-to-subject within most groups (number of exposures and intensity level of the impulse). One of the chinchillas with only one exposure to 155 dB SPL showed stable, normal audiometric thresholds but with reduced DPOAEs between 1.5-3 kHz. Six of the eight chinchillas in the group exposed 100 times to 155 dB SPL showed a large PTS at multiple frequencies and reduced or absent DPOAEs (Hamernik & Hsueh, 1991).

Dunn et al. (1991) completed a study that compared hearing loss in 16 adult chinchillas after being exposed to a continuous noise stimulus (Group I) or an impact noise stimulus (Group II). The impact noise stimulus consisted of a hammer hitting a nail for four hours, five consecutive days. The peak pressure of the impact noise stimulus was 120 dB SPL and the duration of the impact was 116 ms pink noise was used for the continuous noise stimulus, for four hours at 110 dB SPL, five days consecutively. Auditory evoked response (AER) thresholds were obtained at 1, 2, 4, and 8 kHz before the noise exposure and 30 days after the noise exposure. On average, Group I obtained a threshold shift of 22.25 dB at 1 kHz, 32.28 dB at 2 kHz, 29.65 dB at 4 kHz, and 12.45 dB at 8 kHz. Group II obtained threshold shifts of 42.50 dB at 1 kHz, 54.61 dB at 2 kHz, 58.69 dB at 4 kHz, and 49.13 dB at 8 kHz. Using an ANOVA statistical analytical approach, the impulse exposed groups were compared to the continuously exposed groups. The AER thresholds of Group II, who were exposed to the impact noise stimulus were significantly greater than the AER thresholds of Group I, who were exposed to the continuous noise stimulus ($p<0.0001$). (Dunn et al., 1991). The different frequencies tested show variable amounts of threshold shift. This unique audiometric configuration is attributed to the characteristics of NIHL.

Characteristics of Noise-Induced Hearing Loss

Noise-induced hearing loss can be described in terms of audiometric configuration, temporal onset, and laterality. The functional changes in the auditory system in humans are usually identified on a pure-tone audiogram which is used to plot hearing sensitivity as a function of frequency in decibel hearing level (dB HL).

Audiometric Configuration

On a conventional audiogram, SNHL resulting from overexposure to sound initially presents as normal hearing thresholds (≤20-25 dB HL) in the low frequencies with an audiometric notch (poorer hearing thresholds) typically in the range of 3-6 kHz. It is common for the audiogram configuration to return to better hearing thresholds at 8 kHz, especially in the early phases of NIHL. With continued exposure to hazardous sound, the audiometric notch broadens and deepens, affecting the higher frequencies and then the lower frequencies, creating a greater degree of hearing loss over time (Ryan et al., 2016; Sataloff et al., 1983).

Permanent versus Temporary Threshold Shift

Temporary threshold shift (TTS) is a change in hearing thresholds that later recover to the initial baseline hearing sensitivity and may occur after hazardous noise exposure (Kryter et al., 1966; Ryan et al., 2016). Typically, the hearing shift resolves within 16 to 48 hours, however, there have been occurrences where hearing thresholds recovered three weeks after the exposure. Because of this, a threshold shift should not be defined as permanent or temporary until at least three weeks post-exposure. Susceptibility to TTS is dependent on the individual and the precautions taken to prevent a threshold shift including, but not limited to, the use of hearing protective devices (HPDs), rest time between exposures, and auditory status (e.g., hearing loss) present before the hazardous exposure. Temporary threshold shift is a reversible precursor to cochlear hair cell damage leading to permanent threshold shift (PTS) from NIHL (Ryan et al., 2016).

Permanent threshold shift is a form of NIHL that does not resolve after a recovery period following high noise exposure (Ryan et al., 2016). As discussed in the previous section, PTS is a SNHL that can affect many frequencies, depending on the nature of the exposure. Permanent threshold shifts will result in an irreversible decrease in hearing sensitivity as well as the loss of ability to process complex auditory signals such as speech, especially in the presence of background noise (Bielefeld, 2013).

Laterality

Noise-induced hearing loss can affect both ears symmetrically, or the hearing loss can be asymmetric (Hong et al., 2013). Asymmetry is seen frequently in people with NIHL that resulted from shooting firearms without hearing protection. In a study published in 2010 by Rasmussen et al., sound measurements were conducted using different measurement locations and conditions.

Microphones were placed near the muzzle and where the shooter's right or left ears would be positioned when firing the firearm. In some conditions the shooter was present and in other conditions, the shooter was not present to demonstrate the head-shadow effect. For the left and right ears, the measurements were 153.5 and 153.2 dB pk SPL respectively without the head in position. When the shooter's head was present the peak levels were 157.2 dB pk SPL on the left side and 147.4 dB pk SPT on the right side. The peak level reached the shooter's left side slightly quicker than it reached the shooter's right side due to the distance from the muzzle of the firearm. There was a measured difference of nearly 10 dB SPL between the right and the left ear with a slight increase in the time of when the peak level reached each ear when the shooter was present. The difference in SPLs measured at the right and left ear level will lead to asymmetric hearing loss for firearm users if proper prevention methods are not in place.

Percussionists are also susceptible to asymmetric hearing loss. The ear that is closest to the high-hat cymbal is more likely to have greater hearing thresholds than the ear opposite of the high-hat cymbal (Hoffman et al., 2006). In right-handed drummers, the high-hat cymbal usually sits on their left side leading to elevated hearing thresholds in the left ear. Left-handed drummers usually have their high-hat cymbal on their right side leading to elevated hearing thresholds in the right ear (Hoffman et al., 2006). Other conditions that will affect the severity and risk of asymmetric hearing loss are the style of music performed, the history of musical performance of the musician, and the practice and performance set up of the musical group in which the musician is involved (Axelsson et al., 1995; Axelsson & Lindgren, 1981; Behroozi & Luz, 1997; D. W. Johnson et al., 1985; Ostri et al., 1989; Royster et al., 1991;).

Other Symptoms of Noise-Induced Hearing Loss

Noise-induced hearing loss can be accompanied by other auditory symptoms. Of those with NIHL,

> 21.0% of adults aged ≥ 18 years had difficulty following a conversation amid background noise, 11.2% had tinnitus (i.e., the perception of ringing in the ears or other sounds such as buzzing, hissing, and clicking), and 5.9% had sensitivity to everyday sounds (hyperacusis). (Carroll et al., 2017).

Jansen et al. (2009) studied NIHL and other hearing complaints in professional orchestral musicians. To test for diplacusis, musicians' pitch matched a 1 kHz stimuli presented at 60 dB HL from the left ear to the right ear. The results are interpreted as percentages representative of the deviation of pitches between the ears. For example, if a pitch of 10 kHz in the right ear is matched to a 13.33 kHz tone in the left ear, the deviation would be 3.3%. Of the 160 musicians tested, 44% exhibited an interaural pitch difference of 1%, 18% of musicians had a difference of 2%, and 3% of musicians had a difference of 3% or more.

Additionally, high levels of noise exposure and NIHL are associated with many non-auditory effects such as mental illness including anxiety or depression, irritability, high blood pressure, and cardiac disease. (Basner et al., 2014; Carroll et al., 2017; Moore & Lusk, 1997). Both the audiometric characteristics of NIHL and the other non-auditory symptoms may put a musician's job at risk especially since musicians have a heavy reliance on auditory cues and precise auditory perceptions to play and perform music well (Jansen et al., 2009).

Noise-Induced Hearing Loss in Percussionists

Noise-induced hearing loss can cause irreversible auditory damage. The following sections will discuss the risks that percussionists have for hearing loss as well as the need for hearing loss prevention for this population.

Percussionist Risk of Noise-Induced Hearing Loss

Impact noise from drums and drumming may be damaging to the percussionists themselves or to nearby listeners when occupational or recreational noise exposure limits are exceeded. Phillips et al. conducted a study published in 2010 that analyzed the prevalence of NIHL in musicians ages 18-25 years. The students were divided into their instrument sections for data analysis. Instrument sections included voice, percussion, brass, woodwind, string, and keyboard. A Pearson chi-squared analysis revealed that a statistically significant amount of the percussionists had a unilateral notch at 6 kHz ($p=0.5$) when compared to the other instrument groups. Among the full ensemble, the unilateral notches at 6 kHz were more common in the left ear (63%) than in the right ear (37%). The researchers did not note any reasoning behind most unilateral losses being in the left ear. Because the brass and percussionists have a known high exposure and the highest prevalence of unilateral losses, it is suggested that their losses are due to hazardous sound exposure while the bilateral losses were more commonly seen in the other instrument groups may be due to a systemic, genetic predisposition (Phillips et al., 2010).

In another study conducted by Pawlaczyk-Łuszczyńska et al. in 2011, the noise exposures of orchestral musicians were analyzed. During performances and concerts, integrating-averaging sound level meters and personal sound exposure meters were placed among the different instrument groups on tripods with microphones 0.1-0.5 meters from the musician's ears. Continuous noise exposures ranged from 72-97 dBA with peak SPL measurements ranging from

105-146 dBC. Maximum exposures were between 86-123 dBA. Among the highest measured exposures were the percussionists with a maximum exposure level at 103.4 dBA. Measurements were only collected during performances and concerts and not during practice times (Pawlaczyk-Łuszczyńska et al., 2011). Although this study took measurements when the ensemble was playing together in a performance manner, the sound levels are much different when rehearsing on one's own. During solo practice, the sound is amplified by the room differently than when playing with an ensemble. Wenmaekers and Hak (2015) found that the sound levels during individual practice may be 2 -10 dB greater depending on the instrument and the musical piece being played.

These two studies were limited to noise exposure of percussionists during their time playing their instruments. A person's noise dose encompasses noise exposures throughout the whole day, including all hobbies, recreational activities, jobs, or anything else the musician spends their time doing in addition to the practice and performance time with their instrument. Callahan et al. (2011) conducted research regarding collegiate musician noise exposure. In their research, they found that percussionists have the longest playing time per week, averaging 17.1 hours per week. In addition to their practice schedule, Callahan et al. found that musicians partake in many other activities that involve excessive noise levels. Ninety-five percent of music students stated that they attend concerts, 92% listen to music from an iPod or MP3 player, and 87% frequented local bars and restaurants with loud music. Of those students, less than 10% wear hearing protection when partaking in those extracurricular activities (Callahan et al., 2011). With average exposures of 85.4 dB and peak exposures of 103.4 dB in musical practice and performance (Pawlaczyk-Łuszczyńska et al., 2011), their allowed exposure throughout the rest of the day may be limited or completely exhausted, depending upon the duration of the performance.

Need for Hearing Loss Prevention for Percussionists

Musicians, and especially percussionists, are at an increased risk for NIHL. A PTS or other symptoms of NIHL could result in difficulty continuing with their musical career. There is a need for hearing loss prevention programs for musicians including education about NIHL as well as how to prevent it (Jansen et al., 2009). Education from a hearing loss prevention program such as Dangerous Decibels has proven to be effective and successful (Griest et al., 2007; Martin et al., 2013). A program such as this for musicians will likely reduce the risk of NIHL and all accompanying symptoms to protect the musical enjoyment and careers of those in the musical field. The following Chapter 2 will provide examples of current standards of practice for hearing loss prevention targeting musicians as well as other hearing protective measures specific to percussion instruments.

CHAPTER II

APPLICATION TO THE FIELD OF AUDIOLOGY

Hearing loss prevention for percussionists involves teamwork among professionals. These include band/music directors, music educators, venue managers, and employers. Ideally, the audiologist is engaged early in the efforts of the team. More commonly, the audiologist is engaged once a musician is either aware of the need for prevention efforts or following the onset of symptoms of MIHDs when they seek hearing healthcare. This chapter is written to provide the audiologist with an overview of strategies to prevent hearing loss and other auditory disorders among musicians.

Best Practice Guidelines for the Prevention of Music Induced Hearing Disorders

Several organizations such as the National Hearing Conservation Association (NHCA) (NHCA, 2018), NIOSH (1998), the American Academy of Audiology (AAA) (AAA, 2020), and the National Association for Music Education (NAfME) (NAfME, 2007) that have published standards of best practice to prevent music-induced hearing loss (MIHL). Music-induced hearing loss is defined by AAA (2020) as a temporary or permanent decrease in hearing sensitivity because of music overexposure. A music-induced hearing disorder (MIHD) is a temporary or permanent hearing disorder including tinnitus, distortion, hyperacusis, diplacusis, and dysacusis, that is a result of hazardous exposure to music (AAA, 2020). These hearing disorders often extend beyond the loss of hearing sensitivity. Music produces a much more complex acoustic event than industrial noise, which indicates the separation of them in the context of the causality of a hearing disorder from NIHL to MIHD (AAA, 2020; le Clercq et al., 2016; Chesky, 2008). Prevention of MIHD is focused on protecting the health of the musicians and those nearby, enjoying the music.

National Hearing Conservation Association Position Statement

The NHCA published a position statement entitled "Recreational Music Exposure" in 2018 which addresses the prevention of Music Induced Hearing Disorders (MIHD) and can be accessed at https://www.hearingconservation.org/assets/docs/MIHD_Position_Statement_FINA.pdf. This statement outlines the risk of hearing loss after being exposed to unsafe levels of music whether it be through a personal audio system or through listening to live music at a concert.

The NHCA states that MIHD is a 100% preventable disorder if proper precautions are taken. To assess a listening environment, NHCA recommends taking measurements with a sound level meter or noise dosimeter rather than a smartphone app. There are numerous smartphone applications that one can download to collect a sound level measurement in a potentially hazardous listening environment. When possible, the applications should be calibrated using a known noise level. Without calibration, studies have shown that there may be a measurement error of up to 15 dB (E. Murphy & King, 2016; Neitzel et al., 2016). NHCA suggests that when in the presence of hazardous music levels, individuals may reduce their auditory risk by decreasing the level of the music, increasing the distance between the listener and the music source, or using a properly fitted HPD. Different HPDs can be used in certain situations. One option is a product that is designed to attenuate as much sound as possible. These are commonly used in industrial settings but are not preferred by musicians due to their attenuation of high frequencies more than low frequencies. These types of HPDs are also likely to over-attenuate in the context of music enjoyment. The second option is a product designed to maximize a listening environment with equal attenuation across frequencies. NHCA notes that these are less likely to over-attenuate or change the quality of music. Because of this, the second option is preferred by musicians and listeners. Further, education is important to spread awareness and help to prevent MIHD (NHCA, 2018).

National Institute of Occupational Safety and Health Recommendations for Musicians

"Reducing the Risk of Hearing Disorders Among Musicians" is a published guidance document from NIOSH (2015) for musicians and discusses the risk of hearing loss in the context of exposure limits. The document can be accessed at https://www.cdc.gov/niosh/docs/wp-solutions/2015-184/pdfs/2015-184.pdf. The NIOSH REL criterion is relevant to this population of workers. These guidelines serve as an initial line of defense for protecting the hearing of the musician and others. Music venue operators, NIOSH employers, schools and colleges, and anyone responsible for music-related activities should consider the following NIOSH (2015) recommendations:

1. Educate musicians and those involved in the industry about the importance of using increased distances between individuals and arrangements of instruments to reduce overall noise exposure during practice and performances. [For more specific recommendations, see Chasin (2010)].
2. Develop a hearing conservation program that includes annual audiometric testing and training about protecting musicians' hearing.

3. Encourage participation in education and awareness campaigns of music-induced hearing loss, see a list of resources in the "more information" section below.
4. Since music levels fluctuate greatly from one practice or performance to another, conduct regular sound level assessments at a reference location and establish an average and a range of music levels during rehearsals and performances. Conduct personal exposure monitoring of performers and exposed staff. Assessments should be conducted, where practicable, by a certified industrial hygienist or an occupational safety and health specialist.
5. If sound level assessments show elevated levels (consistently exceeding the NIOSH limit of 85 dBA), consider reducing the amount of time musicians and staff are exposed through rotation or offering frequent breaks in quiet areas.
6. Work with musicians and affected workers to identify hearing protection solutions that work best for the individual. A variety of hearing protection options are available from inexpensive foam earplugs to potentially more costly products designed specifically for professional musicians and other entertainers.
7. Although more studies are needed to verify the effectiveness of general noise control solutions for musicians' workspaces, the following features may be effective in reducing the overall sound exposure levels among musicians and staff:
    - Consult with architects, acousticians, and sound engineers to create the best desired and most effective musical workspace.

- If the workspace for musicians or staff is very reverberant, treat certain sections of walls and ceilings with sound absorbent material to reduce reverberation time. Higher ceilings also help reduce reverberation for high energy instruments such as brass instruments and percussion.
- For rehearsal and practice, consider using appropriate size rooms for the number of musicians.
- Placement, spacing, and use of enclosures can help reduce overall sound levels from certain instruments —If rooms or venues have hard reflective surfaces, position instruments and speakers to direct sound away from musicians

Musicians and workers in the music industry should consider the following NIOSH (2015) recommendations:

1. When possible, play music at lower levels during individual and group rehearsals. If using amplified speakers in live performance, work with sound engineer to adjust the volume down to desired but acceptable levels.
2. If you use In-Ear monitors (IEM) to listen to vocals and stage instruments, work with your sound engineer and fitting audiologist to reduce sound output to workable levels, especially during practice and rehearsals.
3. Wear hearing protection when appropriate and ask your employer or audiologist about getting custom-fitted earplugs that work best for your environment.
4. Have your hearing evaluated annually by an experienced audiologist who understands noise exposures in the music industry.

5. Always be aware of your sound exposure level, an easy and practical way is to use your smartphone and a sound meter app (see NIOSH evaluation of smartphone sound measurement apps https://www.cdc.gov/niosh/topics/noise/app.html)
6. Give your ears some rest; ears typically need about eighteen hours of quiet after exposure to loud sounds to return to normal hearing. Take advantage of breaks (in quiet areas) whenever possible (NIOSH, 2015).

By following these behavioral interventions, safe limits of exposure should not be exceeded and the hearing health of the musicians, venue owners, students, and employers will be protected.

American Academy of Audiology Clinical Consensus Document

The goal of the AAA consensus document entitled "Audiological Services for Musicians and Music Industry Personnel" was published in 2020 and can be accessed at https://www.audiology.org/wp-content/uploads/2021/05/Musicians-Consensus-Doc_Final_1.23.20.pdf (AAA, 2020). The goal of the consensus document is to provide best practice recommendations and strategies to audiologists to create a hearing loss prevention plan for musicians and others involved in the music industry. American Academy of Audiology notes that musicians are at risk for asymmetric hearing loss. Musicians performing with violins, violas, and percussion instruments are at the highest risk of asymmetry. The hearing loss, whether symmetric or asymmetric, can cause difficulty communicating in everyday life as well as reduce the musician's ability to hear their performances both independently and within an ensemble. Among all the hearing disorders including hearing loss, tinnitus, diplacusis, dysacusis, and sound distortion, tinnitus is the most reported among musicians. MIHDs such as tinnitus or diplacusis may result in a distraction during practice, performance, and overall enjoyment of music listening due to auditory distraction and distortion. Diplacusis, which is a decrease in the clarity of auditory stimulus, or dysacusis, which is the difficulty in processing the details of a sound, can threaten the musician's musical career. Definitions of these disorders can be found below in Table 2.1.

Table 2.1

Music-Induced Hearing Disorders

Disorder	Definition
Music Induced Hearing Loss (MIHL)	Temporary or permanent loss of hearing sensitivity following overexposure to hazardous levels of music.
Tinnitus	The perception of ringing in the ears or other sounds such as buzzing, hissing, and clicking. Tinnitus is the most common MIHD among musicians. Tinnitus symptoms may worsen following exposure to hazardous levels of music.
Decreased Sound Tolerance	A heightened sensitivity to sound intensity that may occur with a decrease in hearing sensitivity, called "recruitment", or without a decrease in hearing sensitivity, called "hyperacusis". The decrease in sound tolerance may develop into physical pain accompanying moderate sound exposure.
Diplacusis	A change in pitch perception, often different between ears. In musicians, diplacusis may reduce their accuracy of pitch perception.
Dysacusis	A decrease in auditory clarity resulting in distortion to tonal frequency or quality. Distortion often increases as the sound stimuli increases in intensity.

Note. Adapted from American Academy of Audiology (2020). Clinical Consensus Document: Audiological Services for Musicians and Music Industry Personnel. https://www.audiology.org/wp-content/uploads/2021/05/Musicians-Consensus-Doc_Final_1.23.20.pdf

Because of these risks and consequences of MIHD, audiologists should be prepared to recommend and counsel about prevention efforts to musicians (AAA, 2020). The gold standard for a clinical encounter with a musician is briefly summarized in Table 2.2.

Table 2.2

Best Practice for Audiology Clinical Encounters with a Musician

Audiologic Component	Best Practice Recommendation
Case History	A case history specific for musicians should include the reason for the visit, the music exposure(s), symptoms, and noise exposures.
Audiometric Evaluation	Obtain a baseline hearing test to use for comparison to annual evaluations. Include air and bone conduction threshold testing, speech testing, immittance, and otoacoustic emissions. During air and bone conduction, include 0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz. If possible, include the extended high frequencies.
Consultation/Education	Discuss the science behind sound, the anatomy of the hearing system, and MIHDs. Discuss the audiogram paying special attention to the 'noise-notch' frequencies.
Ear Impressions	Use high viscosity impression material to create a product with a tight fit. Take the impression past the second curve of the ear canal and fill the full helix. Take the impression while having the musician mimic what they will be doing while wearing the device.
Fitting, Verification, Orientation to Hearing Protective Devices	Educate on proper insertion, removal, and cleaning of the hearing protection devices by the musician. Utilize real ear testing to verify the attenuation of the product.
Follow-Up Serial Evaluation and Report	Create an ongoing relationship including annual hearing evaluations. Educate on the importance of hearing health.

Note. Adapted from American Academy of Audiology (2020). Clinical Consensus Document: Audiological Services for Musicians and Music Industry Personnel. https://www.audiology.org/wp-content/uploads/2021/05/Musicians-Consensus-Doc_Final_1.23.20.pdf

A thorough case history should be collected with special attention paid to the length of sound exposure, the professional setting, the musician's instrument of specialty, and the personal preferences of the musician. Sound level measurements may be taken at the musician's venue if possible. Additionally, an audiometric evaluation and ear impressions are recommended to inform the fitting and verification of an ear-level hearing protective device (AAA, 2020).

American Academy of Audiology notes that ear level devices can attenuate the sound to a certain amount depending on the style and fit, but they can also create a change in the perception of the music. The optimal frequency response for earplugs is a uniform attenuation across the audible frequency spectrum, sometimes termed "hi-fidelity" attenuation. This will give the musician the best chance at training their ear for hearing protection. Universal-fit earplugs or custom-fit earplugs are available to music industry professionals. If the musician chooses a universal fit product, extensive counseling is required because there is high variability between the product options. Part of this variability includes the fit of the HPD by the musician. Instructions on proper insertion are essential (AAA., 2020).

The AAA consensus document further informs the audiologist that custom-fit earplugs are more reliable and consistent for frequency response and attenuation. The audiologist should consider the material used for the earplug. Medical-grade silicone earplugs tend to last longer than vinyl, as the vinyl will shrink over time. Silicone plugs, therefore, provide the best opportunity for earplug longevity. While taking earmold impressions, the audiologist should use a high-viscosity impression material to distend the ear canal and ensure the impression extends past the second curve of the ear canal. Verification of the attenuation should occur at the time of the HPD fitting. Active attenuation may also be beneficial to the musician as it offers more flexible attenuation. Active attenuation will allow the musician to communicate clearly when there is no presence of high-intensity sound. In-ear monitors may also be worn for hearing protection, and to mix the musical sounds on stage into the ear canal as desired by the musician. These protect the musician from the hazardous levels of sounds from the audience, the acoustics of the venue, and the sound levels of the environmental sound systems used. It is the role of the audiologist to guide the musician toward ear-level equipment that will be consistently used to protect the function of their auditory system. (AAA., 2020).

National Association for Music Education Position Statement

National Association for Music Education's position statement gives the hearing health responsibility to the music educators who are training musicians. A part of the musician's music education should focus on the prevention of MIHD. The education should go beyond just delivering the instruction but should address the musician's beliefs values, and motivations. NAfME's (2007) guidelines for music educators are as follows:

1. Recognize the widespread, serious public health issue that is NIHL and address it within lesson plans and rehearsals. Reduce high levels of sound for long durations.
2. Model to children how to avoid MIHD injury. Model strategies such as taking breaks within repetitive, high level music practice sessions.
3. Be a source of educational information to colleagues in the field of music.
4. Recognize that each music education scenario is unique. Educators should design quality, refined teaching materials for their respective student population.

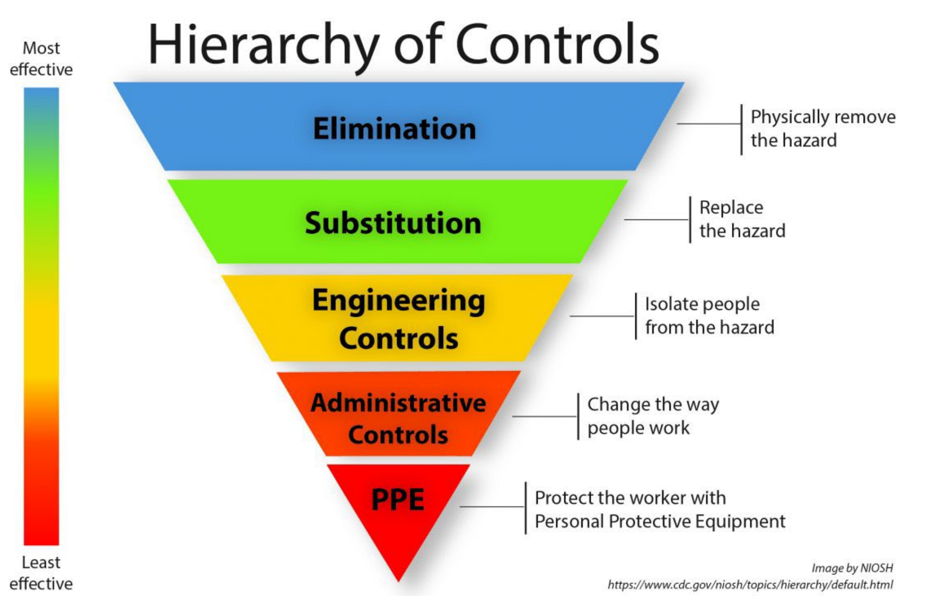
Through music education, different protective measures can be distributed to colleagues and music students to promote hearing and auditory health. The following section will go into detail about protective strategies, that are currently available and when they would be appropriate in the context of hearing conservation programs for drummers.

Hearing Protective Strategies Used by Percussionists

Many different strategies can be implemented to protect the hearing health of musicians. One way of categorizing these measures is by applying the Hierarchy of Controls (Centers for Disease Control and Prevention, 2023). This method separates measures by how accessible they are as well as how effective they are. See Figure 2.1 for a reference to the hierarchy of noise controls. Measures include the elimination of the sound hazard, substitution of the sound hazard, engineering controls, administrative controls, and personal protective equipment (PPE).

Figure 2.1

Hierarchy of Controls



Note. Reproduced from Centers for Disease Control and Prevention. (2023). Hierarchy of controls. Centers for Disease Control and Prevention. https://www.cdc.gov/niosh/topics/hierarchy/default.html

Elimination

The most effective method of sound exposure reduction is the elimination of the sound hazard. Music is sound, so eliminating the sound is not a realistic solution for musicians and music listeners. The following sections discuss other control options to reduce hazardous sound exposure and protect the hearing health of the musicians.

Substitution – Electronic Drums

Substitution includes replacing the source of the hazardous sound. Electronic drums may be substituted for the traditional, acoustic drum set. Electronic drums are designed with a set of drum pads that are constructed to resemble drums and cymbals. These pads are equipped with electronic sensors (piezo pickup) to send an electronic signal through a cable to a sound module which produces synthesized or sampled digital sounds (from real drums) relative to how hard the drummer hit the pad. The sound intensity can be controlled more precisely when using an electronic drum set. A desired volume limit can be set, and regardless of the force that the musician is using, the electronic drums will not elicit a sound higher than the limit setting. This can be especially helpful during practice (Edgoose, 2023). Some disadvantages to using an electronic drum set include the potential for forming poor drumming habits due to a different rebound feel, poor development of dynamic variation between the different drums and cymbals, and striking the instruments with too much force. The drum pad sizes are smaller than on traditional drum sets, which may lead to poor form over time because of the smaller playing space. Some strokes, such as a rimshot, cannot be achieved with electronic drum sets. Some models may have a trigger zone for a rim shot, but it cannot be achieved by the traditional stroke: striking the rim with the middle of the stick while simultaneously striking the end of the stick on the batter head. Electronic drum sets are most commonly recommended by percussion instructors after someone has been trained to play on a traditional set due to the differences listed above (West, 2021).

Engineering Controls

Drum Shields

Engineering sound controls separate individuals from the hazardous sound source. One option to separate individuals from the hazardous sound is a drum shield. Drum shields are set between the drums and those at the performance and are intended to attenuate the sound of the drums. There are many types of drum shields available that vary in size, material, number of panels, and style. Pictured below are two different styles from the brand ClearSonic that include a 5-panel shield (Figure 2.2) and an isolation booth (Figure 2.3). Sandell et al. (2007) measured the attenuation of a drum shield, also called a drum screen, using various sizes of drum shields. They used SLMs to measure the SPL produced by a drummer playing a 50-second excerpt in an anechoic chamber. One microphone was placed by the drummer's right ear and 2 other microphones were placed in front of the drummer. The 50-second excerpt played included all the drums on the drum set and was played 6 times in each condition. Three-paneled drum shields 80, 100, 120, and 150 cm in height and made of plywood were used to alter the conditions in which the drummer was playing. Measurements were taken once without any drum shield and twice with every screen height – once with sound absorbers and once without. Attenuation increased for the simulated audience as the height of the screens increased. The average sound level for the listening audience with an 80 cm screen was 92.7 dBA and the average sound level with a 150 cm screen was 85.3 dBA.Of concern, is that sound level measurements increased at the drummer's ear level from 108.3 dBA without any drum shield to 110 dBA with a 150 cm drum shield. Although sound levels decreased for the simulated listeners located on the opposite side of the screen from the drummer, the sound levels for the drummer remained at a hazardous level regardless of drum shield placement (Sandell et al., 2007). While drum shields are useful and effective in protecting the music listeners, they are not protective for the drummer. If drum shields are used, they should be paired with other protective measure(s) so both the audience and the musician are protected from hazardous sound exposure.

Figure 2.2

ClearPanel 5-Panel Acrylic Drum Shield

Note. Reproduced from A2466X5 - 5-panel acrylic Drum Shield. ClearSonic. (n.d.). https://www.clearsonic.com/collections/clearsonic-panel-csp/products/a2466x5 with permission from ClearSonic Customer Support Specialist

Figure 2.3

ClearPanel MegaPac Isolation Booth

Note. Reproduced from MP - MEGAPAC portable isolation booth. ClearSonic. (n.d.). https://www.clearsonic.com/collections/megapac/products/megapac with permission from ClearSonic Customer Support Specialist

Seat Shakers

Seat shakers (also called "bass shakers", "butt kickers", "booty shakers, or "rump thumpers") are a two-part system that changes the way that the drummer is playing. They work on the basis that low-frequency bass is mostly felt (tactile response) and not heard. The ability of a drummer to monitor the bass output of their drumming is limited by the poor low-frequency response of the human ear and masking of low frequencies during live musical performances.

Seat shakers are comprised of low-frequency woofer loudspeakers that are attached underneath the drummer's throne or to a ¾ inch piece of plywood and placed onto the floor for the drummer's feet. The bass drum microphone is routed to the shaker to provide input. The perception is not entirely tactile as the drummer's ear will also receive the low-frequency sounds via bone conduction. The seat shakers generate improved low-frequency vibrational feedback for the musician, which tends to decrease the sound level that the drummer is playing at. This not only decreases the sound intensity that is produced by the drums but also may reduce arm and wrist damage (Chasin, 2010).

Low Volume Drumheads

Drum equipment manufacturers have created drumheads to use during practice sessions to reduce overall the sound intensity produced by the drum set. While traditional drumheads are made from a solid material, usually made with a mix of plastics, low-volume drumheads are made from a durable mesh. The mesh drumheads come in different forms. There are 1-ply, 2-ply, and 3-ply options currently available on the market. The thickness of each ply is not consistent between manufacturers, so a 1-ply drumhead from one manufacturer may have a similar thickness to a 2-ply drumhead from a different manufacturer. The holes created by the woven mesh material reduce the overall intensity of the sound produced by the drums (Chris, 2021). Low-volume drumheads are advertised for apartments, condos, and dormitories, but can be used in any practice setting (Remo, n.d.). Although formal research has yet to be conducted on the precise differences between the traditional drumheads and the revised drumheads, informal reviews from musicians reflect a noticeable decrease in sound intensity without sacrificing the practice quality when using the low-volume drumheads (Chris, 2021; Petterson, 2023).

Low Volume Cymbals

Many percussion equipment companies have created a low-volume cymbal that is marketed for use in practice spaces, drum lessons, and low-volume performances. These low-volume cymbals are available in many cymbal styles including hi-hats, crash, crash ride, ride, splash, and China cymbal. One brand with a low-volume cymbal option, Zildjian™ states that the cymbals are 80% quieter than the traditional cymbals because of their unique, mesh-like design. Their 16” L80 low-volume crash cymbal is seen below in Figure 2.4. Like the Silentstroke drumheads, there is a lack of formal research conducted to compare the differences between this low-volume cymbal and a traditional cymbal, but informal reviews reflect a noticeable decrease in sound intensity while still creating an articulate and responsive sound (Zildjian, n.d.).

Figure 2.4

Zildjian™ 16” L80 Low Volume Crash Cymbal

Note. Reproduced with permission from 16" L80 low volume crash. Zildjian. (n.d.). https://zildjian.com/collections/cymbals-browse-by-types-crash/products/l80-low-volume-16-crash

Drumhead Dampers

Dampers can be placed on top of drumheads to reduce high-frequency ringing that resonates from a drumhead. Historically, drummers have used household items for damping such as wallets or tape, however, there are also commercially sold dampers including mylar rings or MoonGel® damper pads. Both the rings and the damper pads can decrease the decay rate by up to 6 dB per second. Mylar rings are to be purchased in the appropriate size – for instance, a 12-inch Mylar ring is ideal if a drumhead is 12 inches in diameter. The ideal placement of a MoonGel® damper pad is 120° relative to the drumstick position. Dampers are often used to polish the sound quality of the drums and can be used to protect hearing health when combined with other methods (Worland & Miyahira, 2018).

Administrative Strategies

Administrative noise control is the reduction of sound exposure by limiting the time of exposure for an individual person. This can be done by sharing the job task with more than one person. Having a different drummer rotate in and out of a band or orchestra is not likely. However, the time of exposure could be limited in some instances, such as shortened practice times with quiet rest periods in between, or shortened performances. After especially loud performances or exposures, NIOSH recommends that percussionists give their ears an 18-hour break in after excessive noise exposure (NIOSH, 2015).

Personal Protective Equipment – Personal Hearing Protective Devices

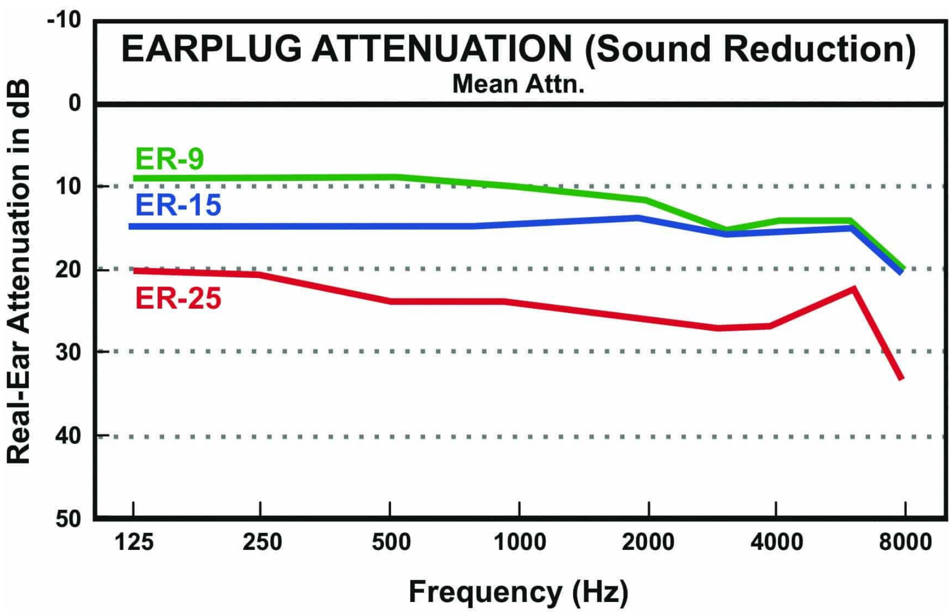
Personal protective equipment (PPE) is worn by the drummer or listener to protect them on an individual level. The only person protected by PPE is the individual that is wearing it and it is dependent on proper fit. Personal HPDs are a form of PPE that may be used during musician practice and performance to attenuate damaging sounds.

Different types of HPDs should be considered for musician use. Conventional passive hearing protection including foam earplugs that are utilized in an industrial setting may result in an undesirable effect on the sound quality, oftentimes a hollow sound due to increased attenuation at the high frequencies relative to the low frequencies (Chasin, 2010).

In 1988, a company called Etymotic Research, Inc. developed a high-fidelity propriety-tuned resonator and acoustic resistor incorporated into an earplug that attenuates approximately 15 dB over a wide range of frequencies. These earplugs today are called ETY•Plugs™ or ER20XS earplugs (https://www.etymotic.com/passive-hearing-protection/). They are widely accepted by musicians due to their even attenuation across a wide range of frequencies and replication of the natural acoustic response of the ear canal. These flanged devices come in a standard or large size and should be sized appropriately to achieve the desired attenuation. Etymotic Research, Inc. also developed the same technology for application within custom earmolds. The amount of attenuation can be changed by selecting one of three attenuator buttons (filters); 9 dB, 15 dB, or 25 dB. The ER-25 custom earplug attenuates approximately 25 dB over a wide range of frequencies. Figure 2.5 shows the attenuation of the different filters from 1.25-8 kHz. Because of the higher intensity sounds produced by a drum set, the ER-25 earplugs are the optimal choice for most percussionists (Chasin, 2010). Many musicians use more than one filter, as they may not need as much attenuation when practicing as when performing live. To obtain custom hearing protection, the musician must go to an informed and trained audiologist. The impressions are then sent to Etymotic Research or an earmold laboratory that complies with rigorous standards of construction so that the same "flat" attenuation is achieved regardless of where the custom hearing protection is manufactured. This includes sound bore dimensions, canal length, and an acoustic mass measurement. Once the product is ready to be fit, the audiologist or other hearing healthcare professional can verify the attenuation using real-ear measurements (Chasin, 2010).

Figure 2.5

Etymotic Earplug Average Attenuation by Filter



Note. Reproduced from Johnson, P. (2014). The High Notes of Musicians Earplugs. The Hearing Review. https://hearingreview.com/hearing-products/accessories/earmolds/high-notes-musicians-earplugs with permission from a Hearing Lab Technician at Etymotic Research, Inc.

The maximum power output should be measured with the HPD in the ear canal to verify that the hearing protection is properly attenuating across the standard frequencies. First, an otoscopic evaluation should be conducted to ensure the ear canal is healthy. Next, the audiologist should measure the MPO. Place the probe tube in the ear canal, about 5 mm away from the tympanic membrane. Next, the audiologist should place a dab of a water-based lubricant over the sleeve of the musician's earplug to reduce the risk of a slit leak which would act like a vent and distort the probe microphone results. Next, the musician should be placed about 0.45 to 0.6 m away from a loudspeaker at 0º azimuth and the audiologist initiates the MPO measurement. The ER-15 plug should provide 15- to 21 dB of attenuation across the frequencies 2-8 kHz. If adequate attenuation is not reached, the earmold should be remade (Fligor, 2002; Pumford & Sinclair, 2001).

Although percussionists are often exposed to high-intensity sounds through their music, there are other factors to consider when choosing an HPD. Chasin (2010) measured a drummer striking a practice pad without hearing protection, with ER-25 hearing protection, and with industrial foam earplugs. He measured the average intensity of the sound produced by the drummer. As measured in the environment, when the drummer was playing without hearing protection, the average intensity was 103 dBA; when the drummer was playing while wearing ER-25 earplugs, the intensity was 104 dBA, and while the drummer was playing while wearing industrial foam earplugs, the intensity was 113 dBA. This increase in intensity is due to using a stronger force to strike the drumhead. This increased force over time may result in arm or wrist damage. When choosing hearing protection, percussionists should choose one that protects their hearing while not over-attenuating the sound.

Etymotic Research, Inc. has also released an electronic hearing protector for musicians (Music PRO Elite® https://www.etymotic.com/product/music-pro-elite/), marketed to band/orchestra directors, performers, front-of-house crew, entertainment industry support staff, security personnel, and audiences. The passive fit of the hearing protector attenuates ambient sounds and loud percussive sounds, while the electronic circuity automatically changes the output levels as sound input levels change (compression). These earplugs will gradually provide

9 or 15 dB of sound reduction, with “natural hearing” restored when attenuation is not applied to levels below 85 dBA. It is fit to the ear with sized flanged ear tips.

There are a variety of other commercial custom and non-custom passive or electronic “musicians” hearing protection devices that have come to market since the development of the Etymotic Research, Inc. products. However, there are no product guidelines in the U.S. that would assure the same acoustic performance across products in terms of fidelity. Consumers and audiologists should review the technical specifications closely before selecting or recommending a product.

Personal Protective Equipment – In-The-Ear Monitors

Another device that a percussionist may benefit from is an in-the-ear monitor. These are either foam plugs or custom-made products that contain a speaker that fits directly into the percussionist’s ear. They are often fit binaurally, although can be fit monaurally, and connected to an amplifier via cable or a wireless route. They may also come in the form of a floor wedge speaker; however, the sound is then broadcasted to all the musicians onstage instead of to an individual musician. When playing with a band, the percussionist can tune into various musicians in the band, as well as their instrument, at their desired sound mix and intensity level. For proper protection, the musician should use a quiet but acceptable level in their monitors for maximum hearing safety. In-the-ear monitors are passive HPDs, however are only protective if the musician is using a safe output level. If they are using an unsafe output level the monitors are not protective and may be creating damage to the musician’s hearing. Federman and Ricketts published a study in 2008 that evaluated a singer’s preferred listening levels and minimum acceptable listening levels for in-the-ear monitors in the presence of simulated crowd noise, background music, and the musician’s own voice. They found that the average preferred listening level was 110.3 dBA, and the average minimum acceptable listening level was 103.2 dBA (Federman and Ricketts, 2008). Following the OSHA regulation, the musician has reached a 100% noise dose after 15 minutes (OSHA, 1983a), and following NIOSH's more conservative guidelines, the musician is at a 100% dose after one minute of exposure (NIOSH, 1998). To prevent overexposure from in-the-ear monitors Dr. Michael Santucci, founder of a company called Sensaphonics, has developed an in-the-ear monitor with a noise dosimeter incorporated into it. This may act as an indicator to the musician as to the intensity level they are exposing themselves to through their monitors and allows them to receive ongoing feedback regarding their exposure (Santucci, 2023). In-the-ear monitor performance can also be verified using real-ear-at-threshold attenuation measurements or microphone-in-real-ear measurements (Wartinger, Vasquez, and Fitzgerald, 2024).

Musicians Acceptance of Hearing Protective Devices

Although the use of hearing protection and in-the-ear monitors can reduce the sound exposure of the musician, their acceptance varies. Hoffman et al. (2006) conducted a study in which they administered a questionnaire to musicians, both amateur and professional, and collected audiometric data on each of the participants. Out of 291 musicians asked how often they wear HPDs during performances, 33% reported that they sometimes or always do. Out of the 281 musicians who were asked how often they wear PPE during practice, 69% reported they sometimes or always do. Professional musicians were more likely to wear PPE during practice and performance than amateur musicians. Foam earplugs were most commonly used amongst the musicians. Overall, musicians who wore any sort of HPD had consistently better hearing thresholds than those who did not report HPD use (p=0.01), which reinforces the efficacy of hearing protective devices on an individual level.

Even with published guidelines about how to protect hearing and the many options available to decrease the exposure of the musicians, Callahan et al., (2011) found that attitudes towards hearing protection are not always favorable amongst musicians. Although 74% of the musicians in their study had received information about hearing protection and its importance, none of the musicians wore HPDs all the time, and only 22% reported wearing them when exposed to what they perceived as potentially dangerous sounds. Following the audiometric monitoring section below are educational resources for musicians and listeners about the risks of MIHD and prevention materials designed to try to change the current beliefs and behaviors towards hearing health in musicians

Audiometric Monitoring

Musicians who are employed by companies with 11 or more employees are required to comply with OSHA regulations. Musicians are considered as part of the "service" industry. As stated in the OSHA 29 CFR 1910.95 (1983a) regulation, for employees that meet or exceed an 8-hour TWA sound exposure of 85 dBA, an audiometric monitoring protocol must be implemented. This testing must be at no cost to the employee. Testing must be done by an audiologist, otolaryngologist, or other physician or technician who is certified by the Council of Accreditation in Occupational Hearing Conservation (CAOHC). For OSHA, a baseline evaluation should be conducted within 6 months of the employee's first exposure that meets or exceeds the action level. Testing should be conducted after at least 14 hours without exposure to workplace noise (the use of hearing protective devices can be used). Following the baseline audiogram, the employee should obtain an updated audiogram annually to monitor for any changes. The audiologist should analyze the audiogram for a standard threshold shift (STS) which is defined as an average change of 10 dB or more at 2, 3, or 4 kHz in either ear. If an STS is present, a retest should occur 30 days after the annual examination. Record of these examinations should be kept through the full duration of the employment of the musician (OSHA, 1983a). Although OSHA limits the requirements for audiometric testing to .5, 1, 2, 3, 4, and 6 kHz, the best practice would be for audiologists to monitor all the test frequencies between .25 and 16 kHz and do so prior to employment as a musician (AAA., 2020).

Otoacoustic emission (OAE) testing is an objective measure of cochlear OHC function. Helleman et al. in 2018 conducted a literature review that suggests that OAE testing can be an accurate predictor of future hearing loss. Implementing OAE testing into the monitoring protocol for musicians may be beneficial as a prediction tool as well as an objective measure of cochlear OHC function.

Educational Resources for Musicians

Musicians should be provided with educational resources to properly learn how to protect their hearing health. Although there are many resources available online, the two resources discussed below are recommended due to their author credibility and provision of thorough and accurate information.

Dr. Marshall Chasin published *Hear the Music: Hearing Loss Prevention for Musicians* in 2010 as a guide for musicians who are learning to protect their hearing. The chapters include hearing and hearing loss, factors affecting hearing loss, strategies to reduce music exposure, five fact sheets for musicians, and frequently asked questions. The book is to be use as an educational resource for all musicians including vocalists, as well as those who play reeded woodwinds, flutes, small strings, large strings, brass, percussion and amplified instruments (Chasin, 2010). Dr. Chasin's book is a free resource available online and can be accessed at https://musicandhearingaids.org/wp-content/uploads/sites/35/2017/06/Chasin-2010-Hear-the-Music.pdf (Chasin, 2010).

The British Broadcasting Corporation (BBC) published an educational resource in 2011 for musicians entitled "Music, Noise and Hearing: How to Play your Part. This guide was published because the BBC believed that because of the high number of musicians they employed, it was their duty to provide education about how to protect their hearing health. This publication can be accessed at https://www.bbc.com/safety/documents/safety-musician_noise_guide_part_i_revised.pdf. This document is written to be read in full, skimmed for main ideas which are highlighted in yellow shaded boxes, or downloaded in a speed-read version to be accessible for anyone interested in the material. It teaches about the basics of hearing, noise exposure, the damage over-exposure can cause, and ways to protect hearing health. Also included throughout the document are quotations from musicians discussing their experience with HPDs and safe listening habits. These are found in the blue-shaded boxes (Hansford, 2016). Similar to Dr. Chasin's book, BBC's document can be useful for all musicians including vocalists or those who play a musical instrument, such as drums.

Providing accurate information to musicians on an individual level is the first step for audiologists who work with musicians. Moving forward the audiologist should reference the previously outlined best practice standards for properly and accurately providing audiologic care to musicians.

CHAPTER III

CRITICAL APPRAISAL OF THE RESEARCH AND FUTURE DIRECTIONS

Gaps in Existing Literature

The research currently available for audiologists who work with musicians is outlined and discussed above. In research, there is a need for clarification of terminology and formal verification of advertised products. There is also a need for employer-based hearing conservation programs for musicians. The following section highlights these gaps in the current literature.

Music Exposure versus Noise Exposure

It is unknown how appropriate the damage-risk criteria in occupational guidelines are for musicians, because of the systematic differences between noise and music such as the spectral content and the dynamic variation. Musicians also do not typically follow the same working hours that the occupational regulations and guidelines are based on. Instead of working a 40-hour work week, 5 days a week, a musician's exposure is during practice and performance time that varies greatly. Although their exposure time may be shorter, the noise dose may meet or exceed that of an industrial employee depending on the amplification of the sound and the setting in which the musician is rehearsing or performing (American Academy of Audiology, 2020). There is a need to develop damage-risk criteria specific to music exposures and consider the kurtosis of the noise as an additional risk factor (Nato Research and Technology Organization Neuilly-Sur-Seine, 2000; Qui et al., 2020; Rasmussen et al., 2010; Smoorenburg, 2003; Zhao et al., 2010).

There is also research regarding the emotional response to the sound source which may reduce the risk of a NIHL or MIHD. Hörmann et al (1970) published a study about the emotional effects of TTS at 4 kHz. They compared the TTS of two groups of participants – one group was given a 95 dB noise for 30 minutes as a reward for completing a task and the other group was given the same noise exposure as a punishment. The group given the exposure as a reward had a TTS of 12.8 dB while the group given the exposure as a punishment had an average TTS of 18.1 dB. There is also older literature suggesting that music may "condition" the ear and be less harmful than industrial noise (Henselman et al., 1994; Lindgren & Axelsson, 1988). It may be useful for future research to evaluate the efferent auditory response as an explanation of this phenomenon, and further explore the role of the central auditory system on individual susceptibility to sound over-exposure.

Formal Verification of Advertised Hearing Protective Devices

Chapter 2 discussed various ways that a percussionist may protect their hearing. While some of these methods (e.g., earplugs) are verified to be effective, there is a lack of formal research to support the advertised protection from products such as the SilentStroke drumheads and the low-volume L80 cymbals. Customer reviews claim a reduction in sound intensity, but formal research should be done to verify the efficacy and give a numeric value to the amount of attenuation. There may be a need to develop standardized methods of measurement for the attenuation of these products.

Employer-Based Hearing Conservation Programs

Businesses that employ over 10 employees must abide by the OSHA 29 CFR 1910.95 (OSHA, 1983) regulation. This includes an employer-based hearing conservation program if the employees are exposed above the action level (OSHA, 1983a). Businesses such as nightclubs and performance halls will often be required to abide by the OSHA 29 CFR 1910.95 (OSHA, 1983a) regulation. There is no current data about how many employed musicians are enrolled in these required employer-based hearing conservation programs. Further inspection is needed to ensure that musicians are receiving the employer support they are entitled to by law.

Challenges

Audiologists have a responsibility to educate musicians about hearing health care. The challenge is that it is up to the musician to hold themselves accountable for their hearing health. In the short term, behaviors may change, however long-term behavior change and changes in beliefs and attitudes are more difficult to accomplish. Callahan et al. (2011) conducted a study to assess the attitudes toward hearing protection in collegiate musicians. They found that 79% of the students reported that they never wear hearing protection when they are playing their instrument in a practice setting and 90% never wear hearing protection when they are playing in a performance setting. The reason given for not wearing HPDs in 53% of the respondents was that they did not feel that they were necessary (Callahan et al., 2011). Additionally, musicians are not seeking audiologic intervention until there are symptoms of a MIHD already present (AAA, 2020). They may also want to have additional privacy protections to hide their MIHD. There is a need to make routine visits to the audiologist a norm amongst musicians to promote preventative care as well as for audiologists to properly select, fit, and verify HPDs for musicians.

One way to overcome this challenge is through early education. This, however, has its challenges. Folmer et al., (2002) discuss three primary challenges to early education regarding hearing health within the school system. First, there is a lack of public awareness of NIHL and MIHDs. Because of this, resources are not allocated to prevention efforts and priorities are focused elsewhere. Second, there is also no standard as to how to disseminate prevention programs into schools. Materials for these programs are expensive and teachers and audiologists do not always have the resources to support the purchase of the program materials. Finally, the prevention program is not sustainable if the key individual retires, moves away, or becomes unavailable. To overcome this, Folmer et al., (2002) suggested that validated hearing healthcare programs should be disseminated into the classroom. Classroom time is in high demand; however, prevention programs contain many science, technology, engineering, and mathematics (STEM) related topics that may promote adaptation by school administration (Folmer et al., 2002). More recently, programs such as Dangerous Decibels® have been developed and shown to be effective at changing knowledge, attitudes, and intended behaviors in youth and high school students (Griest et al., 2007; Welch et al., 2019). This program can be adapted for delivery to music students and can be delivered in alternative settings where youth gather, such as after-school programs, youth groups, faith groups, and music camps. It would be beneficial to research to determine the effectiveness of Dangerous Decibels in promoting hearing health in musicians.

Summary

Noise-induced hearing loss affects 40 million people across the United States aged 20-69. Within this group are percussionists, who are exposed to high levels of sound through practice and performance of their instrument. One study suggests that maximum intensity can reach 123 dBA during orchestral performances (Pawlaczyk-Łuszczyńska et al., 2011). Noise-induced hearing loss can be temporary or permanent, and it can affect one or both ears. It presents audiometrically as normal hearing thresholds (≤20-25 dB HL) in the low frequencies and at 8 kHz with a notch, typically in the range of 3-6 kHz (Sataloff et al., 1983; Ryan et al., 2016). However, with continued over-exposure, hearing thresholds will worsen, and hearing loss will occur in a broader frequency range and negatively impact speech understanding, especially in noisy listening environments. When comparing audiometric configurations among musicians from different instrument groups, a statistically significant number of percussionists had unilateral notches at 6 kHz when compared to the other instrument groups, possibly due to the layout of the drum set and the sound intensity of different drum set components (Phillips et al., 2010). In addition to hearing loss, other MIHDs include tinnitus, distortion, hyperacusis, diplacusis, and dysacusis. MIHD may be preventable if proper precautions are taken (NHCA, 2018).

There are published standards and position statements for musicians from many organizations including NHCA (2018), NIOSH (1998), AAA (AAA, 2020), and NAfME (2007) that outline definitions of MIHD, how they occur, and how to prevent them. Hearing loss prevention should involve teamwork among professionals including band/music directors, music educators, venue managers, and audiologists. Ideally, audiologists should be involved from the beginning of a musician's journey, but commonly they are included only with the onset of MIHD symptoms. Prevention strategies include elimination, substitution, engineering controls, administrative controls, and PPE. Realistically, percussionists' best options are substitution of the sound by the utilization of electronic drums; engineering controls such as drum shields, seat shakers, or instrument modification; or appropriately selected, fit, and verified hearing protective devices and/or in-the-ear monitors.

Moving forward, prevention efforts should be continued and expanded into the school setting to change hearing health behaviors from the start of the musician's career. Further research is needed to create sound exposure guidelines that relate directly to the spectral content produced by music and exposure times that relate more to musicians. Audiologists have a duty to educate and serve musicians about their hearing health. As the prevention team works together to educate and serve musicians, awareness will spread and MIHD will be prevented.

REFERENCES

American Academy of Audiology. (2020). Clinical Consensus Document: Audiological Services for Musicians and Music Industry Personnel. https://www.audiology.org/wp-content/uploads/2021/05/Musicians-Consensus-Doc_Final_1.23.20.pdf

Axelsson, A., Eliasson, A., & Israelsson, B. (1995). Hearing in Pop/Rock Musicians: A Follow-up Study. *Ear and Hearing, 16*(3), 245-253. https://doi.org/10.1097/00003446-199506000-00001

Axelsson, A., & Lindgren, F. (1981). Hearing in classical musicians. *Acta oto-laryngologica. Supplementum*, *377*, 3–74.

Backus, J. (1977). Chapter 14. In *The Acoustical Foundations of Music* (pp. 299–306). essay, W. W. Norton & Company.

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014). Auditory and non-auditory effects of noise on health. *The Lancet, 383*(9925), 1325-1332. https://doi.org/10.1016/s0140-6736(13)61613-x

Behroozi, K. B., & Luz, J. (1997). Noise-related Ailments of Performing Musicians: A Review. *Medical Problems of Performing Artists*, *12*(1), 19–22.

Berglund, B., Lindvall, T., Schwela, D. H., & World Health Organization. (1999). Guidelines for community noise.

Bielefeld, E. C. (2013). Reduction in impulse noise-induced permanent threshold shift with intracochlear application of an NADPH oxidase inhibitor. *Journal of the American Academy of Audiology*, *24*(06), 461-473.

Brownell, W. E. (1997). How the ear works-nature's solutions for listening. *The Volta review*, *99*(5), 9.

Callahan, A. J., Lass, N. J., Foster, L. B., Poe, J. E., Steinberg, E. L., & Duffe, K. A. (2011). Collegiate musicians' noise exposure and attitudes on hearing protection. *Hearing Review*, *18*(6), 36-44.

Carroll, Y. I., Eichwald, J., Scinicariello, F., Hoffman, H. J., Deitchman, S., Radke, M. S., Themann, C. L., & Breysse, P. (2017). Vital Signs: Noise-Induced Hearing Loss Among Adults — United States 2011-2012. *MMWR. Morbidity and Mortality Weekly Report, 66*(5), 139-144. https://doi.org/10.15585/mmwr.mm6605e3

Centers for Disease Control and Prevention. (2023). *Hierarchy of controls*. Centers for Disease Control and Prevention. https://www.cdc.gov/niosh/topics/hierarchy/default.html

Chasin, M. (2010). *Hear the music: Hearing loss Prevention for Musicians*. Musicians' Clinics of Canada.

Chesky, K. (2008). Preventing Music-Induced Hearing Loss. *Music Educators Journal, 94*(3), 36-41. https://doi.org/10.1177/002743210809400308

Chris. (2021). *Mesh head guide for drummers: What's best for your budget?* drumfaster.com. https://drumfaster.com/advice-for-drummers/buying-guides/mesh-head-buying-guide/#:~:text=Mesh%20heads%20are%20a%20type,expect%20from%20a%20drum%20head.

Chung, I.-S., Chu, I. M., & Cullen, M. R. (2012). Hearing effects from intermittent and continuous noise exposure in a study of Korean factory workers and firefighters. *BMC Public Health, 12*(1). https://doi.org/10.1186/1471-2458-12-87

Coles, R. R. A., Garinther, G. R., Hodge, D. C., & Rice, C. G. (1968). Hazardous Exposure to Impulse Noise. *The Journal of the Acoustical Society of America, 43*(2), 336-343. https://doi.org/10.1121/1.1910785

Davis, R. R., & Clavier, O. (2017). Impulsive noise: A brief review. *Hearing Research, 349*, 34-36. https://doi.org/10.1016/j.heares.2016.10.020

Driscoll, D. P. (2022). Chapter 2: Physics of Sound and Vibration. In E. H. Berger, D. K. Meinke, R. L. Neitzel, & K. Bright (Eds.), *The Noise Manual* (6th ed., pp. 11–27). essay, American Industrial Hygiene Association.

Dunn, D. E., Davis, R. R., Merry, C. J., & Franks, J. R. (1991). Hearing loss in the chinchilla from impact and continuous noise exposure. *The Journal of the Acoustical Society of America, 90*(4), 1979-1985. https://doi.org/10.1121/1.401677

Edgoose, S. (2023). *How do electronic drums work?*. Yamaha Music. https://hub.yamaha.com/drums/d-electronic/how-do-electronic-drums-work/

Federman, J., & Ricketts, T. (2008). Preferred and Minimum Acceptable Listening Levels for Musicians While Using Floor and In-Ear Monitors. *Journal of Speech, Language, and Hearing Research, 51*(1), 147-159. https://doi.org/10.1044/1092-4388(2008/011)

Fletcher, H., & Bassett, I. G. (1978). Some Experiments with the Bass Drum. J. Acoust. Soc. Am. 64, S. 1570.

Fletcher, H., & Munson, W. A. (1933). Loudness, Its Definition, Measurement and Calculation. *The Journal of the Acoustical Society of America, 5*(2), 82-108. https://doi.org/10.1121/1.1915637

Fligor, B. (2002). Clinical Verification of Custom-Fitted Musicians' Earplugs.

Folmer, R. L., Griest, S. E., & Martin, W. H. (2002). Hearing Conservation Education Programs for Children: A Review. *Journal of School Health, 72*(2), 51-57. https://doi.org/10.1111/j.1746-1561.2002.tb06514.x

Gan, R. Z., Nakmali, D., Ji, X. D., Leckness, K., & Yokell, Z. (2016). Mechanical damage of tympanic membrane in relation to impulse pressure waveform - A study in chinchillas. *Hearing Research, 340*, 25-34. https://doi.org/10.1016/j.heares.2016.01.004

Garner, M. J., & Brett, S. J. (2007). Mechanisms of Injury by Explosive Devices. *Anesthesiology Clinics, 25*(1), 147-160. https://doi.org/10.1016/j.anclin.2006.11.002

Gelfand, S. A. (2017). Conductive mechanism. *Hearing*, 69-94. https://doi.org/10.1201/9781315154718-3

Griest, S. E., Folmer, R. L., & Martin, W. H. (2007). Effectiveness of "Dangerous Decibels," a School-Based Hearing Loss Prevention Program. *American Journal of Audiology, 16*(2). https://doi.org/10.1044/1059-0889(2007/021)

Gulick, W. L., Gescheider, G. A., & Frisina, R. D. (1989). *Hearing: Physiological acoustics, neural coding, and psychoacoustics*. Oxford University Press.

Hamernik, R. P., & Hsueh, K. D. (1991). Impulse noise: Some definitions, physical acoustics and other considerations. *The Journal of the Acoustical Society of America*, *90*(1), 189–196. https://doi.org/10.1121/1.401287

Hamernik, R. P., Qiu, W., & Davis, B. (2007). Hearing loss from interrupted, intermittent, and time varying non-Gaussian noise exposure: The applicability of the equal energy hypothesis. *The Journal of the Acoustical Society of America, 122*(4), 2245-2254. https://doi.org/10.1121/1.2775160

Hansford, R. (2016). Music, Noise & Hearing: How to play your part. I Musicians' Guide. 10.13140/RG.2.1.4936.1680.

Heckert, N., Filliben, J., Croarkin, C., Hembree, B., Guthrie, W., Tobias, P., & Prinz, J. (2002). Handbook 151: NIST/SEMATECH e-Handbook of Statistical Methods, NIST Interagency/Internal Report (NISTIR), National Institute of Standards and Technology, Gaithersburg, MD. https://doi.org/10.18434?M32189

Helleman, H. W., Eising, H., Limpens, J., & Dreschler, W. A. (2018). Otoacoustic emissions versus audiometry in monitoring hearing loss after long-term noise exposure–a systematic review. *Scandinavian journal of work, environment & health*, *44*(6), 585-600.

Henderson, D., & Hamernik, R. P. (1986). Impulse noise: Critical review. *The Journal of the Acoustical Society of America*, *80*(2), 569–584. https://doi.org/10.1121/1.394052

Henderson, D., Subramaniam, M., Gratton, M. A., & Saunders, S. S. (1991). Impact noise: The importance of level, duration, and repetition rate. *The Journal of the Acoustical Society of America, 89*(3), 1350-1357. https://doi.org/10.1121/1.400658

Henselman, L. W., Henderson, D., Subramaniam, M., & Sallustio, V. (1994). The effect of ‘conditioning’exposures on hearing loss from impulse noise. *Hearing research*, *78*(1), 1-10.

Heupa, A. B., Gonçalves, C. G. de O., & Coifman, H. (2011). Efeitos do ruído de impacto na audição de militares. *Brazilian Journal of Otorhinolaryngology, 77*(6), 747-753. https://doi.org/10.1590/s1808-86942011000600011

Hoffman, J. S., Cunningham, D. R., & Lorenz, D. J. (2006). Auditory Thresholds and Factors Contributing to Hearing Loss in a Large Sample of Percussionists. *Medical Problems of Performing Artists, 21*(2), 47-58. https://doi.org/10.21091/mppa.2006.2011

Hong, O., Kerr, M. J., Poling, G. L., & Dhar, S. (2013). Understanding and preventing noise-induced hearing loss. *Disease-a-Month, 59*(4), 110-118. https://doi.org/10.1016/j.disamonth.2013.01.002

Jacobsen, F. (1997). Sound intensity and its measurement. In *Fifth International Congress on Sound and Vibration*.

Jansen, E. J. M., Helleman, H. W., Dreschler, W. A., & de Laat, J. A. P. M. (2009). Noise induced hearing loss and other hearing complaints among musicians of symphony orchestras. *International Archives of Occupational and Environmental Health, 82*(2), 153-164. https://doi.org/10.1007/s00420-008-0317-1

Jaroszewski, A., Rogowski, P., & Rakowski, A. (2000). Sound pressure levels in emission of percussion instruments during training sessions. *Archives of Acoustics*, *25*(3).

Johnson, D. W., Sherman, R. E., Aldridge, J., & Lorraine, A. (1985). Effects of Instrument Type and Orchestral Position on Hearing Sensitivity for 0.25 to 20 kHz in the Orchestral Musician, Scandinavian Audiology, 14:4, 215-221. https://doi.org/10.3109/01050398509045944

Kryter, K. D., Ward, W. D., Miller, J. D., & Eldredge, D. H. (1966). Hazardous Exposure to Intermittent and Steady-State Noise. *The Journal of the Acoustical Society of America, 39*(3), 451-464. https://doi.org/10.1121/1.1909912

Lataye, R., & Campo, P. (1996). Applicability of the *l*eq as a damage-risk criterion: An animal experiment. *The Journal of the Acoustical Society of America*, *99*(3), 1621–1632. https://doi.org/10.1121/1.414885

le Clercq, C. M. P., van Ingen, G., Ruytjens, L., & van der Schroeff, M. P. (2016). Music-induced Hearing Loss in Children, Adolescents, and Young Adults: A Systematic Review and Meta-analysis. *Otology & Neurotology, 37*(9), 1208-1216. https://doi.org/10.1097/mao.0000000000001163

Lee, L.-K., Kang, T.-S., Ham, S.-H., Kim, J.-I., Yang, Y.-S., & Yoon, C.-S. (2011). Noise exposure according to the time activity pattern and duties of firefighters. *Korean Journal of Environmental Health Sciences*, *37*(2), 94–101. https://doi.org/10.5668/jehs.2011.37.2.094

Liang, J., Yokell, Z. A., Nakmaili, D. U., Gan, R. Z., & Lu, H. (2017). The effect of blast overpressure on the mechanical properties of a chinchilla tympanic membrane. *Hearing Research, 354*, 48-55. https://doi.org/10.1016/j.heares.2017.08.003

Lindgren, F., & Axelsson, A. (1988). The influence of physical exercise on susceptibility to noise-induced temporary threshold shift. *Scandinavian Audiology*, *17*(1), 11-17.

Martin, W. H., Griest, S. E., Sobel, J. L., & Howarth, L. C. (2013). Randomized trial of four noise-induced hearing loss and tinnitus prevention interventions for children. *International Journal of Audiology*, *52*(sup1), S41-S49.

MasterClass. (2021). *Guide to cymbals: 6 common types of cymbals - 2023*. https://www.masterclass.com/articles/guide-to-cymbals

Mayorga, M. A. (1997). The pathology of primary blast overpressure injury. *Toxicology, 121*(1), 17-28. https://doi.org/10.1016/s0300-483x(97)03652-4

Moore, P. V., & Lusk, S. L. (1997). Noise exposures. *AAOHN Journal*, *45*(8), 397–410. https://doi.org/10.1177/216507999704500806

Murphy, E., & King, E. A. (2016). Smartphone-based noise mapping: Integrating sound level meter app data into the strategic noise mapping process. *Science of The Total Environment, 562*, 852-859. https://doi.org/10.1016/j.scitotenv.2016.04.076

Murphy, W. J., Flamme, G., Tasko, S. M., Deiters, K. K., Finan, D. S., Meinke, D. K., Lankford, J. E., & Stewart, M. (2022). Measuring impulse insertion loss of hearing protection device using high-level impulse noise. *The Journal of the Acoustical Society of America, 152*(4_Supplement), A162-A162. https://doi.org/10.1121/10.0015890

National Association for Music Education. (2007). Position Statement: Health in Music Education. https://nafme.org/resource/health-in-music-education/

National Hearing Conservation Association. (2018). *Recreational Music Exposure.* Retrieved January 7, 2023, from https://www.hearingconservation.org/assets/docs/MIHD_Position_Statement_FINA.pdf

National Institutes of Health. (2014, March). *Noise-induced hearing loss - NIDCD*. Retrieved June 13, 2022, from https://www.nidcd.nih.gov/sites/default/files/Documents/health/hearing/NoiseInducedHearingLoss.pdf

Nato Research and Technology Organization Neuilly-Sur-Seine. (2000). Damage Risk from Impulse Noise. (les Risques auditifs et extra auditifs des bruits impulsionnels).

Neitzel, R. L., Heikkinen, M. S. A., Williams, C. C., Viet, S. M., & Dellarco, M. (2016). Pilot study of methods and equipment for in-home noise level measurements. *Applied Acoustics, 102*, 1-11. https://doi.org/10.1016/j.apacoust.2015.08.018

Newman, J. (2008). Waves and Resonance. In: Physics of the Life Sciences. Springer, New York, NY. https://doi.org/10.1007/978-0-387-77259-2_10

NIOSH. (2015). Reducing the risk of hearing disorders among musicians. By Kardous C, Themann C, Morata T, Reynolds J, Afanuh S Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. DHHS (NIOSH) Publication No. 2015–184.

Office of Noise Abatement and Control. (1974). *Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety*. Environmental Protection Agency, Office of Noise Abatement and Control.

OSHA. (1983a). “Occupational Noise Exposure; Hearing Conservation Amendment; Final rule,” Occup. Safety and Health Admin., 29CFR 1910.95. *Fed. Regist. 48(46), 9738-9785*

Ostri, B., Eller, N., Dahlin, E., & Skylv, G. (1989). Hearing Impairment in Orchestral Musicians. *Scandinavian Audiology, 18*(4), 243-249. https://doi.org/10.3109/01050398909042202

Patterson, J. H., Jr., & Hamernik, R. P. (1997). Blast overpressure induced structural and functional changes in the auditory system. *Toxicology, 121*(1), 29-40. https://doi.org/10.1016/s0300-483x(97)03653-6

Patuzzi, R. (1998). Exponential onset and recovery of temporary threshold shift after loud sound: evidence for long-term inactivation of mechano-electrical transduction channels. *Hearing Research, 125*(1-2), 17-38. https://doi.org/10.1016/s0378-5955(98)00126-9

Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zamojska, M., & Śliwinska-Kowalska, M. (2011). Evaluation of Sound Exposure and Risk of Hearing Impairment in Orchestral Musicians. *International Journal of Occupational Safety and Ergonomics, 17*(3), 255-269. https://doi.org/10.1080/10803548.2011.11076892

Petterson, L. (2023, June 25). *Review: Remo Silentstroke Low Volume Drum Heads*. Silent Drumming. https://www.drumsilent.com/review-remo-silentstroke-drum-heads/

Pfander, F., Bongartz, H., Brinkmann, H., & Kietz, H. (1980). Danger of auditory impairment from impulse noise: A comparative study of the CHABA damage-risk criteria and those of the Federal Republic of Germany. *The Journal of the Acoustical Society of America, 67*(2), 628-633. https://doi.org/10.1121/1.383886

Phillips, S. L., Henrich, V. C., & Mace, S. T. (2010). Prevalence of noise-induced hearing loss in student musicians. *International Journal of Audiology, 49*(4), 309-316. https://doi.org/10.3109/14992020903470809

Pourbakht, A., & Yamasoba, T. (2003). Ebselen attenuates cochlear damage caused by acoustic trauma. *Hearing research*, *181*(1-2), 100-108.

Pumford, J., & Sinclair, S. (2001). Real-ear measurement: Basic terminology and procedures. *Audiology Online*.

Purves, D., Augustine, G. J., & Fitzpatrick, D. (2001). Neuroscience. 2nd edition. Sunderland (MA): Sinauer Associates; The Audible Spectrum. Available from: https://www.ncbi.nlm.nih.gov/books/NBK10924/

Qui, W., Murphy, W. J., & Suter, A. (2020). Kurtosis: A new tool for noise analysis. *Acoustics Today, 16(4), 39*. https://doi.org/10.1121/at.2020.16.4.39

Rasmussen, P., Flamme, G., Stewart, M., Meinke, D., & Lankford, J. (2010). Measuring recreational firearm noise. *The Journal of the Acoustical Society of America, 127*(3_Supplement), 1794-1794. https://doi.org/10.1121/1.3384002

Remo. (n.d.). *Silentstroke.* https://remo.com/product/silentstroke

Roberto, M., Hamernik, R. P., & Turrentine, G. A. (1989). Damage of the auditory system associated with acute blast trauma. *Annals of Otology, Rhinology & Laryngology*, *98*(5suppl), 23–34. https://doi.org/10.1177/00034894890980s506

Rossing, T. D. (2001). Acoustics of percussion instruments: Recent progress. *Acoustical Science and Technology, 22*(3), 177-188. https://doi.org/10.1250/ast.22.177

Rossing, T. D., Bork, I., Zhao, H., & Fystrom, D. O. (1992). Acoustics of snare drums. *The Journal of the Acoustical Society of America, 92*(1), 84-94. https://doi.org/10.1121/1.404080

Rossing, T. D., Moore, F. R., & Wheeler, P. A. (2001). Chapter 13. In *The Science of Sound* (pp. 272–309). essay, Addision Wesley.

Royster, J. D., Royster, L. H., & Killion, M. C. (1991). Sound exposures and hearing thresholds of symphony orchestra musicians. *The Journal of the Acoustical Society of America, 89*(6), 2793-2803. https://doi.org/10.1121/1.400719

Ryan, A. F., Kujawa, S. G., Hammill, T., Le Prell, C., & Kil, J. (2016). Temporary and permanent noise-induced threshold shifts: a review of basic and clinical observations. *Otology & neurotology: official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology*, *37*(8), e271.

Sandell, J., Berntson, A., Sjösten, P., Blomgren, G., & Kähäri, K. (2007). Acoustic intervention in a live music club. *Acta Acustica United with Acustica*, *93*(5), 843-849.

Santucci, M. (2023). *In ear monitors - custom molded in ear monitors*. Sensaphonics. https://www.sensaphonics.com/

Sataloff, J., Sataloff, R. T., Yerg, R. A., Menduke, H., & Gore, R. P. (1983). Intermittent Exposure to Noise: Effects on Hearing. *Annals of Otology, Rhinology & Laryngology, 92*(6), 623-628. https://doi.org/10.1177/000348948309200618

Sataloff, J., Vassallo, L., & Menduke, H. (1969). Hearing Loss From Exposure to Interrupted Noise. *Archives of Environmental Health: An International Journal, 18*(6), 972-981. https://doi.org/10.1080/00039896.1969.10665521

Schmidek, M., & Carpenter, P. (1974). Intermittent noise exposure and associated damage risk to hearing of chain saw operators. *American Industrial Hygiene Association Journal*, *35*(3), 152–158. https://doi.org/10.1080/0002889748507017

Smoorenburg, G. F. (1982). Damage risk criteria for impulse noise.

Smoorenburg, G. F. (2003). Damage risk with impulse-noise exposure. In *Proceedings of the 8th International Congress on Noise as a Public Health Problem. ICBEN* (pp. 1-4).

Spongr, V. P., Henderson, D., & McFaddeen, L. (1998). Confocal microscopic analysis of the chinchilla organ of Corti following exposure to high-level impact noise. *Scandinavian Audiology-Supplement Only*, (48), 15-26.

Suter, A. (2017). Occupational Hearing Loss from Non-Gaussian Noise. *Seminars in Hearing, 38*(03), 225-262. https://doi.org/10.1055/s-0037-1603726

U.S. Department of Defense. (2010). Department of Defense *Instruction 6055.12: DoD Hearing Conservation Program.* Washington, DC: Department of Defense.

U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. (1998). *Occupational noise exposure*.

United States Department of Labor Occupational Safety and Health Administration. 1910.95 - Occupational noise exposure. | Occupational Safety and Health Administration. (1970). Retrieved June 13, 2022, from https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.95

Watson, F. R. (1916). An investigation of the transmission, reflection and absorption of sound by different materials. *Physical Review*, *7*(1), 125–132. https://doi.org/10.1103/physrev.7.125

Welch, D., Ma, E., & Reddy, R. (2019). Hearing-health intervention for nightclub staff. *Health Education Journal*, *78*(3), 273-287. https://doi.org/10.1177/0017896918800516

Wenmaekers, R. H. C., & Hak, C. C. J. M. (2015, May). Noise exposure of musicians the own instruments sound compared to the sound from others. In *10th European Congress and Exposition on Noise Control Engineering (Euronoise 2015)* (pp. 1-4).

West, D. (2021). Tone and training: Teaching drum kit students on acoustic versus electronic instruments. *Journal of Popular Music Education, 5*(2), 263-279. https://doi.org/10.1386/jpme_00061_1

Wiggins, I., & Liston, K. I. (2021). Sound pressure levels in close proximity to sound reinforcement loudspeakers.

Worland, R., & Miyahira, W. (2018). Physics of musical drum head damping using externally applied products. Proceedings of Meetings on Acoustics. https://doi.org/10.1121/2.0001011

World Health Organization. (2018). *Environmental noise guidelines for the European region*. World Health Organization. Regional Office for Europe.

Zalewski, T. (1906). Experimentelle untersuchungen uber die resistenzfahigkeit des trommelfells. *Z Ohrenheilkd*, *52*, 109-128.

Zhao, Y. M., Qiu, W., Zeng, L., Chen, S. S., Cheng, X. R., Davis, R. I., & Hamernik, R. P. (2010). Application of the kurtosis statistic to the evaluation of the risk of hearing loss in workers exposed to high-level complex noise. *Ear and hearing*, *31*(4), 527-532.

Zildjian. (n.d.). *16" L80 low volume crash*. https://zildjian.com/collections/cymbals-browse-by-types-crash/products/l80-low-volume-16-crash